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Do multistrata agroforestry, improved fallow, and woodlot systems enhance agricultural productivity and soil fertility compared to shifting cultivation in tropical drylands?

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Abstract Shifting cultivation under high population pressure often results in shortened fallow periods and land degradation. Multistrata agroforestry, improved fallow, and woodlots are promoted as sustainable alternatives, but comparative evidence of their benefits remains limited. We conducted a four-year field experiment in Mozambique to evaluate whether these systems improve land productivity, crop yields, and soil fertility compared to shifting cultivation, and to assess the impact of using native trees or eucalyptus. Multistrata system involved maize, pigeon peas, and bananas with either native trees (MS-N) or eucalyptus (MS-E). Improved fallow combined pigeon peas and maize sequentially with or without native trees, while woodlots included maize with native trees or eucalyptus. Productivity was assessed using land equivalent ratios (LER) based on crop, firewood, and pole yields over three seasons. Soil organic carbon, total nitrogen, available phosphorus, and bulk density were also measured. We found that multistrata systems improved productivity compared with shifting cultivation. LER values of MS-N and MS-E rose from 1.0 in the first season to 2.3 and 1.83, respectively, reflecting productivity gains of 130% and 83% by the third season. Woodlots outperformed shifting cultivation only in the third season after firewood and pole harvests, whereas improved fallows showed no significant productivity gains. No significant changes in soil fertility were observed within three years. Choosing native or eucalyptus trees did not affect maize yields or soil nutrient levels. Our findings highlight that multistrata systems can rapidly improve land productivity compared to shifting cultivation. However, detecting soil fertility changes may require long-term monitoring.

Keywords Multistrata agroforestry · Improved fallow · Land equivalent ratio · Shifting cultivation

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Introduction

Land degradation is a global problem that negatively affects the livelihood and food security of about 1.3–3.2 billion people, most of them living in developing countries (Olsson et al. 2022) and is frequently linked with unsustainable agricultural practices (Curtis et al. 2018; Olsson et al. 2022), such as shifting cultivation, which involves slashing and burning vegetation, cultivating annual crops (for three to four years), and leaving the area in fallow for recovery (Hauser and Van Asten 2010; Bezerra et al. 2024). Shifting cultivation practices are connected

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to deforestation (Hosonuma et al. 2012; Curtis et al. 2018), biodiversity loss, soil nutrient depletion, and erosion (Bezerra et al. 2024) due to shortened (<5 years) periods of fallow (Dalle and Blois 2006; Sharma et al. 2022), and extended periods of cultivation (Wood et al. 2017; Abrell et al. 2024). Moreover, fallows are often used for firewood collection, charcoal production and grazing (Ducourtieux 2015), which slows the recovery.

To tackle the problem of land degradation, agroforestry systems have been promoted within the tropics, given their potential to increase land productivity and food security (Sudomo et al. 2023), improve livelihood (Muthuri et al. 2023), mitigate climate change impacts and promote climate change adaptation (Lasco et al. 2014; Sheppard et al. 2020). Agroforestry systems consist of intentionally growing trees or shrubs on the same land unity as crops or animals, in a simultaneous or sequential temporal arrangement (Nair 1991; Somarriba 1992; Torquebiau 2000). They can be grouped into alley cropping or hedgerow intercropping, improved fallow, multistrata systems, protective systems, silvopasture, and agroforestry woodlots (Nair 2014).

Studies show a wide variability in the performance of the agroforestry system depending on whether they are managed in simultaneous or sequential arrangements (Malézieux et al. 2009; Feliciano et al. 2018), as well as whether they are mixed stands with higher species diversity or monocultures (Richards et al. 2010; Tscharntke et al. 2011; Zemp et al. 2019). In simultaneous systems, where trees and crops grow together, competition for light, water, and nutrients usually occurs between trees and crops (Schroth et al. 2001) and leads to reduced crop yields in the understory (Famuwagun et al. 2017; Xu et al. 2019; Figyantika et al. 2020). In contrast, sequential systems (improved fallow) mitigate this competition by planting trees and crops at different times (Rao et al. 1997). It is also commonly argued that agroecosystems with greater plant species diversity (e.g. multistrata agroforestry) are more sustainable than agroecosystems with lower plant species diversity (e.g. monocultural systems). Mixed stands with high species and structural diversity can create complementary interactions between trees and crops that lead to enhanced resource use efficiency (Benjamin et al. 2001), increased carbon sequestration (Ma et al. 2020; Ngaba et al. 2024), improved soil nitrogen accumulation (Gong et al. 2022; Negash et al. 2022), higher overall productivity, and reduced risk of production loss from climatic events or pests (Malézieux et al. 2009; Isbell et al. 2017) compared to monoculture. However, a significant gap exists in understanding the overall productivity advantage or disadvantage of simultaneous agroforestry systems compared to sequential agroforestry systems. There is also a lack of experimental studies comparing the overall productivity and soil nutrient accumulation between multistorey agroforestry systems and those composed of a few species, indicating a need for further research. In addition, several studies compared the land use efficiency of agroforestry systems to monocropping systems (Yun et al. 2012; Xu et al. 2019), but most focused their analysis on crop yield, excluding other products such as firewood and poles. Evaluating agricultural productivity in terms of the yield of a single crop per unit area fails to capture the overall productivity of more diverse farming systems (Lin and Hülsbergen 2017).

Furthermore, many farmers practising agroforestry prefer exotic species such as eucalyptus over native ones, due to their rapid growth, higher biomass yield (Foroughbakhch et al. 2001), and significant economic returns associated with exotic species (Nath et al. 2016; Rahman et al. 2024), as well as a general lack of knowledge about the cultivation, management, and marketing potential of native species. However, eucalyptus trees are known to consume large quantities of water (Reichert et al. 2021), are claimed to have allelopathic effects (Zhang and Fu 2009; Rahman et al. 2024), which can negatively affect the understory and soil biodiversity (Lemessa et al. 2022; Martello et al. 2024). There is a lack of experimental studies comparing the overall productivity and soil nutrient accumulation between native-tree-based and exotic-tree-based agroforestry systems. The land equivalent ratio (LER) is applied in several studies to compare the productivity or land use efficiency between monocropping systems and intercropping systems (Miah et al. 2018; Figyantika et al. 2020; Sirohi et al. 2022). The LER refers to the relative amount of land required for the monocropping system to produce the same yields as intercropping and can be applied for measuring the relative yield advantage of intercropping over monocropping or comparing different crop combinations (Mead and Willey 1980). It has the advantage of incorporating all the products of the system into a single value (Lin and Hülsbergen 2017). Agricultural productivity refers to the ratio of outputs to inputs (Tangen 2002), and when expressed as crop yield per unit of land per year, it means the efficiency of production (Seufert 2019) or agricultural land-use efficiency (Lin and Hülsbergen 2017).

In the present research, we apply the LER to compare the overall productivity of multistrata agroforestry systems with improved fallow, woodlots, and shifting cultivation in drylands. Moreover, we compare the impact of eucalyptus-based and native-tree-species-based agroforestry systems on soil fertility and the yield of understorey crops. Unlike prior studies that evaluated multistrata agroforestry systems, improved fallow, and woodlots separately, this research evaluates all three together in a single experiment, covering crop, firewood, and pole production over three years. Our study involves three native timber species—*Afzelia quanzensis, Millettia stuhlmannii*, and *Khaya anthotheca*—and one exotic species, *Eucalyptus cloeziana.* Although earlier research has examined agroforestry systems involving *M. stuhlmannii* (Cassamo et al. 2023; Magalhães et al. 2025), *K. anthotheca* (Kasolo and Temu 2008; Santos et al. 2019), and *E. cloeziana* (Couto et al. 1995; Almeida et al. 2021; Teodoro et al. 2023), no information is available regarding the use of *A. quanzensis* in agroforestry systems.

We tested the hypothesis that agroforestry systems increase overall productivity, crop yield and soil fertility compared to shifting cultivation. Furthermore, we hypothesise that the multistrata system, with its higher structure, species, and product diversity, results in higher overall productivity and soil nutrient accumulation than improved fallow and woodlots. Additionally, we hypothesised that native-tree-based agroforestry systems significantly enhance understory crop yields and soil fertility in comparison to eucalypt-based agroforestry systems.

Materials and methods

Study area

The study was conducted from February 2020 to November 2024 at Sussundenga Agrarian Research Station (Fig. 1) in Manica Province, the central region of Mozambique, and lies at a latitude 19° 26′ 12″ S and a longitude 33° 17′ 27″ E, at an altitude of 564 m. Sussundenga has a wet semi-arid climate (Aw) with an average rainfall of 1000–1200 mm, which falls between November and March (Reddy 1986). The cropping season is between November and May. The average temperature is 23.0 °C with 29.1 °C as the maximum and 9.5 °C as the minimum temperature (Wijnhoud 1997). In the central region of Mozambique, drought has occurred once every 5.9 years since 1982, connected with the El *Nino-Southern Oscillation (ENSO)* phenomenon (Araneda-Cabrera et al. 2021). During the 2024 cropping season, the study area registered severe rain shortages (Fig. 2) that caused significant damage to crops (FAO 2024).

The dominant reference soil groups at Sussundenga Agrarian Research Station are Ferralsols (haplics and rhodics), Haplic Lixisols and Haplic Acrisols (Wijnhoud 1997; Famba et al. 2011), and the research plots were established in Haplic Lixisols soils (Wijnhoud 1997; Bolfe et al. 2011). The baseline description (Table 1) shows that the research plots have acid soils and very low levels of soil organic carbon (SOC), available phosphorus and total nitrogen.

The most predominant cropping system in the Sussundenga district, including the study plots, is shifting cultivation (MAE 2014). In the study area, the local farmers are dependent on rainfall for growing their crops and do not use fertilisers, manure or insecticides. They involve family labour in all farming activities and do not use mechanisation. Their main staple crops include maize and sorghum, cultivated in consortia with beans, cassava and vegetables (MAE 2014). The study area is characterised by relatively high population density. Consequently, there are almost no remaining areas available for further deforestation, and local farmers are forced to shorten the fallow period to approximately 3–5 years.

Before 2015, the site was managed as a eucalyptus plantation. After harvesting eucalyptus, the land was used for traditional shifting cultivation between 2015 and 2019, mainly under maize monoculture, with occasional intercropping of maize with cassava, beans, and vegetables. The site remained fallow during 2019 and 2020 prior to the establishment of the agroforestry experiment.

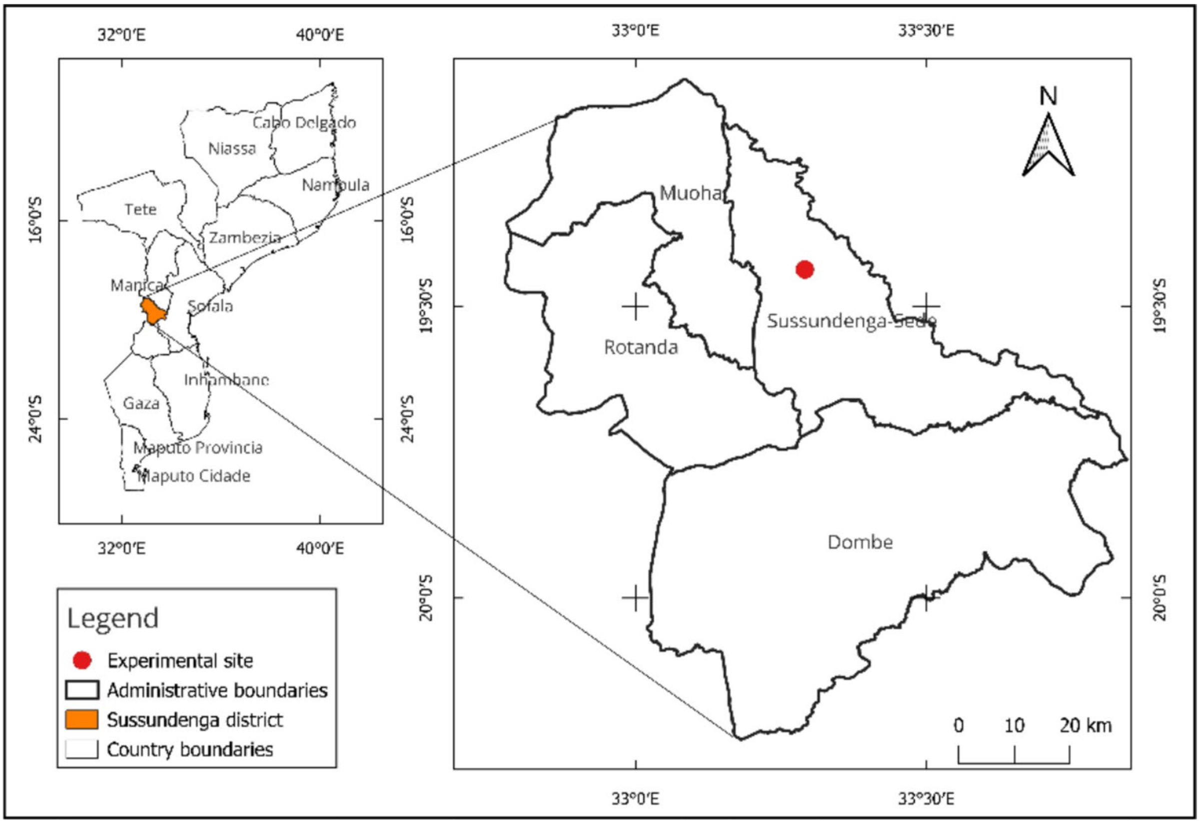

Fig. 1 Location of experiment comparing multistrata, improved fallow and woodlot agroforestry systems with shifting cultivation in the Sussundenga Agrarian Research Station, central region of Mozambique

Fig. 2 Monthly rainfall distribution in the Sussundenga district from 2020 to 2024

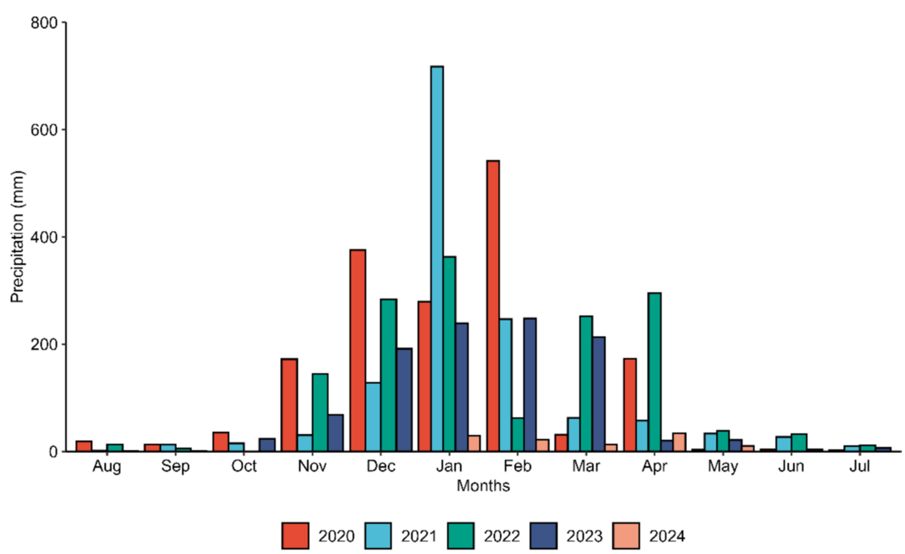

Table 1 Soil characteristics before the establishment of an experiment comparing multistrata, improved fallow and woodlot agroforestry systems with shifting cultivation in the Sussundenga Agrarian Research Station, central region of Mozambique

Parameter	Unit	Value/depth	
		0–20 cm	20–40 cm
pH KCl (1:2.5)		5.46	4.99
Soil organic carbon	%	0.89	0.68
Labile phosphorus	mg/kg	7.66	3.89
Total Nitrogen	%	0.12	0.08
CEC	meq/100 g	8.19	7.47
Clay	%	24.78	31.15

Description of the treatments

The experiment covered an area of 7.5 hectares, and included eight treatments, specifically multistrata agroforestry with local timber trees (MS-N), multistrata agroforestry with eucalypt (MS-E), improved fallow with pigeon peas and local timber trees (IF-N), improved fallow with pigeon peas (IF-Pp), woodlot with local timber trees (WL-N), woodlot with eucalypt (WL-E), monocropping shifting cultivation of maize (SC-M), and natural fallow (C-NF).

The multistrata agroforestry with local timber trees (MS-N) is composed of three layers. The top layer comprises three local timber tree species, namely *Afzelia quansensis* (Welw.), *Millettia stuhlmannii* (Taub.), and *Khaya anthotheca* (Welw.). The medium layer is composed of banana *(Musa spp.)* crops, and the herbaceous layer is made of pigeon pea (*Cajanus cajan* L.) and maize (*Zea mays* L.) crops. We planted trees at a spacing of 4 m between plants and 10 m between rows, corresponding to 250 trees ha^{-1}. At the same time, banana crops were added between the timber trees on the same row. Once the trees and bananas were well established, we sowed pigeon peas as a fallow crop at a spacing of 1 m by 1 m (10,000 plants ha^{-1}), just a season before the maize planting, to accelerate the process of soil fertility recovery. When the pods reached maturity, the pigeon pea plants were cut at ground level to make room for maize crops. The cut biomass of the pigeon pea plants was evenly applied in the respective plots as mulch for soil protection, fertility restoration, and weed suppression. After the clear-felling of the pigeon pea, we sowed maize at a spacing of 1 m between rows and 0.5 m within rows (20,000 plants ha^{-1}). The multistrata agroforestry with eucalypt (MS-E) has the same structure as the MS-N, but we replaced native tree species with trees of *Eucalyptus cloeziana (F. Muell.)* spaced at 3 m between trees and 10 m between rows (333 trees ha^{-1}).

The improved follow-system with pigeon peas and local timber trees (IF-N) has two layers, namely the top layer composed of local timber tree species (*A. quansensis, M. stuhlmannii*, *and K. anthotheca)* and the herbaceous layer of pigeon peas and maize. We planted trees, pigeon peas and maize at a similar spacing and in the same sequence as in multistrata agroforestry systems. The improved fallow system with pigeon peas (IF-Pp) has only the herbaceous layer composed of pigeon peas and maize crops planted in the same sequence described in the previous systems.

The woodlot with local timber trees is a forest stand composed of local timber tree species (*A. quansensis, M. stuhlmannii*, *and K. anthotheca*) planted at a spacing of 4 m by 4 m (625 trees ha^{-1}). The eucalypt woodlot is a plantation of *E. cloeziana* trees established at a spacing of 3 m by 3 m (1111 trees ha^{-1}). In the woodlot agroforestry systems, trees constitute the top layer, and maize crops comprise the herbaceous layer.

The shifting cultivation of maize (SC-M) represents a control treatment where maize crops are grown as sole crops at a density of 20,000 plants ha^{-1}. The control treatment, natural fallow (C-NF), was only considered for soil properties assessments and consisted of leaving the land without any sowing or planting to recover soil fertility.

Establishment of the trial and management

The experiment was laid out in a randomised complete block design (RCBD) with four main plots, eight subplots and six replications (blocks). The main plots (50 × 50 m) were subsequently split into two sub-subplots (50 × 25 m) each. The whole plot treatments were the agroforestry system types, namely, multistrata agroforestry system, improved fallow system, and agroforestry woodlot, while the subplot treatments were the species composition of the multistrata agroforestry system (MS-N and MS-E), improved fallow system (IF-Pp and IF-N), woodlot system (WL-N and WL-E) and the control (SC-M and C-NF) (Fig. 3).

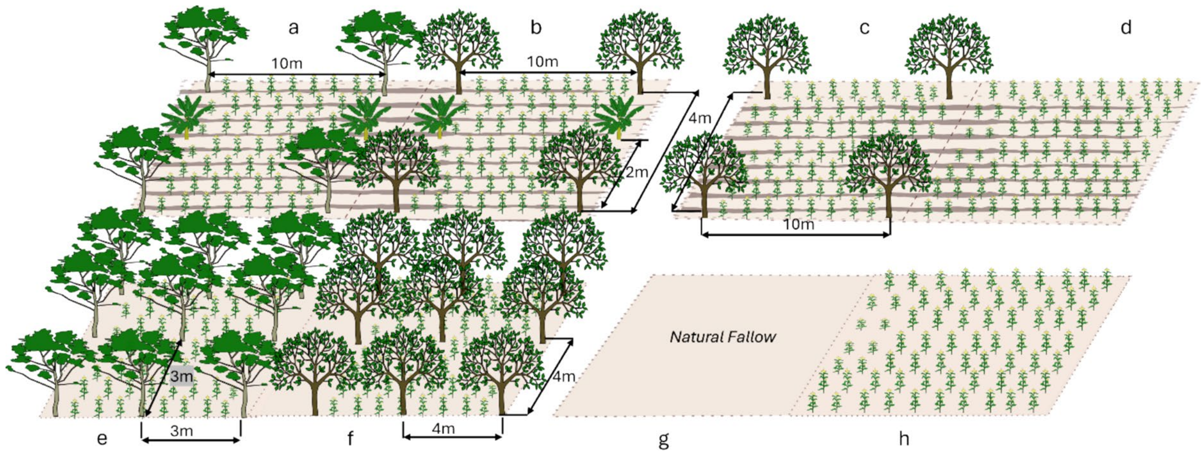

Fig. 3 A replication of an experiment comparing multistrata agroforestry (with eucalyptus–**a** and local timber trees–**b**), improved fallow (with local timber trees–**c** and pigeon peas–**d**), woodlots (with eucalyptus–**e** and local timber trees–**f**), natural fallow (**g**), and shifting cultivation of maize (**h**) treatments, with four whole plots, eight subplots, and a randomised complete block design, in Manica province, Mozambique. Pigeon peas were planted in treatments **a**–**d** one season before maize planting, cut at ground level after pod maturity, and evenly applied as mulch to the respective plots

Table 2 Crops and tree planting schedule in an experiment comparing multistrata agroforestry system (MS-N and MS-E), improved fallow (IF-Pp and IF-N), woodlot (WL-E and WL-N) and shifting cultivation (SC-M) treatments in Manica province, Mozambique. Trees were replanted in 2021 following the widespread death of those established in 2020

Treatments	Cropping season				
	2020	2021	2022	2023	2024
MS-N	Local timber trees	Local timber trees + banana	Local timber trees + banana + pigeon pea	Local timber trees + banana + maize	Local timber trees + banana + maize
MS-E	Eucalypt trees	Eucalypt trees + banana	Eucalypt trees + banana + pigeon pea	Eucalypt trees + banana + maize	Eucalypt trees + banana + maize
IF- Pp	Natural fallow	Natural fallow	Pigeon pea	Maize	Maize
IF-N	Local timber trees	Local timber trees	Local timber trees + Pigeon pea	Local timber trees + Maize	Local timber trees + Maize
WL-N	Local timber trees	Local timber trees	Local timber trees	Local timber trees + Maize	Local timber trees, woodlot + Maize
WL-E	Eucalypt trees	Eucalypt trees	Eucalypt trees	Eucalypt trees + Maize	Eucalypt woodlot + Maize
SC-M	Natural fallow	Natural fallow	Natural fallow	Maize	Maize
C-NF	Natural fallow	Natural fallow	Natural fallow	Natural fallow	Natural fallow

In March 2020 (Table 2), we started the establishment of the trial by planting trees in the plots corresponding to the treatments of the multistrata agroforestry system (MS-N and MS-E), improved fallow system (IF-N), and woodlots (WL-N and WL-E), but almost all died due to drought. Therefore, we replanted the trees in January 2021 and simultaneously introduced banana crops in the MS-N and MS-E plots. After replanting, we left the area fallow for two years to help the new trees establish and improve soil conditions before adding crops. In January 2022, we sowed pigeon peas in the multistrata agroforestry (MS-N and MS-E) and improved fallow (IF-Pp and IF-N) plots to accelerate soil fertility recovery and production of pigeon pea grain. Subsequently, in January 2023 and again in January 2024, we sowed maize across all treatment plots and harvested after a four-month growing period. We conducted manual weeding twice during the crop production cycle, specifically at 7 and 21 days after seed germination. Additionally, we performed another round of weeding in June, but only in plots with trees. All activities related to land preparation and crop management were carried out manually to mimic the production methods used by the local community. The seeds for pigeon peas and maize, as well as banana seedlings, were obtained from the local market, whereas the tree seedlings were produced by the Sussundenga Agrarian Research Station.

In November 2024, thinning was applied in the MS-N, MS-E, IF-N, WL-N, and WL-E treatments to remove malformed, diseased, pest-damaged, and dead trees. The remaining trees were pruned by removing approximately one-third of the green crowns (West 2014) to reduce shading for understorey crops. Subsequent management includes regular pruning and thinning to regulate tree–crop competition, generate biomass for improving soil fertility, enhance stem form and timber quality, and provide firewood. To mimic traditional shifting cultivation, SC-M plots are cultivated for 4 years, then left to fallow for another 4 years.

Data collection

Crop yield estimates

Crop yields were assessed at the physiological maturity stage from a net subplot area measuring 46 m by 21 m, ensuring a 2 m buffer around the 50 m by 25 m subplot. We systematically selected 20 plants in a zigzag pattern from each subplot, harvested and weighed the grain (fresh mass of the sample), and subsequently dried in an oven at 105 °C for 48 h (Tang et al. 2000) to obtain the dry mass of the sample. Then, we calculated the total dry weight of the grain by multiplying the ratio of the dry to the fresh mass of the sample by the total fresh weight of the grain. The same procedure was applied to the pigeon peas, but samples of 0.5 kg of pigeon peas per subplot were collected to determine the dry mass of the sample. The maize and pigeon pea grain yields are reported at 13% moisture content (Ziegler et al. 2021). The banana crop yields were obtained from the total fresh weight of fruits harvested per subplot. The crop yield data were collected in three cropping seasons: 2022, 2023 and 2024.

Poles and firewood estimates

To estimate the number of poles and the weight of firewood per hectare to be collected at the age of three years, we first measured the diameter at breast height (dbh), total height, stem quality, and signs of pest or disease attacks on all trees within a net subplot of 46 m by 21 m, excluding trees of *A. quansensis* due to their small size. We then selected trees with crooked stems and signs of damage caused by diseases or pests for thinning. In plots with over 70% survival, we selected 30% of the trees that were initially planted. For plots below 70% survival, we ensured even distribution or a spacing of 6 by 10 m in the MS-E plots. The remaining trees were pruned. Selected trees with a DBH exceeding 5 cm, slightly crooked stems, and a total height of over 4 m were counted as poles, while those with crooked stems and lower DBH and height were converted to firewood biomass, as per Eq. 1 (Guedes et al. 2018). Wood from pruned branches was weighed in the field, and then samples were collected and dried in the oven at 105 °C to constant weight to obtain the dry mass of the sample. Then, we calculated the total dry biomass of the pruned firewood by multiplying the ratio of the dry to the fresh mass of the sample by the total fresh weight of the pruned branches (Guedes et al. 2018; Magalhães et al. 2021).

$$tDW = 0.1754 * (dbh)^{2.3238} \quad (1)$$

where tDW is the total above-ground dry weight in kilograms (stem, branches and foliage) of individual trees, and dbh is the diameter at breast height of individual trees.

Land Equivalent ratio

The land equivalent ratio (LER) was calculated from crop yields, firewood and poles by applying Eq. (2) (Mead and Willey 1980) to measure the overall productivity of the agroforestry systems compared to sole maize cropping.

$$\text{LER} = \frac{Y_A}{S_A} + \frac{Y_B}{S_B} + \frac{Y_C}{S_C} + \frac{Y_D}{S_D} + \frac{Y_E}{S_E} \tag{2}$$

where Y_A, Y_B, Y_C, Y_D, and Y_E are respectively the production yields of maize grain, pigeon pea grain, banana fruits, firewood and poles in intercropping, and S_A, S_B, S_C, S_D, and S_E are the production yields of maize grain, pigeon pea grain, banana fruits, firewood and poles in monocropping. The reference values for banana yield in monocropping were 9839 kg ha^{-1} and 5484 kg ha^{-1} in 2023 and 2024, respectively. The pigeon pea yield from the IF-Pp treatment served as the reference for pigeon pea monocropping, since pigeon pea was cultivated as a monoculture before being replaced by maize. Reference yields for firewood and poles were derived from the woodlot treatments (WL-E and WL-N).

In our experiment, we did not plant bananas as a monocrop. Therefore, we estimated banana yield using a farmer survey method (Sapkota et al. 2016; Kosmowski et al. 2021), as the data from the local governmental agricultural institution (SDAE) do not distinguish between production by small farmers (rainfall-dependent) and large producers (irrigated systems). We interviewed local small farmers about their harvested weights for 2023 and 2024, measured the respective farm sizes, and then calculated banana yield per hectare by dividing total annual yield by farm area for the respective year. Banana yields per hectare were confirmed by SDAE experts and verified against FAOSTAT data (FAO 2025) to ensure unbiased yield estimates.

Soil sampling and analysis

Soil samples were collected from each subplot before planting any crops in November 2019 and again after the first harvest of the maize crop in 2023. Undisturbed and composite samples were obtained using an auger from three locations within each subplot, following a systematic zigzag pattern with a randomly chosen starting point (Pennock et al. 2007) at depths of 0–20 cm and 20–40 cm. From the undisturbed soil samples, we calculated the soil bulk density (BD) (Singh et al. 2014). We determined the soil organic carbon (SOC), plant available phosphorus (Av-P), and total nitrogen (N) contents from composite samples. The SOC was measured using the Walkley and Black method (Bremner and Jenkinson 1960), the total nitrogen was quantified via the Kjeldahl procedure (Bremner 1960), and labile phosphorus was measured using the Olsen method (Do Carmo et al. 2007).

Statistical analysis

To evaluate the effect of agroforestry treatments on land equivalence ratio (LER), crop yield (Eq. 3), soil nutrient accumulation and soil bulk density (Eq. 4), we fitted a linear mixed effects model, using the restricted maximum likelihood (REML) method through the *lmer* function of the *lme4 package* in R (Kuznetsova et al. 2017).

$$Y_{ij} = \mu + treatment_j + (1|block_i) + (1|block * wholeplot)_{ij} + e_{ij} \tag{3}$$

$$Y_{ijk} = \mu + treatment_j + (1|block_i) + (1|block * wholeplot)_{ij} + X_{jk} + e_{ijk} \tag{4}$$

where Y_{ij} is either LER or crop yield, and Y_{ijk} are stocks of SOC or total N, or available P or bulk density for the *j*th treatment in the block *i*; μ is the overall mean; treatment$_j$ is the fixed effect of *jth* treatment (j = MS-N, MS-E, IF-Pp, IF-N, WL-N, WL-E, SC-M and C-NF), in block$_i$ ($i = 1,2,\ldots,6$); $(1|block_i)$ and $(1|block*wholeplot)_{ij}$ are random effects for block and whole plot nested within block, respectively; $X_{jk\_}$ is the stock of SOC or total N, or available P or bulk density before the establishment of *j*th treatment; e_{ij} and e_{ijk} are independent and normally distributed residual errors with a mean of zero.

We used the standard QQ plot to check if the residuals are normally distributed, and the plot of standardised residuals versus fitted values to evaluate variance homogeneity. The powerTransform function from the R car package was used to identify the suitable transformation type (Fox and Weisberg 2019). If error terms did not follow a normal distribution or were not constant, we performed a log-transformation of the response variable. We applied the Holm-corrected Dunnett test at a 5% significance level (Bender and Lange 2001; Lee and Lee 2020) to determine which agroforestry systems differ from the monocropping shifting cultivation of maize, and the Holm-corrected multiple contrast test (Bender and Lange 2001; Konietschke et al. 2013) to assess the difference among agroforestry systems.

Results

Land equivalent ratio

It took one year before the multistrata agroforestry systems (MS-N and MS-E) were more productive (Fig. 4) than shifting cultivation. In the 2022 season, both MS-N and MS-E performed similarly to monocropping (LER ≈ 1.0), but the productivity of MS-N and MS-E increased by approximately 50% in the following season. By the third season, MS-N reached an LER of 2.3 (130% higher than monocropping; $p < 0.001$), while MS-E reached an LER of 1.83 (83% higher than monocropping; $p < 0.01$) (Fig. 4). In contrast, woodlots only surpassed the productivity of shifting cultivation when firewood and pole harvests were first realised in the 2024 season ($p < 0.05$; Fig. 4). The improved fallows (IF-N and IF-Pp) did not differ significantly from shifting cultivation in any season ($p > 0.05$). Furthermore, no significant differences were detected between treatments within the same agroforestry system type ($p > 0.05$).

Across agroforestry types (Fig. 5), the multistrata system matched improved fallows in the first season ($p > 0.05$) and was significantly more productive in the following two ($p < 0.01$ in 2022; $p < 0.001$ in 2024). Multistrata also outperformed woodlot in 2023($p < 0.001$), while both systems were equally productive in 2024 ($p > 0.05$), mainly due to firewood and pole harvests. From 2020 to 2024, multistrata and improved fallow produced three harvests, compared to two in woodlots and shifting cultivation.

Crop yields

The maize and pigeon pea grain yields in the agroforestry systems MS-N, MS-E, IF-Pp, and IF-N were not significantly different ($p > 0.05$) from the corresponding monocropping. Additionally, the presence of trees in improved fallow plots and the type of woody tree species in multistrata agroforestry and woodlot plots had no significant effect on maize, pigeon pea, and banana crop yields (Table 3). However, there was a substantial reduction in maize and banana crop yields across all production systems in 2024 compared to 2023, due to drought in the 2024 cropping season. The maize yields have halved in multistrata agroforestry, improved fallow and sole maize plots, while they decreased to a third in woodlot plots. Similarly, banana fruit yields declined by half in both multistrata agroforestry treatments. Harvests of firewood and poles were significantly ($p < 0.05$) higher in woodlots than in other agroforestry systems.

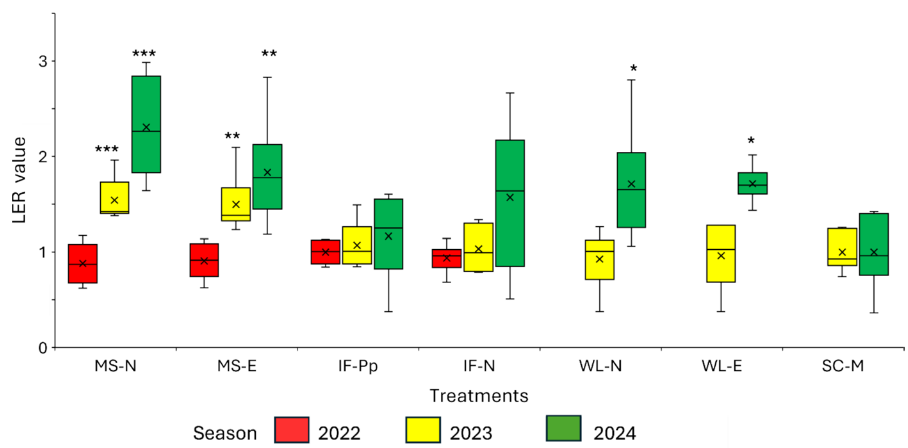

Fig. 4 Land equivalent ratios (LER) of the cropping seasons 2022, 2023 and 2024 in an experiment comparing multistrata agroforestry system (MS-N and MS-E), improved fallow (IF-Pp and IF-N), woodlot (WL-E and WL-N) and shifting cultivation (SC-M) treatments in Manica province, Mozambique. The 'x' represents the mean LER. The symbol '*' indicates a significant difference between the agroforestry systems and shifting cultivation, as determined by a Holm-corrected Dunnett test. Levels of significance are denoted as ('***'$p < 0.001$; '**'$p < 0.01$, and '*'$p < 0.05$). In the 2022 season, LER values were not calculated for SC-M, WL-E, and WL-N because there were no crops or harvests in these treatments

Table 3 Comparison of the impacts of multistrata agroforestry (MS-N, MS-E), improved fallow (IF-Pp, IF-N), woodlots (WL-E, WL-N) and shifting cultivation (SC-M) on yields of maize, pigeon pea, and banana, as well as on the production of firewood and poles in the cropping seasons 2022, 2023 and 2024. There are differences in the respective maize and banana crop yields between 2023 and 2024 due to the lower rainfall during the cropping season of 2024. Values with the same lower-case letters within a column or capital letters within a line are not significantly different ($p > 0.05$) according to the Holm-corrected multiple contrast test, at a 5% significance level. The 95% CI is the 95% confidence interval

Treat-ment	Cropping season 2022		Cropping season 2023				Cropping season 2024							
	Pigeon pea (kg ha^{-1})		Maize (kg ha^{-1})		Banana (kg ha^{-1})		Maize (kg ha^{-1})		Banana (kg ha^{-1})		Firewood (Kg ha^{-1})		Poles (m^{-3} ha^{-1})	
	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95%CI	Mean	95% CI	Mean	95% CI	Mean	95% CI
MS-N	1190^{a}	[981, 1399]	1011^{aB}	[780, 1243]	5658^{aB}	[4973, 6343]	494^{aA}	[341, 715]	2716^{aA}	[2451, 2981]	1272^{ab}	[895, 1809]		
MS-E	1228^{a}	[1018, 1437]	1056^{aB}	[823, 1286]	4806^{aB}	[4121, 5491]	495^{aA}	[342, 716]	2648^{aA}	[2383, 2914]			0.63^{a}	[0.48, 0.84]
IF-Pp	1351^{a}	[1142, 1560]	1121^{aB}	[889, 1352]			455^{aA}	[314, 659]						
IF-N	1268^{a}	[1058, 1477]	1082^{aB}	[850, 1313]			440^{aA}	[304, 637]			797^{a}	[561, 1133]		
SC-M			1046^{aB}	[815, 1277]			431^{aA}	[298, 624]						
WL-E			1007^{aB}	[776, 1239]			300^{aA}	[207, 434]					3.24^{b}	[2.45, 4.29]
WL-N			970^{aB}	[738, 1201]			303^{aA}	[210, 439]			1951^{b}	[1372, 2774]		

Values with the same lower-case letters within a column or capital letters within a line are not significantly different (p 0.05) according to the Holm-corrected multiple contrast test, at a 5% significance level

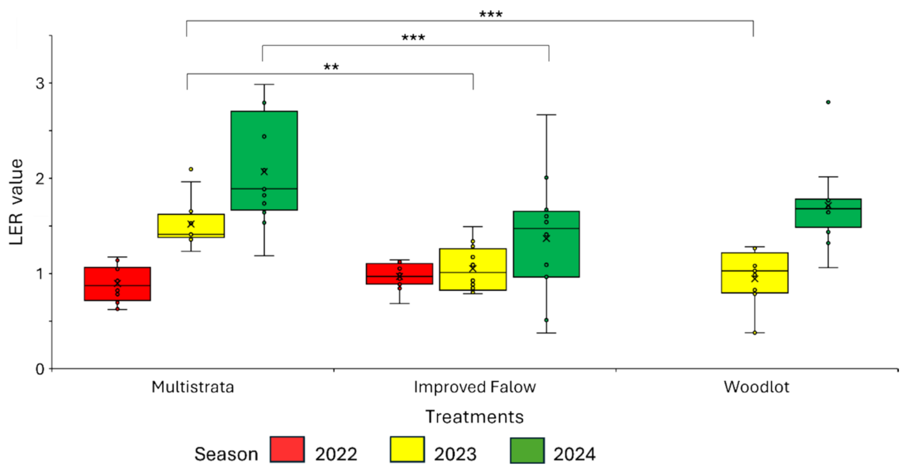

Fig. 5 Land equivalent ratios (LER) for the cropping seasons 2022, 2023 and 2024 in an experiment comparing a multistrata agroforestry system, improved fallow and woodlot treatments in Manica province, Mozambique. The 'x' represents the mean LER. The symbol '*' indicates a significant difference between the treatments, as determined by a Holm-corrected multiple contrast test. Levels of significance are denoted as ('***'$p<0.001$; '**'$p<0.01$, and '*'$p<0.05$). In the 2022 season, LER values were not calculated for the woodlot because there were no crops or harvests in this treatment

Table 4 Comparison of the effects of multistrata agroforestry (MS-N, MS-E), improved fallow (IF-Pp, IF-N), woodlots (WL-E, WL-N), shifting cultivation (SC-M) and natural fallow (NF) on soil nutrient concentration (SOC, total N, available P, pH), and bulk density, at depths of 0-20 cm and 20-40 cm, three years after the establishment of the experiment. There are no differences in soil nutrient concentrations and bulk density values ($p>0.05$) according to the Holm-corrected multiple contrast test at the 5% significance level. The 95%CI is the 95% confidence interval

Depth (cm)	Treatment	SOC (%)		*P* (mg kg^{-1})		N (%)		Bulk-density (Kg m^{-3})	
		Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI
0–20	IF-N	1.10	[0.80, 1.40]	1.20	[0.11, 3.37]	0.08	[0.04, 0.12]	1297	[1239, 1355]
	MS-E	1.08	[0.77, 1.38]	2.89	[0.96, 6.71]	0.09	[0.05, 0.14]	1278	[1220, 1336]
	MS-N	1.08	[0.77, 1.34]	2.56	[0.80, 6.07]	0.09	[0.05, 0.14]	1256	[1198, 1314]
	WL-E	0.91	[0.61, 1.21]	1.67	[0.35, 4.30]	0.06	[0.03, 0.10]	1251	[1193, 1309]
	NF	0.88	[0.57, 1.18]	3.53	[1.28, 7.99]	0.09	[0.05, 0.14]	1253	[1195, 1312]
	WL-N	0.86	[0.55, 1.16]	2.08	[0.55, 5.10]	0.06	[0.03, 0.11]	1208	[1150, 1267]
	C-M	0.84	[0.54, 1.15]	1.87	[0.45, 4.70]	0.07	[0.03, 0.11]	1270	[1212, 1329]
	IF-Pp	0.69	[0.39, 0.99]	2.87	[0.95, 6.67]	0.08	[0.04, 0.12]	1257	[1199, 1315]
20–40	NF	1.08	[0.84, 1.32]	0.45	[0.02, 2.51]	0.12	[0.06, 0.18]	1301	[1258, 1344]
	MS-N	1.02	[0.78, 1.26]	2.04	[0.37, 9.66]	0.03	[0.01, 0.05]	1336	[1293, 1379]
	IF-Pp	0.87	[0.64, 1.12]	1.88	[0.34, 8.88]	0.08	[0.04, 0.12]	1306	[1263, 1349]
	WL-E	0.84	[0.60, 1.08]	0.48	[0.03, 2.55]	0.06	[0.03, 0.10]	1355	[1312, 1397]
	MS-E	0.82	[0.58, 1.06]	1.30	[0.21, 6.26]	0.05	[0.02, 0.08]	1302	[1302, 1387]
	C-M	0.72	[0.47, 0.96]	0.32	[-0.01, 1.91]	0.05	[0.02, 0.08]	1336	[1292, 1379]
	WL-N	0.66	[0.42, 0.90]	0.80	[0.10, 4.04]	0.06	[0.03, 0.09]	1356	[1313, 1398]
	IF-N	0.58	[0.34, 0.82]	0.46	[0.02, 2.46]	0.09	[0.04, 0.13]	1316	[1273, 1359]

Soil nutrient stocks and bulk density

Three years after the experiment was established, in 2023, there were no significant differences in soil measurements taken between the different treatments ($p>0.05$) at depths of 0–20 cm and 20–40 cm

(Table 4). Across treatments at a depth of 0–20 cm, the soil organic concentration ranged from 0.69 to 1.10%, while available phosphorus content ranged from 1.67 to 2.89 mg kg^{-1}, total nitrogen stocks were below 0.1%, and bulk density varied between 1208 and 1297 kg m^{-3}. At a depth of 20–40 cm, soil organic content ranged between 0.58 and 1.08%, available phosphorus concentration varied from 0.32 to 2.04 mg kg^{-1}, total nitrogen content remained below 0.1%, and bulk density ranged from 1301 to 1356 kg m^{-3}. Furthermore, four years of natural fallow (2020–2023) were not effective in improving soil nutrients.

Discussion

We found that the multistrata agroforestry system outperformed improved fallow, woodlot, and shifting cultivation in terms of overall productivity over the first four years after establishment. However, we did not observe significant differences in soil nutrient stocks among the agroforestry systems, nor between these and shifting cultivation. Also, the choice of native wood species or eucalypt in multistrata agroforestry and woodlot plots did not affect maize crop yields or soil nutrient stocks.

Already from the second cropping season onwards, multistrata agroforestry consistently outperformed shifting cultivation, improved fallow, and woodlots. By the third season, MS-N achieved an LER of 2.3, which is 130% higher than monocropping ($p < 0.001$), while MS-E reached an LER of 1.83, corresponding to 83% higher than monocropping ($p < 0.01$) (Fig. 4). The high land-use efficiency of multistrata agroforestry lies in its ability to produce four products across three seasons (pigeon peas, bananas, maize, and firewood or poles), compared to three in improved fallow and two in woodlots. Productivity levels of woodlots and improved fallow remained similar ($p > 0.05$) across two consecutive cropping seasons (Fig. 5). Previous studies found that agroforestry systems outperform monocropping systems when maize was intercropped with pigeon pea (LER > 1) (Renwick et al. 2020), eucalyptus (LER = 1.68) (Ramesh et al. 2023), or with beans cultivated under a combination of 13 different tree species (LER = 1.97) (Pohlmann et al. 2024). Because bananas were not grown as a monoculture in our experiment, we estimated banana monocrop yields using data from nearby local farms, which were then used to calculate LER values. In 2023, the average banana monocrop yield was estimated at 9839 kg ha^{-1}, and in 2024, at 5484 kg ha^{-1}. These numbers have been confirmed by experts from the local governmental agricultural institution (SDAE) and align with FAOSTAT banana yield data for Mozambique from 2019 to 2023, which ranged between 5565 and 7592 kg ha^{-1} (FAO 2025).

Maize, the main staple crop in the region, had low yields (0.5–1.1 tons ha^{-1}) across all treatments (Table 3). This is in line with the average maize production in semi-arid zones of sub-Saharan Africa, which ranges between 0.9 and 1.4 tons ha^{-1}, due to the prevalence of hot-droughts, prolonged dry spells (Marcos-Garcia et al. 2024), soil fertility depletion and inadequate crop management practices (Muoni et al. 2025). The low maize yields in agroforestry plots with trees (MS-N, MS-E, WL-N, WL-E, and IF-N) are likely because maize crops were grown before the biomass from tree pruning and thinning was incorporated into the soil to improve soil fertility. In a maize-Gliricidia intercropping system in Malawi, Akinnifesi et al. (2006) found that adding Gliricidia biomass into the soil increased maize yields compared to unfertilized monocropping over nine consecutive years, because maize crops benefited from N released from Gliricidia biomass. Moreover, growing maize in woodlots and multistrata agroforestry at the early growth stage (up to 3 years) did not reduce maize yields compared to shifting cultivation, probably because the negative trade-offs of tree-crop competition are not yet apparent, as the trees remain young. Furthermore, high mortality rates (33–73%) of eucalyptus trees in the multistrata and woodlot plots may have reduced competition between the remaining trees and maize crops. The absence of improvement in maize yield in improved fallow plots compared to shifting cultivation may be because of a short duration (one year) of pigeon pea fallow. A study in a subhumid zone of West Africa found that maize yields were higher after two years of pigeon pea fallow compared to one year, as the longer fallow added more biomass to the soil (Ochire-Boadu et al. 2020). Additionally, the decrease in maize yields from 1.1 tons ha^{-1} in the first cropping season to less than 0.5 tons ha^{-1} in the second season is apparently due to reduced rainfall during the latter season (Fig. 2). Madamombe et al. (2025) evaluated the impact of seasonal rainfall variation on maize yields in a dry region of Zimbabwe across four cropping seasons. They found that in wet years, maize yields ranged from 3.0 to 5.8 t ha^{-1}, whereas in dry years, yields declined to 0.7–1.2 t ha^{-1}.

Soil properties (SOC, total N, available P, pH and bulk density) did not differ across all treatments, and soil nutrient stocks remained low three years after the experiment was established (Table 4). Low soil nutrient stocks were reported by Serrani et al. (2022) after examining soil profiles in plots under two-year shifting cultivation in Sussundenga, Mozambique, and were attributed to unsustainable farming practices. The limited impact of agroforestry on soil fertility may be due to the tree biomass not yet being incorporated into the soil before sampling. A study from Tanzania found that after five years of tree fallows, soil organic carbon, inorganic nitrogen, and extractable phosphorus were higher compared to continuously farmed land (Kimaro et al. 2007). The same study attributed these improvements to the ability of trees to accumulate litter, fix nitrogen, retrieve nutrients from deep soil layers, and efficiently recycle phosphorus during fallow periods. Furthermore, in our experiment, the pigeon pea fallow period for the improved fallow and multistrata agroforestry treatments lasted only one year, which might not be enough to produce substantial improvements in soil fertility. In a subtropical region of South Africa, Musokwa and Mafongoya (2021) found no differences in soil properties between two-year pigeon pea fallow plots and continuous maize plots. This was attributed to the short duration of the fallow.

Four years (2020–2023) of natural fallow showed no improvement in soil nutrients, indicating that this time frame is insufficient for soil recovery. Serrani et al. (2022) found no differences in nutrient stocks between a 35-year-old miombo forest and two-year shifting cultivation plots in the Sussundenga district. This was attributed to frequent disturbances, such as bush fires, the extraction of firewood, charcoal, and timber within the forestry plots. However, such disturbances were absent in our experimental plots. It is plausible that, in our case, an evaluation period of more than three years would be necessary to fully capture the benefits of agroforestry systems in enhancing soil fertility.

Management interventions such as tree pruning and thinning are critical for maintaining or enhancing the long-term productivity of the MS-N and MS-E systems, as they mitigate tree–crop competition and generate biomass to improve soil fertility. In dry tropics, some studies demonstrated that pruning reduces light competition between trees and crops, thereby increasing maize yields (Dilla et al. 2018), while thinning improves soil carbon accumulation by increasing fine root necromass, annual fine root production, and turnover (Asaye and Zewdie 2012).

Some studies in the dry tropics show that young agroforestry systems can improve soil fertility within 5 years (Kimaro et al. 2007; Sirohi et al. 2022), especially when pruned tree biomass is added to the soil. These improvements tend to increase with the age of the stands (Sirohi et al. 2022; Syano et al. 2023), due to the cumulative effects of organic matter inputs. Although soil fertility changes were not significant after three years of our experiment, short-term improvements may be observed as recurrent tree pruning, and the addition of organic matter to the soil continues. Consequently, long-term monitoring of soil nutrients is essential to understand the cumulative impacts of agroforestry practices in our experiment. Moreover, studies also show that perennial pigeon pea varieties remain in the field longer and generate more biomass than annual ones (Mapfumo et al. 2001; Waldman et al. 2017) resulting in higher organic matter inputs to the soil. Since our experiment showed that the annual pigeon pea variety did not significantly improve soil fertility, future research should consider including perennial pigeon pea varieties to maximise soil fertility benefits. Moreover, replicating similar studies across diverse dryland regions for longer time horizons (more than 5 years) and integrating socio-economic cost–benefit analyses would contribute to informed knowledge-based management and policy decisions.

Conclusion

We demonstrate that, within three cropping seasons, multistrata agroforestry systems substantially increased land productivity relative to shifting cultivation, without reducing maize yields or depleting soil nutrients. However, none of the agroforestry systems improved soil fertility within three years, and a four-year natural fallow was similarly ineffective. These findings indicate that short fallow periods of three to four years are insufficient to restore soil fertility in degraded tropical drylands. Longer-term monitoring is therefore required to detect soil fertility recovery and to provide robust evidence for knowledge-based management and policy decisions.

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Author contributions All authors were responsible for the conceptualisation of the study and evaluation of results.

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Data availability Data will be available upon request.

Declarations

Competing interests The authors declare no competing interests.

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