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Alley width and slope position influence soil carbon storage, nutrient dynamics and hydrology at a mature silvoarable site, SW England

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ABSTRACT

Optimising benefits from agroforestry requires better understanding of spatial factors such as alley width and slope position. We sampled soil (0–50 cm) from a mature organic silvoarable site in SW England with tree rows at 12 and 24 m spacing to determine the impact of these factors on soil physical properties, carbon (C) storage and fertility. We consider how functioning differs in cropped alley and tree-row components, and how alley width influences trade-offs in ecosystem benefits. Benefits from rows extended into alleys which were 8.8 % less compacted and contained 70 % more available P than an adjacent, treeless control. Competition for nutrients and moisture was observed at the row-alley boundary, with lower subsoil concentrations attributable to tree root uptake. Agroforestry mitigated soil erosion despite being parallel to slope: in the control area 0.8 % more soil organic matter and a 3.5 % higher clay fraction was observed downslope than upslope, with no equivalent effect under agroforestry. Fertility traded off with alley width, with more N and P stored in 12 m alleys. Soil and tree-biomass C differences (700 kg C ha^{-1} year^{-1}) compared with the control were only significant in the 12 m system (110 stems ha^{-1}) and three times lower than estimated silvoarable contributions to future UK C budgets. Moreover, planting at lower densities (~50 stems ha^{-1}) is likely due to constraints of modern farm machinery. Assessment of silvoarable contributions to temperate ecosystem service provision must therefore consider additional benefits beyond C sequestration if agroforestry is to contribute to future landscape resilience.

1. Introduction

Agroforestry is promoted as a solution capable of reconciling food production and ecosystem service provision from farmland (Burgess, 1999; Araujo et al., 2012; Torralba et al., 2016; Judson et al., 2023). Arable soils are among the most degraded worldwide in terms of soil organic carbon (SOC) loss (Guo and Gifford, 2002; Wei et al., 2014), biodiversity loss (Robinson and Sutherland, 2002; Banerjee et al., 2024) and structural deterioration (Greenland, 1977), and schemes such as agroforestry which aim to attenuate these losses from arable land are critical for future climate resilience (IPCC, 2013; CCC, 2020; CCC, 2025). By incorporating a perennial, woody component, silvoarable agroforestry increases the spatial heterogeneity of conventional annual cropping systems, with potential concomitant benefits for soil functioning, food production and wider ecosystem service delivery from farmland. Demonstrated soil benefits from agroforestry include C sequestration (De Stefano and Jacobson, 2018; Mayer et al., 2022) improved nutrient cycling (Oelbermann and Voroney, 2007), altered hydrological functioning (Marshall et al., 2014; Monger et al., 2022b) and biodiversity improvements (Varah et al., 2013).

However, scaling up agroforestry in temperate areas has been restricted by limited information for practitioners on benefits and trade-offs specific to context, weak policy incentives and high capital cost (Sollen-Norrlin et al., 2020). In the United Kingdom, only 3.3 % of utilised agricultural land area is currently under agroforestry, less than half of the average value for Europe (den Herder et al., 2017). Recent policy has sought to address this with Sustainable Farming Incentive (SFI) payments supporting both establishment and management of low-density agroforestry (AGF1 and AGF2) (Defra, 2024), support for denser agroforestry systems (CAGF1, CAGF3) under the Countryside Stewardship scheme (Defra, 2025) and a target of 10 % agroforestry cover on arable land by 2050 in order to promote an extra 2.2 t ha^{-1} year^{-1}C storage (8 t CO_2e ha^{-1} year^{-1}) from silvoarable areas over 30 years (Woodland Trust, 2022). From both a policy and practitioner perspective, better understanding is needed on how ecosystem benefits are transferred laterally from rows of trees into cropped inter-row or

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'alley' areas. Valuable recent work has focussed on determining how soil function indicators vary with distance from unmanaged tree rows (e.g. Cardinael et al., 2015a; Mettauer et al., 2022; Vaupel et al., 2023). Yet significant knowledge gaps still exist related to system design for various practitioner contexts, interactions and trade-offs between ecosystem benefits and how these relate to specific farm objectives for planting.

The aim of this study is to consider how the spatial distribution of soil benefits in a silvoarable system is controlled by hillslope position and alley width, and the implications of these controls for ecosystem benefit delivery from agroforestry. Dealing with hillslope layout and choosing alley width are important considerations for adopters of temperate agroforestry, yet there is limited research on their effects on soil because dedicated, replicated experimental sites isolating them are very rare and little data exists to inform practitioner design choices. We use a working horticulture farm in Devon, SW England with mature agroforestry trees conducive to study these factors to begin the process of understanding the impacts of alley width and hillslope position on soil functions.

We compare two adjacent silvoarable plots with differing alley widths alongside a third, also adjacent, treeless control plot to address three research questions. The first asks how land-use change from arable to silvoarable influences soil function indicators – bulk density, saturated hydraulic conductivity, SOC and nutrient content – in tree and alley components of agroforestry systems compared with an identically-managed treeless control area. Secondly, we consider how soil functioning varies spatially across alley and row components of agroforestry, and with hillslope position. Thirdly, we consider how selection of silvoarable alley width influences trade-offs in benefit delivery, including whether agroforestry at these planting densities can contribute to nationally-determined targets for carbon (C) storage in soil and tree biomass.

2. Methodology

2.1. Study site

The study site is a certified organic arable and horticulture farm 5 km south of Exeter, southwest England. Mean annual precipitation is 829 mm and mean annual temperature is 10.9 °C (1991–2020, Exeter Airport, 11 km away) (Met Office, 2020). The soils of the study site are Eutric Chromic Endoleptic Cambisols of the Crediton Series: red, well-drained, very stony, loamy brown earths found on Permo-Triassic breccias and conglomerates predominantly in Devon (Cranfield University, 2022). Soil depths can exceed 1 m, and bedrock was not reached at the soil depths surveyed in this study (0–50 cm). The land is well-draining and easily worked in most conditions, with strong horticultural tradition in addition to mixed arable and grassland use. Agroforestry was first incorporated at the study site in 2002, the same year in which the farm was certified organic. This study focusses on this earlier area with 12 m wide alleys (hereafter referred to as 'AF_{12}'), and the second area planted in 2012 with 24 m wide alleys (hereafter referred to as'AF_{24}'), in addition to an adjacent treeless control area (hereafter referred to as 'Co') which has been managed in the same way as the alleys. Prior to establishment of agroforestry, all areas were in continuous arable cultivation.

Silvoarable agroforestry was first established using 12 m-spaced alleys aligned parallel to slope over an area of approximately 0.8 ha (AF_{12}), with a whole-system (row plus alley) tree density of 110 stems ha^{-1}. This field is on a south-south-east-oriented slope with a mean slope angle of 6.6° (11.5 %). A mixed assortment of 13 cultivars of apple tree (*Malus domestica*) were planted using a semi-vigorous MM111 rootstock between December 2002 and January 2003: Discovery, Egremont Russet, D'Arcy Spice, Sturmer Pippin, Herrings Pippin, Grenadier, Blenheim Orange, Sunset, Newton Wonder, English Codlin, Adams Pearmain, Golden Noble and James Grieve. Trees were planted parallel to slope in single rows, with 3 m spacing between trees (Fig. 1). Beneath the trees were 3 m uncultivated strips, with 9 m cultivated alleys between each tree row. Before planting, the soil was tilled with a rotovator to 10 cm depth in a strip, and mulched using a 1 m wide permeable, woven polypropylene MyPex weed membrane (Don & Low, UK) which deteriorated following planting. Soil in the tree rows has not been tilled since, with spontaneous annual vegetation growth periodically cut with a strimmer to reduce bramble pressure in the understorey.

In 2012, a second area of agroforestry was established approximately 400 m to the west of the first area, with the same tree-row orientation and on a similar mean slope of 5.8° (10.2 %), but using 24 m-spaced alleys over an area of approximately 2.5 ha (AF_{24}), resulting in a whole-system tree density of 55 stems ha^{-1}. A mixed assortment of apple cultivars was planted using a moderate MM106 rootstock between December 2012 and January 2013, this time consisting of D'Arcy Spice, Pixie, Winston, Sturmer Pippin, Egremont Russet, Jupiter, Claygate Permain and Sunset varieties. Trees were planted in 3 m wide rows, with 21 m cultivated alleys between uncultivated tree rows. As at the AF_{12} site, ground was prepared with tillage to 10 cm depth, but was mulched using a mixed wool and plastic sheet membrane. Additionally, an area of 1 m radius surrounding each tree was composted using green manure derived from on-farm rotational grass-clover leys (see below), at

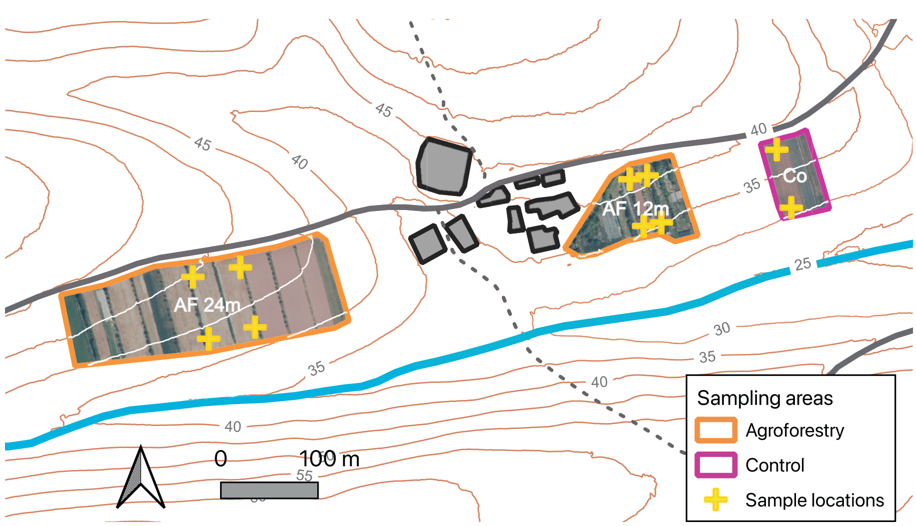

Fig. 1. Map of study site illustrating agroforestry areas ('AF 24 m' – 24 m agroforestry alleys, 'AF 12 m' – 12 m agroforestry alleys) and control area ('Co'). Built areas shown in grey. Topographic contours shown at 5 m intervals. Yellow crosses indicate the locations of the sampling layout shown in Fig. 2 (four sample positions per yellow cross). Aerial photography © Getmapping Ltd., accessible at EDINA Aerial Digimap Service (2022).

planting and again in 2021. Areas beneath trees were once again left uncultivated and periodically strimmed to remove brambles.

A third, treeless control field (Co, Fig. 1) was sampled 150 m east of AF_{12}. This field shares the same soil type, aspect and similar mean slope angle (6.4°, 11.2 %) to the two adjacent agroforestry areas, and has been managed in the same way as the agroforestry alleys in AF_{12} and AF_{24}. The agroforestry systems differ in tree age, some small differences in rotation are encountered and there are some minor variability in slope between the three fields. However, with sufficient replication the effect of random, uncontrolled variables is minimised (e.g. Moore et al., 1998), and even carefully-designed experimental sites can produce significant random effects on soil properties between replicates (Judson et al., 2024). The issue of tree age is only encountered when comparing the two agroforestry systems, and we control for this by comparing the magnitude of differences in soil properties with the size of the tree age difference.

Between 1983 and 2001 all three study areas were in the same continuous conventional arable rotation of wheat (*Triticum aestivum*) and barley (*Hordeum vulgare*). Since 2002, following organic conversion and initial tree planting, a six-year rotation has been in operation in the cultivated areas of all three fields as follows: brassicas (year 1), alliums (year 2), *Umbelliferae* (year 3) and legumes (year 4), and finally two years (years 5 and 6) in which cultivated areas are left in a fertility-building grass-clover ley. The only exception is for the recent period for AF_{12}, in which one of the sampled alleys had been planted with strawberries since 2021, and sample locations were sited to avoid interference with this new crop. A multispecies seed mix is used for the two-year ley, sowed at 55 kg ha^{-1} and consisting of 45 % common vetch (*Vicia sativa*), 9 % red clover (*Trifolium pratense*) 5 % crimson clover (*Trifolium incarnatum*) and 41 % Italian ryegrass (*Lolium multiforum*). Additionally, fields are sowed with 67.5 kg ha^{-1} ryegrass/vetch cover crop mix over winter, consisting of 70 % common vetch (*Vicia sativa*) and 30 % westerwold ryegrass (*Lolium westerwoldicum*). Cultivated areas are fertilised using green manure obtained from ley areas which is ploughed into cultivated areas before sowing and following harvesting of the main crop. This is supplemented with municipal compost from the local authority. All three treatments (AF_{12}, AF_{24}, Co) are tilled parallel to tree rows (and slope) to help weed suppression and nutrient mineralisation.

2.2. Experimental design

All soil samples were collected in a single week in May 2023, when study areas were predominantly in the ley phase of the rotation. Space-for-time substitution was used (e.g. Cardinael et al., 2015a; Biffi et al., 2022), in which agroforestry and control areas are assumed to have been equivalent before tree planting. Co is thus assumed to represent the baseline ($t = 0$) state for both of the agroforestry areas before the planting of trees. This is a reasonable assumption given the similarity in aspect and equivalent management of the three sampled areas before introduction of agroforestry.

At each location (Fig. 1, yellow crosses), four soil samples were collected for each measurement depth at the positions shown in Fig. 2: row centre (RC) parallel to tree row at 1 m from tree, row edge (RE) perpendicular to tree row and at 1 m from tree (0.5 m distance to row edge), alley edge (AE) perpendicular to tree row and 2 m from tree (0.5 m to row edge) and alley centre (AC) at the midpoint of the alley. Each location (instance of Fig. 2) was replicated twice (on different rows and on opposite sides of the tree row) at both the top and bottom of the slope within each agroforestry treatment (Fig. 1), resulting in 16 sample locations each for the two agroforestry treatments. Locations were chosen within fields such that hillslope was as similar as possible between treatments while remaining within the same rotation. The chosen locations and sample positions minimise common biases associated with agroforestry transect sampling in terms of orientation, alley and tree row positions and sampling depth (Minarsch et al., 2024). An intermediate

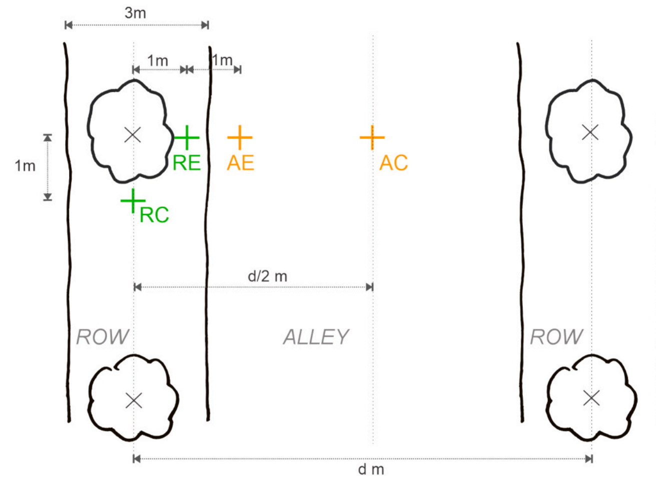

Fig. 2. Diagram of sampling layout within agroforestry alleys, where *d* represents alley width. Sample positions RC (row centre), RE (row edge), AE (alley edge) and AC (alley centre) are shown.

(d/4) alley data point would have been desirable but was not feasible within resource constraints of the study. These four positions were chosen to balance area coverage and replication with constraints on time and resources for sample processing. The control field was sampled using the same layout as the four agroforestry sample positions, albeit repeated just once each at the top and bottom of the slope to produce a total of eight control sample positions.

In addition to soil samples, tension infiltrometers were used to determine surface-level saturated hydraulic conductivity at each of the four sample positions (RC, RE, AE, AC). Three infiltrometers were placed on a levelled soil surface at each of the four positions at the same distance-to-tree, following removal of surface vegetation and avoiding stones. A constant tension of −0.1 cm was used, and infiltration estimates were combined with constants for loam soil (particle size distribution analysis indicated loam soil at all sampling locations, see Section 2.3) derived from the method of van Genuchten (van Genuchten and Nielsen, 1985) to determine near-surface saturated hydraulic conductivity (K_s).

Finally, tree height and diameter at breast-height (1.3 m, DBH) were measured from two tree rows in each of the two agroforestry treatments, with five trees selected at random from each row. Height was measured using a rule placed up to the full tree height, and DBH with a measuring tape placed around the circumference of the trunk and pre-marked with corresponding diameter values. These measurements were combined with allometric equations from the Forestry Commission Woodland Carbon Code: Carbon Assessment Protocol (Jenkins et al., 2018) to determine estimates of above- (AGB) and below-ground biomass (BGB) C stock for the trees.

2.3. Soil sampling and analysis

At each sample position soil samples were collected at three depth intervals: 0–10 cm, 10–20 cm and 20–50 cm. For the uppermost two samples, a 5 cm diameter, 100 cm^3 ring corer (Eijkelkamp, Holland) was used to extract intact soil cores at 2.5–7.5 and 12.5–17.5 cm depth, representing 0–10 and 10–20 cm intervals, respectively. For deeper soil samples, a 5 cm diameter, 600 cm^3 liner sampling soil corer (Eijkelkamp, Holland) was used to extract an intact 30 cm soil core representing 20–50 cm soil depth. On return to the laboratory, all soil samples were weighed and then oven-dried at 105 °C for 24 h (48 h for the larger 20–50 cm samples) before being re-weighed for determination of bulk density. Moisture content was determined for each sample by comparing soil mass before and after drying at 105 °C. Roots and stones were extracted with a 2 mm sieve and weighed to correct for their presence in the soil. Bulk density was calculated by subtracting the root and stone fraction from the initial mass and dividing by the volume of the corer (Poeplau et al., 2017). Sub-samples of the oven-dry soil were heated to 550 °C for 12 h in order to determine soil organic matter (SOM) content (%) using the loss-on-ignition (LOI) method. These samples were subsequently weighed with LOI determined as the difference in mass between 105 °C (oven-drying) and 550 °C (ignition) samples, divided by the oven-dry mass and multiplied by 100 to give a percentage value.

Separate, loose soil samples from the same sample positions and depth intervals were collected for determination of SOC, nitrogen (N) and phosphorus (P) concentrations. On return to the laboratory, the field moist soil was passed through a 5 mm sieve as soon as possible to homogenise samples. For determination of plant available N, approximately 10 g field-moist sample was combined with 50 mL 1 M KCl solution and shaken for 1 h at 150 cycles min^{-1} using a shaker table. These samples were subsequently passed through Whatman 42 filter paper into centrifuge tubes, with nitrite (NO_2-N), nitrate (NO_3-N) and ammonium (NH_4-N) content determined using a Skalar San ++ (Skalar Analytical B. V., Netherlands) continuous flow auto-analyser. The remaining field-moist sample was dried at room temperature and passed through a 2 mm sieve, weighed and subsequently ground to < 150 μm using a Retsch MM400 ball mill (RETSCH GmbH, Germany) for determination of soil C and N content. For analysis of total C and N approximately 4 mg of < 150 μm sample was weighed using a six-figure balance into tin capsules, crushed into a small cube to remove air from the sample, and subsequently introduced into an Elemental Vario EL cube (Elementar Analysensysteme GmbH, Germany) combustion analyser to determine concentrations of each element. For SOC a similar procedure was adopted, with the exception that 30 μL of 15 % HCl was added to each sample to remove carbonates. The samples were left to react and settle for 24 h and oven dried for 2 h at 80 °C before being analysed for C content using an Elemental Vario EL cube (Elementar Analysensysteme GmbH, Germany). Olsen's P (Olsen, 1954) was determined using the < 2 mm fraction of loose soil samples. Approximately 2.5 g air-dried soil was weighed into a shaker bottle, combined with 50 mL of 0.5 M $NaHCO_3$ solution and mixed for 30 min at 150 cycles min^{-1} using a shaker table. These samples were subsequently passed through Whatman 42 filter paper into centrifuge tubes, with Olsen P (PO_4-P) content determined using a Skalar San ++ (Skalar Analytical B.V., Netherlands) continuous flow auto-analyser.

At each sample position, soil particle size distribution was determined on the surface sample only (2.5–7.5 cm, representing 0–10 cm) by gravimetry using the < 2 mm fraction of loose soil. Approximately 10 g air-dry soil was weighed and combined with 100 mL deionised water followed by 20 mL dispersing agent (5 % m/v sodium hexametaphosphate), with the mixture left to stand for 12 h. The mixture was then agitated for 10 min before being passed through a 53 μm sieve, with the sand fraction left on the sieve removed and dried for 48 h at 105 °C before being weighed. The mixture that passed through the sieve was then left in a 1 L sedimentation cylinder for a quantity of time determined by ambient temperature (see Black *et al.*, 1983) (1 h 57 min for 21 °C), after which 20 mL sample was extracted 5 cm below the liquid surface, dried at 105 °C and weighed to determine clay content (<2 μm). Silt content (2–53 μm) was determined by subtraction. Measured soil particle size distributions for each site were used to inform estimates of saturated hydraulic conductivity (see Section 2.2).

Soil pH was measured using the < 2 mm fraction of air-dry soil. Approximately 20 g air-dry soil was combined with 40 mL deionised water and stirred for 15 min. The pH was measured in the deionised water only, before being measured again after the addition of 250 μL $CaCl_2$.

2.4. Mineral soil mass corrections

All ratio-based soil measurements were normalised according to a reference quantity of mineral soil in order to correct for land-use change effects on bulk density and SOM. For this purpose, the aggregated Co samples were used, as they are assumed to represent $t = 0$ under space-for-time substitution. Mineral soil was calculated as the mass of dry soil per unit area in the aggregated control area samples to three reference depths, corresponding to sample depths used in the study (0–10 cm, 0–20 cm and 0–50 cm). For a given soil property at the agroforestry locations (e.g., moisture, SOC), its cumulative mass was calculated to the same reference depths, and plotted against cumulative mineral soil mass. A cubic spline function (von Haden et al., 2020) was considered for interpolating these data, however this can produce significant artefacts (including negative values) if used to infer adjusted values outside the interpolated region. An exponential function of the form $y = A(1 - \exp(-Bx))$ was therefore used to fit data, from which corrected (or equivalent soil mass – ESM) values were interpolated using cumulative mineral soil values from the reference (control) area. Where cumulative mass data did not plateau with depth such that an exponential fit could not be used, a linear fit of the form $y = Ax$ was used in its place. Fit data for all variables is illustrated in the Supporting Information.

2.5. Calculation of whole-system C, N and P stock

Contributions of tree row and alley to whole system C, N and P stock must be area-weighted in order to avoid overestimation when upscaling results (Minarsch et al., 2024). For each of the two systems (AF_{12}, AF_{24}), soil C, N and P stocks were calculated by multiplying the mean stock for row (RC, RE) and alley (AE, AC) components according to the fractional land area each comprised in the 12 m and 24 m systems. Specifically, stock contributions of the tree row were multiplied by 25 % and 12.5 % for the AF_{12} and AF_{24} systems, respectively, with contributions from the alley multiplied by 75 % and 87.5 %, respectively, before being summed to calculate total stock in each system. The row edge (RE) and alley edge (AE) soil C stock values were taken to represent the stock values immediately on either side of the row-alley boundary, with the distribution of stock values between the edge and centre of each component assumed to be linear. In the case of C stock, estimates of above- (AGB) and below-ground tree biomass (BGB) (Section 2.2) were included in tree row contributions and area-weighted according to stem density.

2.6. Statistical analysis

Data were analysed in three stages. Firstly, all data for row and alley areas were homogenised across the two agroforestry systems to create two treatment groups (Row and Alley), each of which could be compared with control group values for a given depth interval. This facilitates comparison of soil properties between row and alley components of agroforestry and the treeless control area.

Secondly, data within Row and Alley groups were disaggregated by position (lateral – RC, RE, AE, AC; and with hillslope – UP and DOWN) and compared with control group data (control data disaggregated by hillslope position). These groups were compared in order to determine rudimentary spatial dynamics within agroforestry in sectional view, and compare these with the control area. Spatial maps were generated using linear interpolation between sample points.

Finally, Row and Alley groups were disaggregated by agroforestry system (AF_{12}, AF_{24}), to determine differences in stocks of key soil properties by alley width and compared with the control area. Stock contributions of each of the row and alley components were area-weighted as described in Section 2.5. Similarly, estimates of tree biomass C were weighted according to whole-system stem density.

Data used for determination of all soil indicator values were tested for normality (Shapiro-Wilk) and homogeneity of variance (Bartlett) in order to meet assumptions for ANOVA and pairwise Tukey tests. Where these assumptions were not met, a non-parametric Kruskal-Wallis test was used in place of ANOVA, followed by pairwise Dunn's tests with a Bonferroni correction. Effect sizes between groups were determined using Cohen's d value. Comparison of whole system C, N and P stocks was undertaken using independent two-sample t-tests of the combined contributions of agroforestry area components to total stock values. A mixed effect modelling approach incorporating fixed and random factors was considered, however this approach requires more sophisticated experimental design with block replication and paired data points between groups. Moreover, the purpose of this study is not to compare relative effect strengths between factors as mixed effect models can, but simply to detect the presence of significant differences between treatments. ANOVA is known to be robust when comparing unbalanced groups provided assumptions of normality and homogeneity of variance are met (Sawyer, 2013), and these were tested throughout. All tests were undertaken using *SciPy* (Virtanen et al., 2020) and *statsmodels* (Seabold and Perktold, 2010) within the Python environment (v. 3.10). Generation of spatial variability plots for Section 3.2 was undertaken using two-dimensional, linear interpolation between sample points using *RegularGridInterpolator*, also within Python's *SciPy* library (Virtanen et al., 2020).

3. Results

3.1. Differences in soil properties between tree row, alley and treeless control areas

3.1.1. Soil physical properties

Agroforestry did not have a significant effect on bulk density in topsoil (0–20 cm) compared with Co (all figures shown as mean ± standard error; tables of mean and standard error values for all indicators are included in the Supporting Information) (AF: 0.98 ± 0.02 g cm^{-3}, $n = 32$; Co: 1.02 ± 0.02 g cm^{-3}, $n = 8$; $d = 0.45$, $p = 0.262$) (Fig. 3, Supp. Table 1). However, at 20–50 cm depth, bulk density of soil in agroforestry areas (1.07 ± 0.02 g cm^{-3}) was significantly lower than in Co (1.20 ± 0.03 g cm^{-3}, $d = 1.12$, $p = 0.007$). Thus, over the whole measured soil profile (0–50 cm), bulk density was significantly lower overall in agroforestry areas (1.04 ± 0.02 g cm^{-3}) compared with Co (1.13 ± 0.02 g cm^{-3}, $d = 1.19$, $p = 0.005$) (Fig. 2b). Bulk density of the row and alley components of agroforestry was not significantly different for either topsoil (0–20 cm, $d = 0.37$, $p = 0.299$) or subsoil (20–50 cm, $d = 0.17$, $p = 0.633$), nor over the whole soil column (0–50 cm, $d = 0.02$, $p = 0.962$).

Significant difference in topsoil SOM content was found between agroforestry (7.01 ± 0.13 %) and Co (6.43 ± 0.19 %) ($d = 0.83$, $p = 0.044$) (Fig. 3, Supp. Table 1). However, SOM content did not differ between agroforestry (4.98 ± 0.09 %) or Co (5.07 ± 0.31 %) treatments over the whole measured soil profile (0–50 cm) ($d = 0.17$, $p = 0.669$).

No significant difference was observed in surface K_s between the agroforestry areas (7.98 (6.04–10.54) mm hr^{-1}) and Co (3.57 (2.51–5.05) mm hr^{-1}) ($d = 0.48$, $p = 0.089$) (Supp. Table 1). However, the tree-row component of the agroforestry areas exhibited significantly faster surface K_s (12.37 (8.64–17.70) mm hr^{-1}) than Co ($d = 0.82$, $p = 0.029$). There was no significant difference between alley surface K_s (5.04 (3.33 – 7.61) mm hr^{-1}) and Co ($d = 0.21$, $p = 0.569$). Soil moisture was similar for row, alley and control areas (Fig. 3).

Particle size distribution varied significantly between row and alley components of agroforestry, with significantly higher clay percentage in the alley areas (18.2 ± 0.3 %) compared with the tree rows (16.5 ± 0.4 %, $d = 1.10$, $p = 0.004$) (Supp. Table 1). Tree rows (45.9 ± 0.7 %) had higher sand percentage than Co (42.6 ± 0.9 %, $d = 1.20$, $p = 0.012$), whereas rows had lower clay percentage (16.5 ± 0.4 %) than Co (18.7 ± 0.9 %, $d = 1.10$, $p = 0.019$). Particle size fractions were similar between the alley areas and Co for all three size classes.

3.1.2. Soil carbon

SOC concentration in topsoil (0–20 cm) was higher beneath agroforestry (2.89 ± 0.09 %) than in Co (2.33 ± 0.06 %, $d = 1.21$, $p = 0.005$, Fig. 4, Supp. Table 2). However, within subsoil there was no significant difference between the agroforestry and Co areas ($d = 0.23$, $p = 0.612$). Over the whole soil profile (0–50 cm) there was significantly higher SOC content in the agroforestry (1.71 ± 0.06 %) than the Co area (1.45 ± 0.05 %, $d = 0.85$, $p = 0.016$). SOC content (0–50 cm) in the tree-rows (1.68 ± 0.05 %) was significantly higher than the control ($d = 1.23$, $p = 0.009$), but there was no difference between Co (1.45 ± 0.05 %) and alley areas (1.74 ± 0.11; $d = 0.81$, $p = 0.111$), nor between alley and tree row ($d = 0.19$, $p = 0.651$).

SOC stock in topsoil was greater in agroforestry (59.2 ± 1.9 t ha^{-1}) than in Co (47.3 ± 1.3 t ha^{-1}, $d = 1.20$, $p = 0.007$, Fig. 5), which equates to a difference of 11.9 ± 2.3 t ha^{-1} in the uppermost 20 cm between the two systems. Both tree-row (59.7 ± 2.8 t ha^{-1}, $d = 1.31$, $p = 0.014$) and alley areas (58.8 ± 2.7 t ha^{-1}, $d = 1.24$, $p = 0.014$) had significantly more topsoil C compared with Co. Over the whole soil profile, SOC stock was also significantly greater in agroforestry (96.4 ± 3.3 t ha^{-1}) than Co (82.0 ± 2.8 t ha^{-1}, $d = 0.83$, $p = 0.018$). Only tree rows contained significantly more SOC stock at 0–50 cm (94.5 ± 2.9 t ha^{-1}) compared with Co ($d = 1.19$, $p = 0.012$); in alley areas high spatial variability between locations meant there were no significant differences with Co

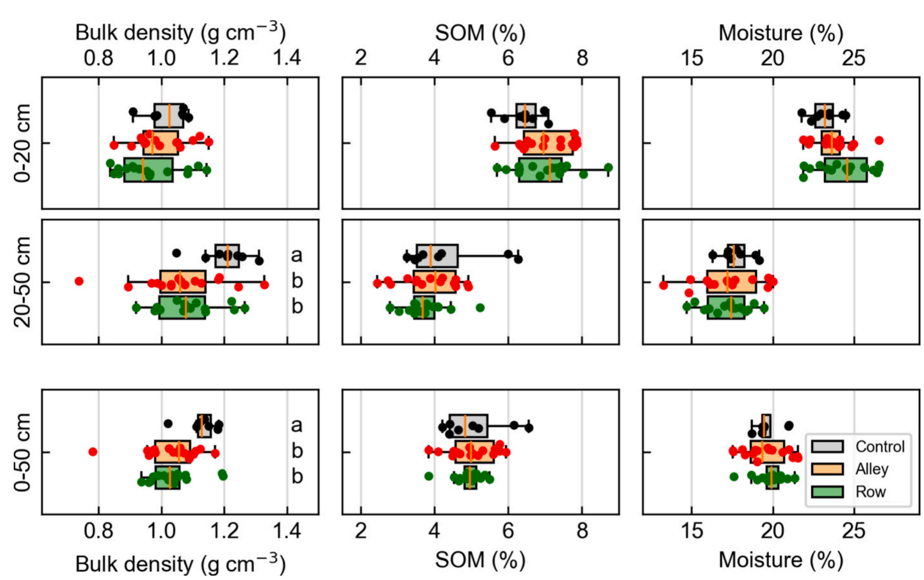

Fig. 3. Soil bulk density, organic matter (SOM) and moisture in Control, Alley and Row sample locations for topsoil (0–20 cm), subsoil (20–50) and whole measured soil column (0–50 cm). Mean soil property values (0–20 cm, 0–50 cm) are calculated as weighted averages, corrected for soil mass in each depth interval.

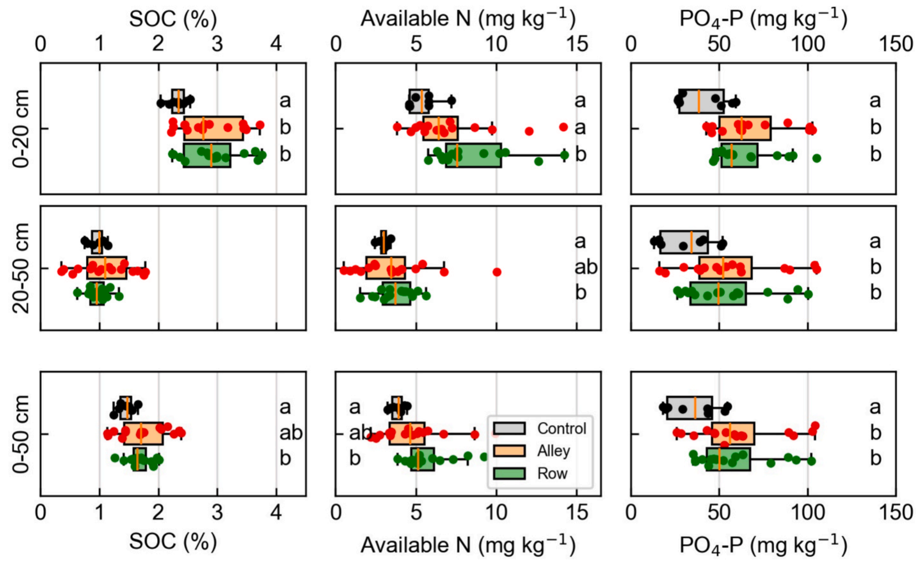

Fig. 4. Concentration of SOC, available N and PO_4-P at Control, Alley and Row sample locations for topsoil (0–20 cm), subsoil (20–50) and whole measured soil column (0–50 cm). Mean soil property values (0–20 cm, 0–50 cm) are calculated as weighted averages, corrected for soil mass in each depth interval.

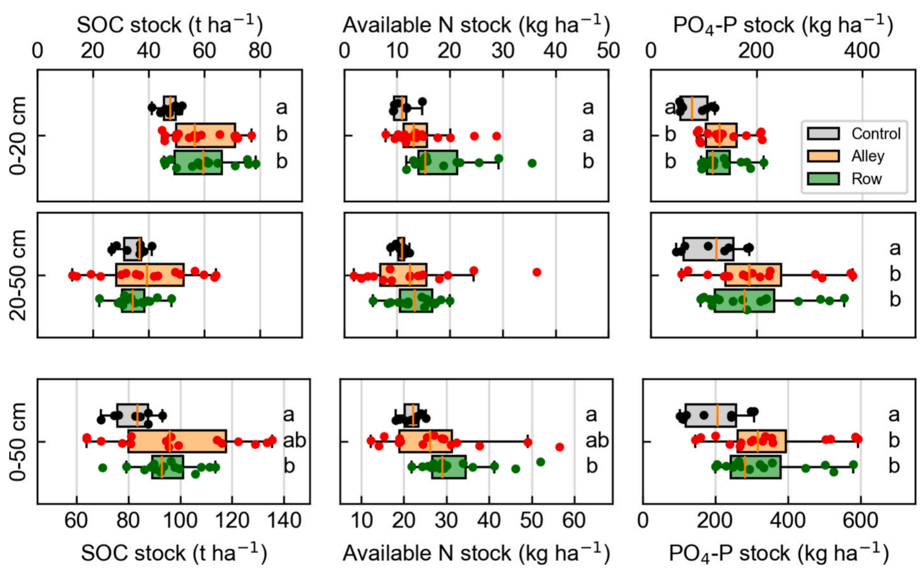

Fig. 5. Stock of SOC, available N and PO_4-P at Control, Alley and Row sample locations for topsoil (0–20 cm), subsoil (20–50) and whole measured soil column (0–50 cm). Mean soil property values (0–20 cm, 0–50 cm) are calculated as weighted averages, corrected for soil mass in each depth interval.

($d = 0.79$, $p = 0.111$).

3.1.3. Soil nutrients

Topsoil available N (NO_3-N + NO_2-N + NH_4-N) was higher in agroforestry areas (8.04 ± 0.55 mg kg^{-1}) than in Co (5.42 ± 0.32 mg kg^{-1}, $d = 0.92$, $p = 0.006$, Fig. 4, Supp. Table 2), whereas in subsoil there was no significant difference between the treatments (AF: 3.66 ± 0.33 mg kg^{-1}, Co: 2.99 ± 0.11 mg kg^{-1}, $d = 0.40$, $p = 0.250$). Topsoil beneath tree-rows had significantly higher available N content than Co (R: 8.96 ± 0.82 mg kg^{-1}, $d = 1.29$, $p = 0.001$), whereas there was no difference in topsoil available N between the alley and Co (A: 7.13 ± 0.69 mg kg^{-1}, $d = 0.73$, $p = 0.111$). Measured as a stock to 50 cm depth, significantly more available N (+7.8 ± 2.0 kg ha^{-1}) was present beneath agroforestry areas (29.6 ± 1.9 kg ha^{-1}) compared with Co (21.8 ± 0.9 kg ha^{-1}, $d = 0.82$, $p = 0.008$, Fig. 5).

Available P (PO_4-P) content was significantly higher beneath agroforestry than the Co area in both topsoil (AF: 65.9 ± 3.4 mg kg^{-1}, Co: 40.8 ± 5.1 mg kg^{-1}, $d = 1.36$, $p = 0.003$, Fig. 4) and subsoil (AF: 55.5 ± 4.5 mg kg^{-1}, Co: 32.4 ± 5.6 mg kg^{-1}, $d = 0.96$, $p = 0.021$), and across the whole measured soil column (AF: 59.3 ± 4.0 mg kg^{-1}, Co: 35.4 ± 5.4 mg kg^{-1}, $d = 1.10$, $p = 0.009$). This equated to a PO_4-P stock difference of 134 kg ha^{-1} (+67 %) between agroforestry (334 ± 23 kg ha^{-1}) and Co (200 ± 30 kg ha^{-1}) treatments to a depth of 50 cm ($d = 1.10$, $p = 0.009$, Fig. 5). Both alley (60.5 ± 6.2 mg kg^{-1}, $d = 1.13$, $p = 0.016$) and row (58.1 ± 5.4 mg kg^{-1}, $d = 1.15$, $p = 0.020$) components of agroforestry contained significantly higher PO_4-P content to 50 cm than Co (35.4 ± 5.4 mg kg^{-1}).

C:N (SOC:total N) was significantly higher beneath agroforestry (7.19 ± 0.24) than the Co area (5.92 ± 0.16) to 20 cm depth ($d = 1.01$, $p = 0.008$). However, there was no significant difference in C:N at 20–50 cm ($d = 0.321$, $p = 0.437$) or 0–50 cm ($d = 0.60$, $p = 0.166$) between agroforestry and Co. C:N was similar between alley (7.03 ± 0.35) and tree-row (7.35 ± 0.35) areas ($d = 0.23$, $p = 0.521$) at 0–20 cm.

3.2. Spatial variability in soil properties within agroforestry areas

Sample positions in this section are abbreviated as follows: row centre (RC), row edge (RE), alley edge (AE) and alley centre (AC). Figs. 6 and 8 represent cross-sectional variability in indicator values with lateral position in both upslope and downslope positions, and with depth. Soil textural data (Fig. 7) was only measured in surface soil (0–10 cm).

3.2.1. Soil physical properties

Although 0–50 cm bulk density was higher in the alley centre (AC: 1.06 ± 0.01 g cm^{-3}, $n = 8$) than at the edge of the tree row (RE: 1.00 ± 0.01 g cm^{-3}, $n = 8$, $d = 1.46$, $p = 0.011$), differences in mean bulk density between lateral sample positions were not significant at $p < 0.05$ ($p = 0.169$, Fig. 6a). Similarly, differences in bulk density between upslope agroforestry sample positions (AF_{up}: 1.02 ± 0.02 g cm^{-3}, $n = 16$) and downslope positions (AF_{down}: 1.06 ± 0.02 g cm^{-3}, $n = 16$) were not significant ($d = 0.50$, $p = 0.166$). Bulk density was generally lower in the agroforestry plots compared with control plots ($d = 1.19$, $p = 0.005$, Fig. 6a), however this difference was more pronounced in downslope sample positions (AF_{down}: 1.06 ± 0.02 g cm^{3}, $n = 16$; Co_{down}: 1.15 ± 0.02 g cm^{-3}, $n = 4$; $d = 1.51$, $p = 0.015$) compared with upslope positions (AF_{up}: 1.02 ± 0.02 g cm^{-3}, $n = 16$; Co_{up}: 1.11 ± 0.03 g cm^{-3}, $n = 4$; $d = 1.04$, $p = 0.081$).

SOM content varied significantly in the lateral direction between alley and row sample positions ($p = 0.001$) and also between upslope

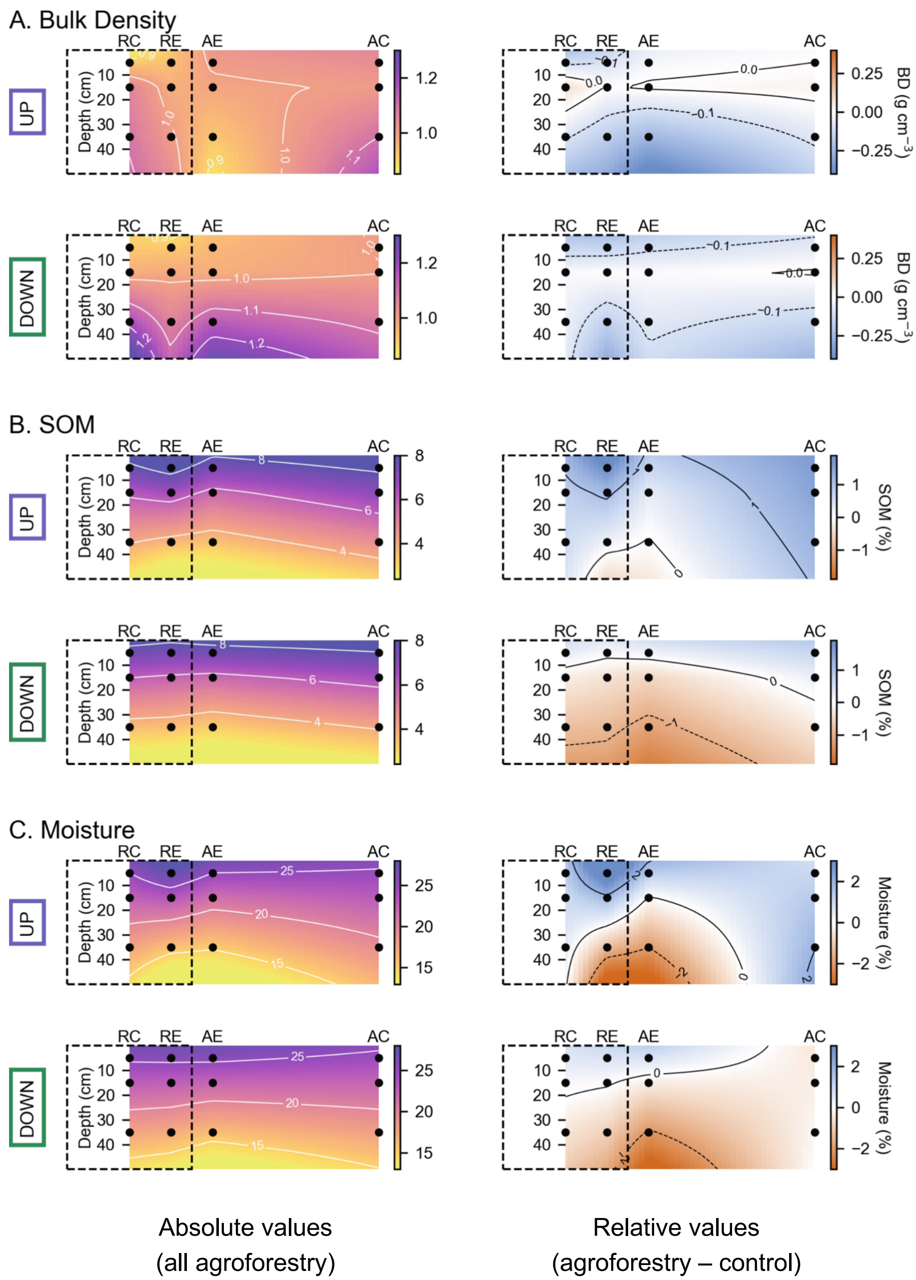

Fig. 6. Cross-sectional variability in a. soil bulk density, b. SOM and c. moisture in upslope (UP – purple) and downslope (DOWN – green) positions, and row centre (RC), row edge (RE), alley edge (AE) and alley centre (AC) positions. Lateral distances between points are not shown to scale. Left column of plots shows variation in absolute values within combined agroforestry areas, right column shows differences between agroforestry and control areas. Data points are shown as black dots, with $n = 4$ for each point. Contours mapped using two-dimensional linear interpolation between data points. Plots for C:N are included in the Supporting Information.

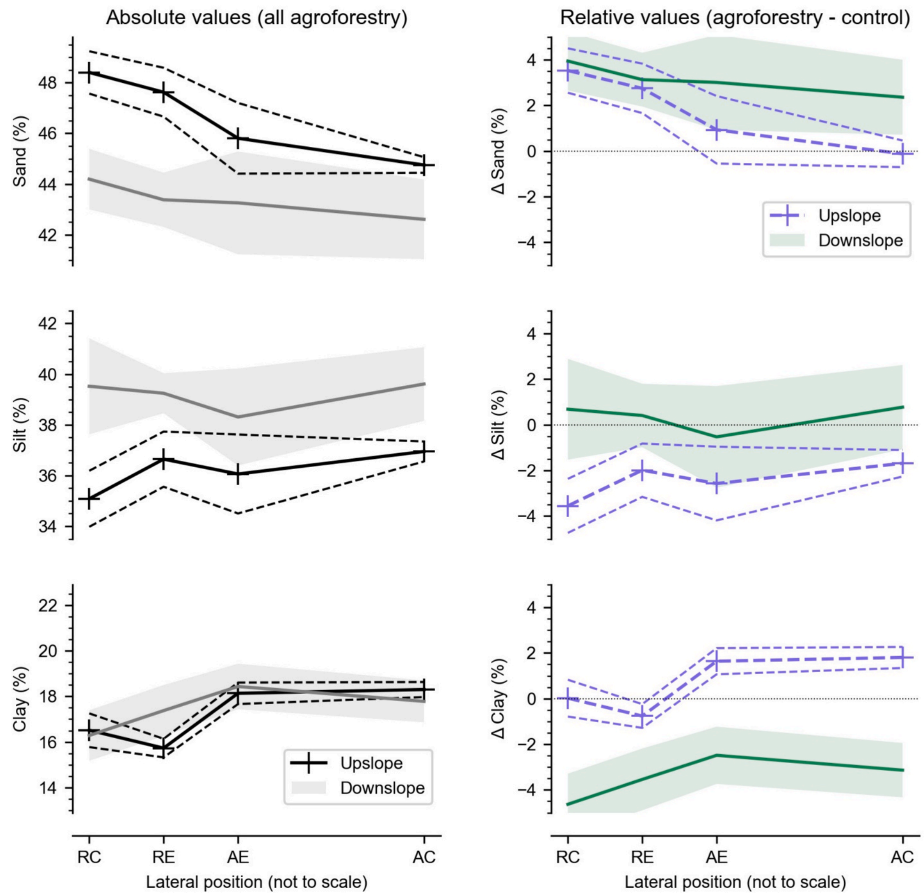

Fig. 7. Surface variation in soil textural classes for upslope and downslope positions, and row centre (RC), row edge (RE), alley edge (AE) and alley centre (AC) positions. Shaded/dotted areas indicate standard error bounds. Left column of plots shows variation in absolute values within combined agroforestry areas, right column shows differences between agroforestry and control areas.

and downslope positions (p = 0.044). SOM was highly uniform across the tree row (RC: 4.96 ± 0.12, RE: 4.88 ± 0.16, d = 0.19, p = 0.916), but varied strongly between the alley edge (AE: 4.52 ± 0.14 %) and alley centre (AC: 5.51 ± 0.12 %, d = 2.65, $p < 0.001$, Fig. 6b). Compared with Co, agroforestry areas had higher SOM content upslope (+0.74 %, d = 1.61, p = 0.010), and lower SOM content downslope (–0.46 %, d = 1.04, p = 0.080).

Moisture content was also significantly variable with lateral position (p = 0.003) but not with slope position (p = 0.906). Although not varying significantly within the tree row (d = 0.445, p = 0.389), moisture content significantly increased between alley edge and alley centre (AE: 18.6 ± 0.4 %, AC: 20.5 ± 0.3 %, d = 1.90, p = 0.002) (Fig. 6c). These differences were apparent when comparing with Co, particularly upslope. Agroforestry areas contained higher upslope moisture content across 0–50 cm depth than Co at RC (+0.74 %, d = 2.06, p = 0.021) and at AC (+1.70 %, d = 2.56, p = 0.021), whereas downslope moisture content was very similar between agroforestry and Co treatments. The majority of moisture content difference at the alley edge was observed in subsoil and was much less pronounced in topsoil (Fig. 6c).

3.2.2. Particle size analysis

Soil particle size distributions were only measured for surface soil samples (0–10 cm). Among particle classes, only clay content varied significantly in surface soil between lateral sample positions (p = 0.045), with no significant lateral variation in silt (p = 0.865) or sand (p = 0.336) content (Fig. 7). However, significant differences were observed within agroforestry areas between upslope and downslope positions for both silt content (AF_{up}: 36.2 ± 0.5 %, AF_{down}: 39.2 ± 0.7 %, d = 1.18, p = 0.002) and sand content (AF_{up}: 46.6 ± 0.6 %, AF_{down} 43.4 ± 0.7 %, d = 1.30, p = 0.001), with higher silt content downslope, and higher sand content upslope.

In general, spatial variation in particle size fractions implied that, for agroforestry areas, silt (p = 0.002) and sand (p = 0.001) content were most sensitive to slope position, with minimal effect on clay (p = 0.634); whereas in the treeless control area clay (p = 0.002) and sand (p = 0.001) content were most sensitive to slope position, with minimal effect on silt (p = 0.874). Significantly higher clay content (+3.45 %) was observed downslope in the Co area compared with the same part of the agroforestry areas (d = 1.77, p = 0.005).

3.2.3. Soil carbon stock

SOC stock varied significantly with lateral position across alley and row components of agroforestry ($p < 0.001$) (Fig. 8a). Stocks were similar within the row (RC: 92.1 ± 3.0 t C ha, RE: 97.1 ± 5.0 t C ha^{-1}, d = 0.43, p = 0.400), but varied significantly within the alley (AE: 78.5 ± 4.4 t ha^{-1}, AC: 118.3 ± 5.3 t ha^{-1}, d = 2.88, $p < 0.001$), with the highest SOC stock found at the centre of the cropped alley. Variation in SOC stock between upslope and downslope agroforestry sample positions was minimal (p = 0.243). However, the difference in SOC stock in the sampled soil profile (0–50 cm) between agroforestry and control treatments was five times larger and significant at the top of the slope (+24.2 t C ha^{-1} in AF, d = 1.29, p = 0.033) compared with the bottom of the slope (+4.8 t C ha^{-1} in AF, d = 0.305, p = 0.508).

3.2.4. Available N and P stock

Available N stock over the whole measured soil column varied significantly both laterally (p = 0.040) and with slope position (p = 0.019) (Fig. 8b). Stock was similar in the tree row (d = 0.79, p = 0.134)

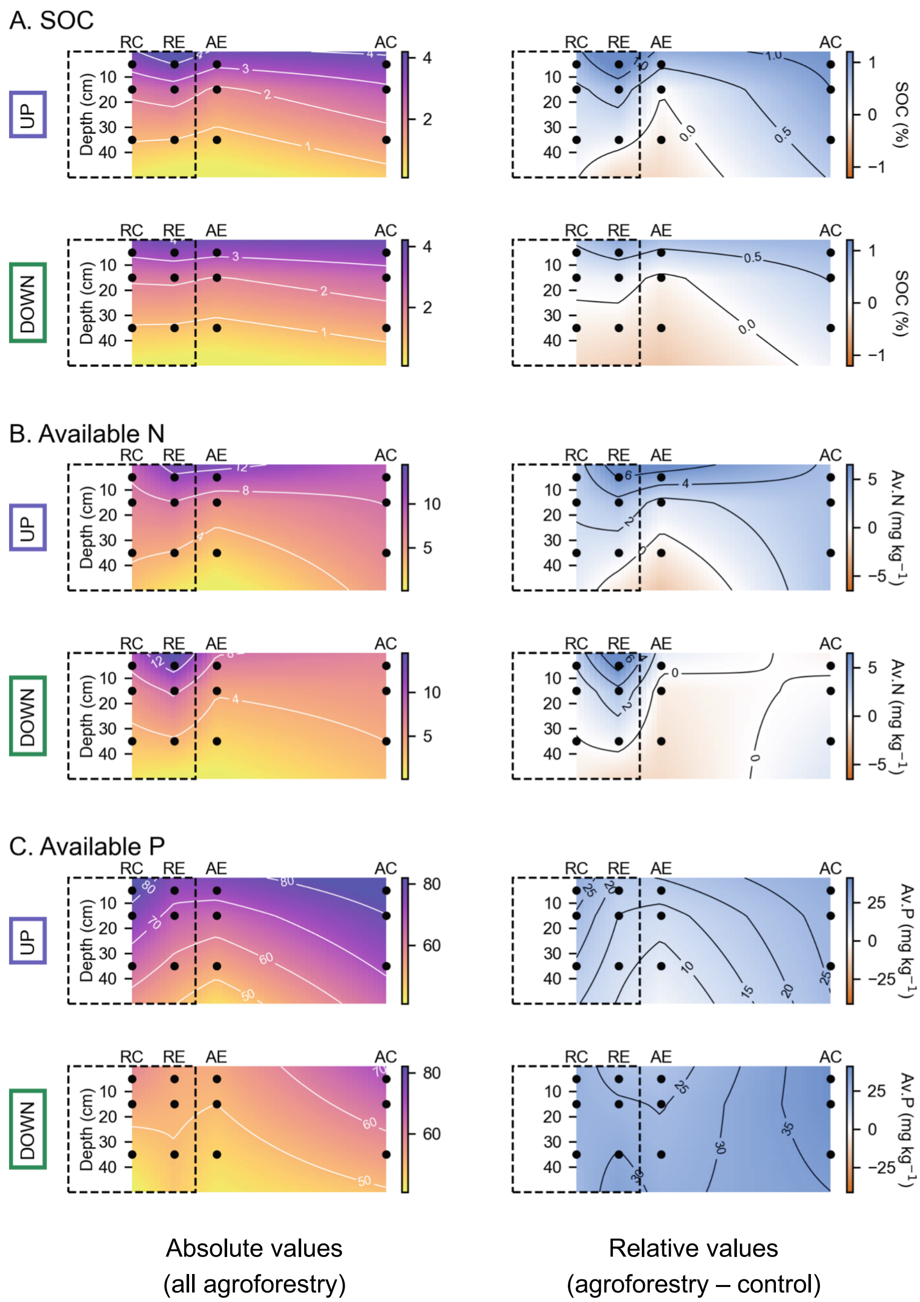

Fig. 8. Cross-sectional variability in a. SOC, b. available N and c. available P content in upslope (UP) and downslope (DOWN) positions, and row centre (RC), row edge (RE), alley edge (AE) and alley centre (AC) positions. See caption to Fig. 6 for a full description.

but was significantly reduced at AE (21.1 ± 3.2 kg ha^{-1}) compared with RE (34.9 ± 3.4 kg ha^{-1}, d = 1.47, p = 0.011). Slope differences in available N stock between agroforestry and Co were more exaggerated in the alley than the tree row. A significant difference in N stock was only observed upslope (AF + 12.2 kg ha^{-1}, d = 1.16, p = 0.023) and there was no significant difference in N stock between the treatments downslope (d = 0.44, p = 0.299). At downslope AE, N stocks were lower in agroforestry compared with Co (AF −5.1 kg ha^{-1}, d = 2.29, p = 0.021), with differences driven by lower N availability in downslope subsoil at the alley edge.

Available P (PO_4-P) stock did not vary significantly with either lateral position (p = 0.323) or slope (p = 0.407) in agroforestry areas (Fig. 8c). Stocks were uniformly greater in the agroforestry area compared with Co (AF + 136 kg ha^{-1}, d = 1.10, p = 0.009), although the difference in available P stock between the treatments was more pronounced downslope (AF + 167 kg ha^{-1}, d = 3.18, p < 0.001) than upslope (AF + 104 kg ha^{-1}, d = 0.68, p = 0.450). The difference between upslope and downslope P stocks was significant and pronounced in Co (–148 kg ha^{-1}, d = 4.69, p = 0.001) but there were no such slope position differences in the agroforestry area (d = 0.69, p = 0.407).

3.3. *Comparing agroforestry systems: Organic C and nutrient stocks*

Nutrient and SOC stocks were significantly different between the three treatments (AF_{12}, AF_{24} and Co) when adjusted for proportional area (tree row, alley). Measurement depth also controlled differences between stocks for each treatment type.

3.3.1. *Carbon stock*

When combining the AGB and BGB C stocks with the topsoil (0–20 cm) SOC, total C stocks were variable between the three treatments. The greatest total C stock was found in the AF_{24} system (Fig. 9a), a difference of + 17.2 t C ha^{-1} compared with Co ($d = 1.53$, $p = 0.001$), with + 7.2 t C ha^{-1} in AF_{12} compared with Co ($d = 1.10$, $p = 0.018$).

For the whole measured soil column (0–50 cm), higher uncertainty meant there was no significant difference in total C stock between AF_{24} and Co ($d = 0.62$, $p = 0.104$), however AF_{12} contained a significant difference of +14.7 t C ha^{-1} compared with Co ($d = 0.93$, $p = 0.028$) (Fig. 9b). Estimated AGB and BGB C stocks were very small (AF_{12}: 1.02 t C ha^{-1}, AF_{24}: 0.13 t C ha^{-1}) compared with SOC stocks.

3.3.2. Available N stock

Available N stock in topsoil was greatest in AF_{12} with a difference of +6.4 kg ha^{-1} compared with Co ($d = 1.05$, $p = 0.011$). Available N stock in AF_{24} was intermediate and did not differ significantly from either AF_{12} ($d = 0.71$, $p = 0.065$) or Co ($d = 0.70$, $p = 0.072$). In the whole measured soil column, the ranks were the same, with +10.8 kg N ha^{-1} in AF_{12} compared with Co ($d = 0.98$, $p = 0.015$), and AF_{24} intermediate and not differing significantly from either AF_{12} ($d = 0.73$, $p = 0.058$) or Co ($d = 0.21$, $p = 0.562$).

3.3.3. Available P stock

The greatest topsoil available P stock was found in AF_{12}, approximately double (+78 kg ha^{-1}) the quantity found in Co ($d = 1.72$, $p < 0.001$). Stocks in AF_{24} were intermediate and also significantly higher (+29 kg ha^{-1}) than Co ($d = 0.85$, $p = 0.030$). Over the whole measured soil column, stocks beneath AF_{12} remained approximately double (+ 221 kg ha^{-1}) those in Co ($d = 1.57$, $p = 0.001$). Stocks in AF_{24} were not significantly different from Co at 0–50 cm ($d = 0.53$, $p = 0.153$).

4. Discussion

Examining soil functioning at a working farm allows us to consider the contributions of a practical agroforestry system to ecosystem benefit delivery. We discuss differences in soil functioning, firstly considering row and alley differences compared with the control area, secondly examining spatial effects, and finally separating the two agroforestry systems to consider ecosystem benefit delivery and trade-offs associated with alley width choice.

4.1. Functioning in tree rows and cropped alleys compared with control area

Agroforestry had a significant influence over common soil function indicators, compared with the treeless control area. We discuss which differences were significant in the tree row only, and which were also significant between control and identically-managed agroforestry alleys.

Bulk density was nearly 10 percent lower beneath agroforestry tree rows and alleys compared with the control, implying that trees can reduce soil compaction in cultivated areas as well as uncultivated areas. Decreased compaction due to afforestation is well known and observed elsewhere (Messing et al., 1997; Olszewska and Smal, 2008; Korkanç, 2014; Ashwood et al., 2019), derived from OM additions from tree root, shoot and exudate material (Jobbágy et al., 2001; Haichar et al., 2014; Judson et al., 2023b). However, our findings differ from others in that reduced compaction was not confined to tree row areas but extended into adjacent cultivated alleys. Notably, the difference we observed in bulk density between control and cultivated alleys was not apparent in topsoil but was significant in subsoil. Differences in subsoil compaction may be due to the influence of tree roots extending beyond the tree rows and into the alleys at greater soil depth, an effect which has been demonstrated elsewhere (Cardinael et al., 2015b). Reduced compaction in alleys carries several benefits, such as better water and nutrient uptake by plants (Arvidsson, 1999) with positive implications for agricultural productivity. Addition of SOM from trees as root and shoot litter and C-dense exudates leads to aggregate formation and increased

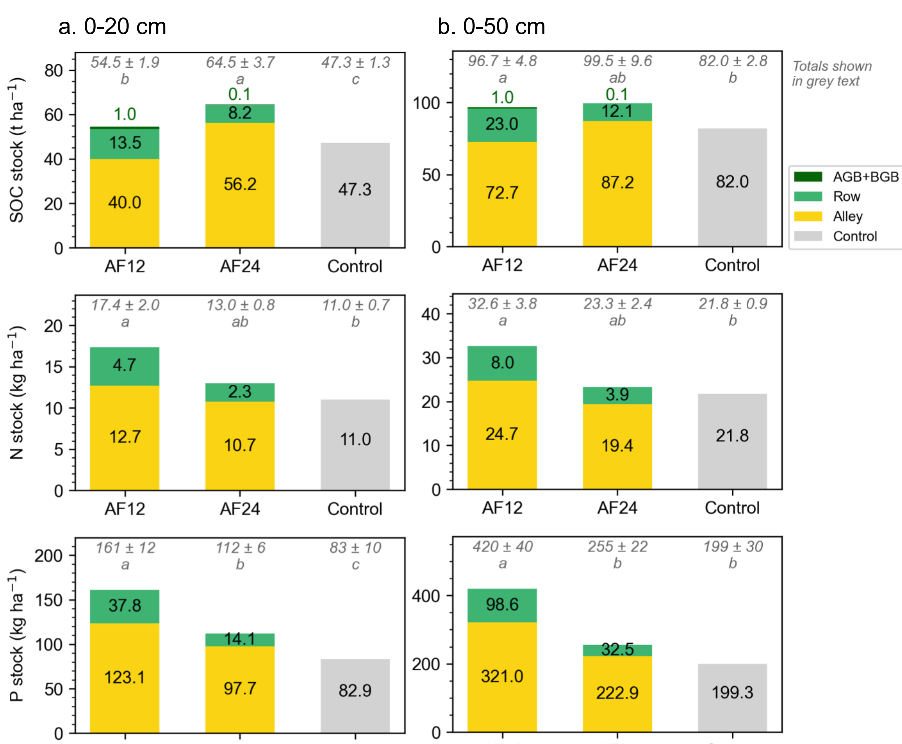

Fig. 9. Stock of SOC, available N and available P for a. 0–20 cm and b. 0–50 cm, by agroforestry system design (AF12 – 12 m-spaced tree rows planted 2002 with 110 stems ha^{-1}; AF24 – 24 m-spaced tree rows planted 2012 with 55 stems ha^{-1}). Per-hectare contributions of each agroforestry component to total stock are given by coloured blocks, control area contribution given by grey block. AGB + BGB represents estimated above-ground- and below-ground tree biomass C stock for the two agroforestry systems. Total stock for each system given in grey italic text, with letters denoting significant differences between totals.

infiltration rates (Franzluebbers, 2002). Extra organic matter in the vicinity of trees can further reduce compaction indirectly by stimulating earthworm diversity and activity (Lavelle et al., 1998).

Similarly, available P content was elevated by 70 % beneath agroforestry alleys, compared with the control. Unlike bulk density, higher available P was found in alley topsoil as well as subsoil, despite alleys having the same agricultural management as the control. Additional P is most likely derived from tree litter dispersed into the alleys decomposing into surface soil, as has been shown for other species (e.g. Guazuma ulmifolia, Hoosbeek et al., 2018). As Pardon et al. (2017) noted, soil nutrient concentration tends to decline more gradually with distance from mature trees (>15 years) compared with younger trees, and we found considerably more P in the alley of the older (AF_{12}) of the two treatments. Trees and crops in agroforestry are known to share networks of arbuscular mycorrhizal (AM) fungi (Ingleby et al., 2007) which in-turn thrive in and facilitate access to soil P (Qiao et al., 2022). Mature trees can therefore have significant positive influence on soil fertility in the cropped area of agroforestry systems.

For other soil indicators, soil function in agroforestry alleys more closely resembled the control area. For example, an additional 12.5 t ha^{-1} SOC stock to 50 cm depth was found beneath the tree row compared with the control, although no significant difference in SOC stock was found between alley areas and control. Smaller SOC stock differences in alleys compared with tree rows is a common finding – for example, Cardinael et al. (2015a) in a study of similar age trees (18 years) found a difference of +17.7 t ha^{-1} between tree row and control for soils across the 0–50 cm depth range, and a difference of only +2.6 t ha^{-1} between alley and control. Annual harvesting and regular tillage in the alley have been shown to result in higher C losses from the soil compared with undisturbed tree rows (Hooker et al., 2005; Dawson and Smith, 2007).

Similarly, K_s was three times faster in surface soil beneath tree rows, presumably due to lowered surface soil bulk density, with no significant difference in K_s between agroforestry alleys and the control where bulk density was similar. Trees and hedges are known to increase surface K_s in farm soils (Marshall et al., 2014; Holden et al., 2019). Limited evidence exists for this effect extending far from trees themselves and we did not observe the same effect in the agroforestry alleys, although hydraulic gradients may be produced up to 10 m either side of drier hedge soils (Caubel et al., 2003). On sloping ground, agroforestry can alter hydraulic functioning of soil at a distance from trees, provided rows are planted cross-slope. Siriri et al. (2006) in a study of a sloping (10 %) silvoarable terrace system found the hydrological influence of *Calliandra calothyrsus* trees to extend well into the cropped area due to their extensive rooting system. K_s in their alley crops adjacent to trees were nearly three times higher (22 mm hr^{-1}) than for a sole crop control (8 mm hr^{-1}). Although cross-slope planting produces complications for modern agricultural machinery, this nonetheless demonstrates the extra benefit of cross-slope planting for soil infiltration and potential flood mitigation compared with downslope alley planting.

4.2. Spatial and hillslope interactions between silvoarable soil properties

Lower available N, available P and moisture content at the alley edge sample positions imply competition for these resources between tree and crop at the row-alley boundary at the time of measurement, particularly given that lower N and P at the alley edge was found more in subsoil than topsoil. Studies utilising artificial soil barriers at the tree-crop boundary (Jose et al., 2000a; Jose et al., 2000b; Zamora et al., 2009) found that trees successfully compete for both water and available N at the alley edge. In these studies, crop water uptake was higher with a barrier in place, whereas tree water uptake was higher (at the expense of the crop) with no barrier as tree roots took up water from beneath the crop. Moreover, crop plants acquired a higher proportion of mineralised N from soil in the presence of a barrier. The row-alley competition zone we observe may coincide with tree dripline effects, however soil moisture is often higher at the dripline and particularly in subsoil (Alva et al., 1999), which is the opposite of what we observe. It must be noted, however, that although our study found lower N and P content at the alley edge, overall abundance of N and P in the agroforestry alleys was no lower (and in some cases, significantly higher) than in the control area. Moisture content was lower at the alley edge when compared with the control area, although this is less likely to inhibit crop productivity in areas of low water stress. Pardon et al. (2018) found that tree age and crop type were the major determinants of yield changes at alley edge locations. Only near mature trees were yield losses significant, and there was minimal effect on winter cereals for any tree category. Similarly, Cardinael et al. (2015b) found that trees and crops may form complementary rooting systems, facilitating better resource capture and circularity much deeper in the soil profile, in addition to the positive effect of complementary AM fungal networks (Ingleby et al., 2007). Spatial knowledge of yield data, which was not available at our study site, would be useful for determining the influence of competition effects on crop productivity at the alley edge.

Differences in particle sizes between treatments and slope positions implied that agroforestry influenced erosion susceptibility across the study area. In the absence of trees, a 3.5 % higher clay fraction, 0.83 % higher SOM content and 15 % higher SOC stock were observed downslope, with no equivalent effect in the agroforestry areas. This implies downslope fine soil movement in the absence of trees, explaining why SOC stock differences between agroforestry and the control were only significant in upslope positions. Water erosion selectively transports finer particles from soil, leaving coarser material behind along with stones (Durán Zuazo and Rodríguez Pleguezuelo, 2008). Given that most SOM is stored in shallow topsoil, this 'fining' process leads to downslope transport and loss of organic matter from soil to watercourses, in addition to possible respiration loss of SOM as CO_2 through disturbance (e.g. Six et al., 2001). Agroforestry at this study site is therefore likely contributing to ecosystem service provision by limiting downslope erosive transport and loss of organic matter, even though trees are planted in rows parallel to slope. In addition to trees, the understorey within the tree rows is likely to be contributing to this particle size effect, as others have found (e.g. Dabney et al., 2001; Anderson et al., 2009; Monger et al., 2022a), and further study focussed on the understorey would be welcome to confirm this. Inhibiting OM loss protects soil aggregates, which in turn improve soil porosity, infiltration and ultimately, productivity (Boyle et al., 1989; Franzluebbers, 2002; Durán Zuazo and Rodríguez Pleguezuelo, 2008); meanwhile C stocks in soil undisturbed by erosion are not lost to respiration or downstream transport (Harden et al., 1999; Kirkels et al., 2014).

4.3. Choice of alley width and whole-system benefits of agroforestry

Narrower, 12 m tree row spacing exhibited higher soil fertility compared with the control area, equivalent to alley areas contributing 122 kg ha^{-1} more available P stock to 50 cm depth over 21 years. In contrast, the difference was only 24 kg ha^{-1} in 24 m alleys compared with the control. Although trees in the 12 m system are twice the age of trees in the 24 m system and age is likely to be contributing to some of the difference between systems, a five-fold difference in effect size between them implies that age cannot be the only contributing factor to differences in P stock. Two other effects may be contributing. Firstly, Steinfeld et al. (2024) found that more densely-planted agroforestry systems produce litter with higher concentrations of both N and P, which then decomposes in both the row and alley in the vicinity of the trees, contributing to soil nutrient stocks. Elevated N in soil has also been shown to produce higher N concentration in apple tree litter (Kowalczyk et al., 2017). The AF_{12} system has higher planting density (110 stems ha^{-1}) than AF_{24} (55 stems ha^{-1}) and is therefore likely to generate a higher density of root and shoot litter. Secondly, closer tree rows are likely to form a more 'closed loop' system, with nutrients leached into subsoil better intercepted by denser subsurface tree root and AM fungal networks beneath the main crop (Rowe et al., 1999; Ingleby et al., 2007; Tully et al., 2012; Cardinael et al., 2015b). Available soil fertility for crops therefore trades off against alley width and cultivatable arable area. Although greater fertility is available in an agroforestry system with narrower alleys, this will trade-off against factors such as shading at alley edges (Karim et al., 1993; Swieter et al., 2021) and evaluation of best width will therefore depend on the relative weighting of factors. Including tree row contributions to fertility in the AF_{12} system, extra available P stock nearly doubles to 220 kg ha^{-1} over 21 years, although extra fertility beneath trees is considerably less available to crops.

Recent policy recommendations in the UK advise that 10 % of cropland (440,000 ha) be converted to silvoarable agroforestry, in order to store an extra 2.2 t C ha^{-1} $year^{-1}$ (3.5 Mt CO_2e $year^{-1}$) contributing to net-zero emissions by 2050 (Woodland Trust, 2022; Defra, 2023; CCC, 2025). However, of the two agroforestry systems surveyed here, only the 12 m system stored significant extra total C to a depth of 50 cm, compared with the control system (Table 1). The control-agroforestry C stock difference in the 24 m system, although slightly larger, was not significant at 95 % confidence (Table 1). Nonetheless we can use the AF_{12} total C (SOC + tree biomass C) difference of +14.7 t ha^{-1} to consider the feasibility of stated policy recommendations. The SOC component of this difference (+13.7 t C ha^{-1}) corresponds to an annual soil C storage of 650 kg C ha^{-1} $year^{-1}$ over the 21-year lifespan of trees in the AF_{12} system, which represents a contribution of 29 % to the 2.2 t C ha^{-1} $year^{-1}$ figure for potential annual C storage in silvoarable systems (Woodland Trust, 2022). However, we estimate only 1.0 t C ha^{-1} (50 kg C ha^{-1} $year^{-1}$) extra C contributed by tree biomass in the AF_{12} system, for a total of 700 kg C ha^{-1} $year^{-1}$ which is more than three times less than the target storage figure.

For SOC storage rates similar to this study, more than 70 % of total C storage must therefore come from tree biomass for the 2.2 t C ha^{-1} $year^{-1}$ target to be reached. Yet literature values for proportional tree biomass contributions to silvoarable C storage are frequently much lower than 70 %. Shi et al. (2018), in a *meta*-analysis of C sequestration potential of 217 silvoarable (alley cropping) systems globally, found C stock increases in silvoarable systems to be similar in soil and above ground biomass. Delivering 2.2 t C ha^{-1} $year^{-1}$ from silvoarable systems is therefore likely to require a large and significant SOC storage contribution of > 1 t C ha^{-1} $year^{-1}$, and where tree biomass is regularly harvested or pruned or where planting densities are lower than 150 stems ha^{-1}, SOC storage will have to be considerably greater still. In contrast, our study found that tree biomass C represented just 7 % of annual C additions, with 93 % derived from SOC. Trees in this study were regularly pruned for apple production, limiting the contribution of tree biomass C to overall C storage to an extent, but this highlights practical considerations about the magnitude and longevity of above ground silvoarable C stocks.

Shi et al. (2018) found the sum of AGB C and SOC stock differences in silvoarable systems to be lower than for other systems such as shelterbelts and silvopasture, in part due to planting densities. Yet even shelterbelt and silvopastoral systems rarely generate forecast C storage at planting densities equivalent to this study. In a silvopastoral system of 14-year-old trees with a planting density of 110 stems ha^{-1} (equivalent to AF_{12} in this study), Upson et al. (2016) found area-adjusted tree biomass contributions to be just 4.0 t C ha^{-1} (290 kg ha^{-1} $year^{-1}$). A 2.2 t C ha^{-1} $year^{-1}$ figure was only reached in the case of continuous woodland (1,600 stems ha^{-1}), for which contributions from tree biomass C rose to 2.6 t ha^{-1} $year^{-1}$.

Finally, planting density for the 2.2 t C ha^{-1} target is assumed to be 150 stems ha^{-1}. This is high for conventionally cropped silvoarable land and is 1.5 and 3 times denser than that used in the AF_{12} and AF_{24} systems, respectively. Although new Countryside Stewardship funding (Defra, 2025) in England supports planting at 150 stems ha^{-1}, the 110 stems ha^{-1} figure from this study corresponds to 12 m alleys and it is considerably unlikely that new adopters of silvoarable agroforestry will plant in excess of this density due to the constraints it places on the size of modern farm machinery. Planting densities of ~50 stems ha^{-1}, appropriate for a 24 m system, are more likely in newly planted silvoarable agroforestry.

A realistic annualised SOC storage figure for silvoarable agroforestry is therefore likely to be considerably lower for the majority of systems. A number of explanations for low observed soil C sequestration are possible. For example, C stocks in the soils prior to planting may have been near saturation, such that organic matter derived from trees would not increase storage further (Stewart et al., 2007; Breure et al., 2025). However, this is unlikely as storage rates in this study are comparable to those found elsewhere for a range of soil types (Table 1). It is possible that the small difference in C storage between agroforestry and control areas in this study is due to similar incorporation of green manure in both treatments as they are under organic management, promoting build-up of C stocks in both and thus minimising the difference between them. However, comparable studies of non-organic agroforestry systems (Table 1) did not observe C storage differences close to the modelled figures.

5. Conclusions

Using soil samples and measurements from a working silvoarable site first planted with trees in 2002 and subsequently in 2012, in Devon, SW England, we demonstrate how key soil functions – C storage, nutrient availability and hydrological functioning – are influenced spatially by hillslope position and with alley width. Benefits commonly associated

Table 1
Comparison of control-agroforestry differences in SOC stock and sequestration rates between this study and studies with similar tree age and climate zone. Differences marked *(ns)* are not significant at 95% confidence. 'LFH/OH' refers to LFH/OH soil horizons.

Study	Location	Age	Land Use Change	Difference in SOC stock LFH/OH Amount ($t\ ha^{-1}$)	Rate ($t\ ha^{-1}\ yr^{-1}$)	0–20 cm Amount ($t\ ha^{-1}$)	Rate ($t\ ha^{-1}\ yr^{-1}$)	0–50 cm Amount (t ha-1)	Rate ($t\ ha^{-1}\ yr^{-1}$)
This study (12 m system)	Devon, UK	21	Arable to silvoarable	–	–	+7.2	+0.34	+14.7	+0.70
This study (24 m system)	Devon, UK	11	Arable to silvoarable	–	–	+17.2	+1.56	*+17.5(ns)*	*+1.59(ns)*
Judson et al. (2024)	Yorks, UK	35	Arable to woodland	+8.9	+0.26	+15.8	+0.45	*+1.0(ns)*	*+0.03(ns)*
Mayer et al. (2022)	Various temperate	28	Various[†]	–	–	+7.0	+0.21	+10.1	+0.36
Cardinael et al. (2015a)	Hérault, France	18	Arable to silvoarable	–	–	+4.5	+0.25	+5.0	+0.28
Ashwood et al. (2019)	Midlands, UK	50	Arable to woodland	+9.1	+0.18	+37.2	+0.74	+63.5	+1.27
Upson and Burgess (2013)	Beds, UK	20	Arable to silvoarable	–	–	+7.2	+0.36	+20.8	+1.04

[†] Mayer et al. (2022) is a *meta*-analysis which includes the following land-use change (LUC) types: pasture to silvopasture, arable to silvoarable or hedge.

with tree rows such as reduced compaction and nutrient addition to soil were readily transferred from tree rows to adjacent cultivated alleys, most likely via litterfall and lateral tree root influence. Reduced compaction was delivered in subsoil beneath crops, implying that SOM addition from tree roots extended into the cropped area. Alleys were 70 % enriched in available P in both topsoil and subsoil compared with treeless areas. The strongest soil fertility improvements were observed in narrower 12 m cropped alleys, implying greater circularity in system nutrient dynamics and denser root and AM fungal networks than wider, 24 m alleys, albeit producing a trade-off between soil fertility benefits and cultivatable arable area. Future work incorporating yield data to estimate land-equivalent ratio would be welcome for determining the extent of this trade-off. Demonstrable soil structure and fertility improvements in agroforestry alleys imply that loss of cropable area from afforestation can be offset by improved functioning, in addition to known benefits from tree rows.

Several important spatial effects were found. Competition at the tree row/alley boundary was observed for N, P and soil moisture, which were depleted at the alley edge compared with the tree row and alley centre. Differences were predominantly found in subsoil, implying that tree roots extending into alleys were successfully competing with crops for resources. Nonetheless, overall alley N and P concentrations remained greater in the alley than the control area, implying that the competition effect had not diminished overall fertility. Agroforestry successfully mitigated erosive loss of SOM, despite tree rows being orientated parallel to the slope. Reduced erosion improves downstream water quality and limits C loss from topsoil. Although it presents issues for use of modern farm machinery, we hypothesise that this effect would be considerably stronger with cross-slope alleys, which would provide greater flood mitigation potential due to elevated saturated hydraulic conductivity in the vicinity of tree rows. Erosion and flood mitigation studies on cross-slope silvoarable systems would greatly enhance knowledge of these effects.

Considerable attention has been given to the contribution of agroforestry to C emissions mitigation from arable land. We found a significant difference of +14.7 t C ha^{-1} stored in the 12 m agroforestry system, compared with the treeless control. At 700 kg C ha^{-1} $year^{-1}$, this is more than three times smaller than the UK target for extra C storage in silvoarable systems of 2.2 t C ha^{-1} $year^{-1}$ (8 t CO_2e ha^{-1} $year^{-1}$). C storage contributions modelled in policy scenarios assume planting densities considerably higher (150 stems ha^{-1}) than is practicable for most silvoarable practitioners. Potential for silvoarable systems to contribute to national C budgets may therefore have been overestimated, although organic management in all treatments may explain small differences in soil C stock between control and agroforestry in this study. Further work could usefully compare C sequestration in organic systems with conventionally-managed agroforestry, and we note the need for dedicated experimental sites at which factors such as hillslope and silvoarable alley width can be more carefully constrained. We conclude that the contribution of silvoarable systems to temperate ecosystem service provision must be considered in terms of demonstrated multiple benefits that go beyond C sequestration, such as soil fertility benefit, natural flood management and biodiversity improvements. A holistic view of the ecosystem benefits of temperate agroforestry will ensure it contributes to future landscape resilience.

CRediT authorship contribution statement

Josiah B. Judson: Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Pippa J. Chapman:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Joseph Holden:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Marcelo V. Galdos:** Writing – review & editing, Supervision, Methodology, 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.catena.2025.109439.

Data availability

Data associated with this paper are available from the University of Leeds at https://doi.org/10.5518/1594.

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