Shea tree agroforestry systems in Northern Ghana: Population structure, management of trees and impact of canopy microclimate

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Research Article

Keywords: Vitellaria paradoxa, shea tree, Agroforestry, Tree population structures, Northern Ghana, Yams

Posted Date: December 19th, 2023

DOI: https://doi.org/10.21203/rs.3.rs-3446255/v1

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Additional Declarations: No competing interests reported.
Abstract

The shea tree (*Vitellaria paradoxa*) is an important tree species in agroforestry systems and bushlands in West Africa and shea nuts are a fundamental resource for rural livelihoods. In this study, sustainability and interactions in agroforestry systems of shea trees were investigated around the Nakpalli village in Northern Ghana. Focus of the study was structure and density of shea tree populations, below-canopy microclimate and co-cultivation of yams (*Dioscorea rotundata*) under shea tree canopies, and water stress of the trees in the driest season. Shea tree populations are well conserved in this area, but Weibull-distributions of the tree populations and quantification of seedlings showed a lower tree density, especially of seedlings and small trees, in agroforestry fields and fallows, as compared to uncultivated bushlands. This indicates that intensified agroforestry practices might negatively affect the regeneration of shea populations and their long-term regeneration in these agroforestry systems. Co-cultivation of yams in shea canopies allowed production of 11.5 t/ha as compared to 20.8 kg/ha at open field conditions. The lower production may have been caused by an almost 74% reduction of photosynthetically active radiation below canopies, relative to outside the canopies. Shea trees in fields, fallows and bushlands had high predawn leaf water potentials, indicating a low water stress, even in the middle of the dry season. The thriving of shea in the area underlines the importance of conserving this well-adapted indigenous tree in the agroforestry systems and avoiding removal, e.g., by mechanical soil preparation and negative impacts from future climate extremes.

Introduction

The Sheanut tree, *Vitellaria paradoxa* Gaertn. (Family – Sapotaceae, syn. *Butyrospermum paradoxum*), is a semi-domesticated, slow-growing fruit tree, and a major component of the woody vegetation in the semi-arid Sudan and Guinean zones (Lovett and Haq 2000; Masters 2002). Shea trees grow across 16 African countries in sub-Saharan Africa, from Senegal to Ethiopia. In Western sub-Saharan Africa, farmers often keep shea trees as part of their parkland agroforestry systems where crops are cultivated on the same lands as trees (Aleza et al. 2015; Elias 2015; Lovett and Haq 2000; Raebild et al. 2012). The agroforestry consists of sequential farm-fallow systems where cropping is followed by a fallow period to allow regeneration by leaving the soils uncultivated. In addition to this farming approach, shea trees in these regions also grow in uncultivated bushlands (Cronkleton et al. 2021; Lovett and Haq 2000; Poudyal 2011). Bushlands are characterized by mixed, self-established remnant vegetation with minimal human disturbance.

Shea trees have a prominent role for the subsistence of rural households and, in particular, for the female population, that is main responsible for collection of kernels of the tree and processing them into shea butter (Chalfin 2004; Schreckenberg 2004; Gausset 2005; Poulion 2012; Boffa 2015; Hammond 2019). A study on anthropic selection of shea trees in Northern Ghana shows that farmers describe shea trees as “wild”, since they rarely plant them, meaning that most trees stem from natural regeneration (Lovett and Haq 2000). However, it is widely agreed upon that shea trees, due to human selection, are semi-domesticated species (Hale et al. 2021; Martial et al. 2020; Yao et al. 2020). According to local farmers in
Northern Ghana, they select which shea trees are wanted on their lands based on yields, health, size, growth, age, competition with crops and spacing allowing for mechanical soil preparation (Baziari et al. 2019; Lovett and Haq 2000).

A recent meta-analysis of agroforestry as a solution for maintaining ecosystem services in Sub-Saharan Africa showed that agroforestry systems generally deliver higher yields and improve soil fertility by providing higher contents of soil nitrogen, organic carbon and available phosphorus, as compared to non-agroforestry systems (Kuyah et al. 2019). The analysis also indicated that agroforestry practices improve the soil structure by increasing the soil infiltration rates and moisture content, causing a reduction in run-off and erosion. Furthermore, studies show that agroforestry practices improve livelihood resilience in Sub-Saharan Africa by diversification of farming activities and livelihood strategies (Kuyah et al. 2020; Quandt et al. 2019).

However, agroforestry practices are also known to cause certain trade-offs and losses. Younger trees with abundant roots in the top 30 cm soil compete with crops for nutrients and water, and certain plant species produce below-ground allelopathic compounds that are toxic to other plants and inhibit their growth (review by Atangana et al. 2014). Above ground, modification of the microclimate by trees plays a role, and competition for light may lower growth and yields of understory crops. Shaded and humid below-canopy microclimates promote the growth and thriving of certain plant pathogenic fungi and bacteria (ibid). Despite these risks, the creation of more stable microclimates in agroforestry systems can protect crops from climate- and soil-moisture extremes. Therefore, agroforestry systems may provide economically feasible solutions as strategies for farmers to adapt to climate extremes (Lin 2007). A recent study of agroforestry as a remedy for climate change adaptation showed that local farmers in Northern Ghana are aware of the positive impacts that agroforestry practices may have (Apuri et al. 2018). The farmers perceived that agroforestry contributed to improved soil nutrient content, reduction in wind and water erosion of soils, soil moisture retention, and increased the availability of foodstuff for the households.

Most studies on shea trees have focused on production of butter from the nuts and the related impact on local economy. Less attention has been paid to the interactions between crops and trees in the agroforestry systems, including the sustainability of shea tree populations on different land-use types in village communities. In this study, we analysed structure, density and water status of shea tree populations in fields, fallows and bushlands during the dry season in the village of Nakpalli in Northern Ghana. Further, effects of the trees on the below-canopy microclimate and options for cultivation of crops beneath the trees were examined. We hypothesise that canopies of shea trees create a microclimate that allow a successful co-cultivation of important produce, such as yams. Additionally, we hypothesize that land-use affect for population structures and densities of shea trees.

**Material and methods**

Study area and community
The study was conducted in Nakpalli (8°58’52.1"N, 0°19’13.4”E) in the North-Eastern part of Ghana (Fig. 1a,b) and included two months of fieldwork from January 20 to March 2, 2022. Data collection took place in the dry season and no rainfall occurred during the stay.

Nakpalli is a medium-sized village situated in the Northern Region of Ghana, around 180 km South-West from Tamale and less than 30 km from the border to Togo. The village has a population of over 4000 people, living in around 318 households. The population is mainly constituted by the Dagomba ethnic group, with a minority of Fulani, a few Kokomba and Ewe. The main activities in the village include farming, small businesses, petty trading and shea nuts collection. Crop cultivation is carried out by farmers who manage and decide over particular land plots, following a customary land tenure system. The chief is vested with the authority to allocate land for cultivation to people who ask for it (Amanor 2009).

Characteristics of the Land and Climate

Nakpalli is located in the ecoregion of Sudanian Savanna (Liu et al. 2017). Farming seasons are defined by a mono-modal rainfall system. Only one rainy season occurs between July and September, which constitutes the major farming season. A minor farming season occurs in the following drier months. The average annual rainfall is 1,000 mm (Ministry of Food and Agriculture in Ghana 2016). Analysis of soil types at the sampling sites was not possible. According to the ISRIC World Soil Information (ISRIC 2023), soils in this region are ferric luvisols, which typically are characterized by an argic horizon overlaid by loamy sand.

The vegetation is characterized by trees and bush with a herbaceous layer of forbs and annual and perennial grasses (Sawadogo et al. 2010). Agriculture is predominated by rainfed smallholder farming, and most farm holdings do not exceed 2 hectares in size (ibid.). Most farmers in Nakpalli managed agroforestry parkland systems by practicing a seasonal crop rotation with sequential cultivation and fallow periods. Farmers kept their land fallow for an average duration of 2.8 years and cultivated the lands for 3 years on average (Stoppini and Jepsen 2022). Almost every household had one or more farmland plots situated around the village, where they mainly cultivated yam (Dioscorea rotundata (Poir.) J. Miége), maize (Zea mays L.), sorghum (Sorghum bicolor (L.) Moench), cassava (Manihot esculenta Crantz) and millet (Pennisetum glaucum (L.) R. Br). The parklands were dominated by tree species of anthropogenic interest, such as shea, locust bean (Parkia biglobosa (Jacq.) R.Br. ex G. Don), mango (Mangifera indica L.), neem (Azadirachta indica A. Juss) and teak (Tectona grandis L.f.) trees.

Size distributions and densities of shea trees in fields, fallows and bushlands

Shea tree circumferences and numbers of minor-sized shea trees and seedlings were registered in fields, fallows and bushlands. These three land types are shown in Fig. 2.

The registration of trees was done to obtain knowledge on shea tree population structures and to evaluate the size-distributions, densities and regeneration of tree populations in the sequential
agroforestry system (fields and fallows) and in lands that were minimally used for human activities (bushlands) for comparison. A total of 10 plots of fields, 10 plots of fallow lands and 10 plots of bushlands, each containing 20 shea trees as a minimum, were selected. Plot sizes were measured using the perimeter function on a Garmin eTrex(R) 10 Global Positioning System (GPS) (www.garmin.com).

In the defined plots, circumferences of the trunks at breast height (130 cm) of all shea trees > 130 cm height were measured using measuring tape and registered. Circumferences at breast height were converted into the widely used unit, diameter at breast height (dbh). Five subplots of 5 × 5 m were placed in corners and centres of the main plots. All shea trees < 130 cm in height, including seedlings and coppices within the sub-plots, were counted and used for estimating the total number for the whole plot by extrapolation. A graphic overview of the sampling setup is presented in Fig. S1.

The average durations of land-use in the registered lands were 3.2 ± 0.57 (n = 10) years of fallow and 3.1 ± 0.57 (n = 10) years of cultivation. The spatial distribution of locations of measurements of densities and size-distributions of shea tree populations according to land-use type are shown in Fig. 1b.

To describe and compare the shea tree size distributions in fields, fallows and bushlands, the continuous datasets of shea tree diameters at breast height in the three land-use types respectively were fitted to a Weibull distribution and shape and scale parameters were extracted. Weibull functions are described as follows:

\[ f(d) = \frac{\lambda}{\alpha} \left(\frac{d}{\alpha}\right)^{\lambda-1} e^{-\left(\frac{d}{\alpha}\right)^{\lambda}} \]

Where \( f(d) \) is the probability density, \( d \) is the tree diameter at breast height, \( \lambda \) is the shape parameter determining the shape of the distribution, and \( \alpha \) is the scale parameter determining the width and the height of the distribution.

To detect whether the shape and scale parameters provided by the functions for the Weibull distribution curves were different for the three land-use types, a one-way ANOVA with the land-use type as the single factor was applied. Dependent data were the scale and shape parameters respectively for each individual land plot (Appendix A). To detect the effects that land-use may have on shea tree densities of larger shea trees > 130 cm in height and of minor shea trees and seedlings < 130 cm in height respectively a one-way ANOVA test was applied with the land-use type as the single factor and the shea tree (> or < 130 cm) density (expressed in trees/ha) for each individual land plot as the dependent factor (Appendix B).

Below-canopy microclimate

Between January 30 and February 3, 2022, three different climate variables were measured underneath and outside shea tree canopies in the fields to evaluate the microclimate under shea trees. Soil surface temperatures and air temperatures were measured using a Laserliner CondenseSpot Plus (082.046A)
This device is a combined thermometer for measuring ambient temperatures and an IR thermometer that detects infrared radiation (heat) emitted from surfaces. Emissivity level of the IR thermometer was set to 0.94 as suitable for soil surface temperature measurement (Manual, Laserliner CondenseSpot Plus). A LI-COR Quantum sensor (LI-250A Light Meter) (www.licor.com) was used for measuring the penetration of Photosynthetic Active Radiation (PAR) through the shea tree canopies. In accordance with Agena (2014) the data collection took place at midday, in this case at 12.05–12.25 pm, when the sun was at its highest point.

To ensure that measurements of the climate variables occurred as close to midday as possible, the data collection took place on five different, but consecutive days. Days of clear sky were chosen for the data collection, ensuring that cloud cover would not interfere with the measurements.

The climate variables were measured under the shea trees in the following zones: next to the trunk and at 1/3, 2/3 and 3/3 of the canopy radius. Five shea trees with similar characteristics were chosen for the microclimate data collection (Table 1). This was done in four different angles, resulting in 16 points of measurement per tree and 80 measurements in total per parameter (Fig. S2). For control, PAR and soil surface temperatures were measured in full sunlight outside the canopy, and air temperatures were measured in shaded conditions outside the canopy. Control measurements were done in the same field as the tree, at four points as far away from any trees as possible.

| Characteristics of the trees used for measuring below canopy microclimate. |
|-----------------------------|------------------|
|                              | Average          |
| Diameter breast height (cm)  | 20.0 ± 5.7 (n = 5) |
| Tree height (m)              | 6.1 ± 1.2 (n = 5) |
| Lower canopy height (m)      | 1.9 ± 0.4 (n = 5) |
| Canopy width (m)             | 2.6 ± 0.6 (n = 20) |

Weather data were registered at midday for the five days of data collection using a portable climate station (GMR Strumenti, Italy). The average values of PAR, air temperature and air humidity are shown in Table 2.
Table 2

Mean PAR, air temperature and air humidity at midday on the days for microclimate data collection (January 1 to February 3, 2021). The values are recorded using a climate station.

<table>
<thead>
<tr>
<th>Time for measurement</th>
<th>Mean Photosynthetically Active Radiation (µmol/s)</th>
<th>Mean Air Temperature (°C)</th>
<th>Mean Air Humidity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12:21:01</td>
<td>1691.2 ± 103.7 (n = 5)</td>
<td>36.2 ± 0.8 (n = 5)</td>
<td>9.2 ± 0.6 (n = 5)</td>
</tr>
</tbody>
</table>

One-way ANOVA tests with random effects were applied to detect the effects that shea trees may have on soil temperature, air temperature and photosynthetically active radiation at different distances to the trunk, as compared to outside shea tree canopies (Appendix C).

Yields of yams cultivated underneath and outside shea tree canopies

Yam is an essential subsistence and cash crop in the village, which is widely cultivated in the agroforestry systems. Yams were planted in approximately 50 cm tall manually prepared mounds 1.5 meters apart as can be seen on Fig. 2a. To evaluate whether yields of yams were affected by shea trees, weights of yams cultivated in mounds underneath and outside shea tree canopies were determined. Yams were weighed in two different farms from 25 mounds located outside shea tree canopies and from 25 mounds underneath 9 different shea trees using a SALTER Hanging Scale Model 235 6S. The mounds were located in the following zones under shea trees: at 1/3 canopy radius (n = 8), 2/3 canopy radius (n = 8), 3/3 canopy radius (n = 9) and on open land (n = 25).

Each yam mound contained between 1 and 3 yam tubers. All yam tubers from each mound were harvested and weighed separately and locations, and site, tree, mound and the zone from where the yams were harvested were registered. In order to obtain information on yam yields per hectare, the number of mounds per hectare was estimated by extrapolating the number of yam mounds per 5 × 5 m² plots (n = 5). To detect possible effects of shea trees on yam yields at different distances to the trunk (expressed in zones) compared to yam yields outside shea tree canopies, a linear mixed model i.e., a one-way ANOVA test with random effects was applied to the data (Appendix D).

Pre-dawn water potentials of shea tree leaves in fields, fallows and bushlands

To evaluate the water status of shea trees during the dry season and determine whether this differs between shea trees located in fields, fallows or bushlands, the predawn leaf water potentials (ψₚ) were measured in all three land-use types. Only mature trees were assessed. ψₚ was measured from 2 leaves from the lower canopies of 10 shea trees per land-use type, resulting in 20 measurements pr. land-use type and 60 measurements in total. Measurements were made using a Pump-up Pressure Chamber (PMS Instrument Co., OR) before dawn (6.15 AM), i.e., between 4.28 am at earliest and 5.42 am at latest. Three consecutive days (February 24 to 26, 2022) without any major changes in weather were chosen for the data collection.
The precautions for data collection stated by Turner (1988) were considered. Thus, right before harvesting a leaf, it was sealed loosely by a zip-lock aluminium bag to avoid evaporative water loss. The leaf stem was cut with a razor blade, ensuring that the length of the petiole external to the sealing was as short as possible. The leaf was placed in the pressure chamber within 30 seconds. The pressure chamber was filled slowly, to avoid heating and to capture the exact endpoints.

Locations for measurements of $\psi_p$ are shown in Fig. S3. The fallow land was located 166 metres above sea level (MASL), the field was located at 147 MASL and the bushland was located at 176 MASL. To detect the effects that land-use may have on shea tree predawn leaf water potentials, a linear mixed model namely a one-way ANOVA with random effects was applied (Appendix E).

Statistical analyses

The statistical analyses were performed using the software RStudio (version 4.2.0). Figures were generated using the R package ggplot2 (https://www.R-project.org/). Weibull curves for distribution of tree size classes was estimated in the R-software using the package fitdistrplus. Weibull curves were fitted to size distribution histograms (trees/ha) by overlay in Microsoft Excel version 16.59.

Results

Densities of larger shea trees in fields, fallows and bushlands

The densities of larger shea trees (> 130 cm height) varied between bushland, fallows and fields. In the natural and non-cultivated bushland, the mean density of shea trees > 130 cm in height was significantly higher than in fields ($p = 0.0007$) and fallows ($p = 0.007$) (Fig. 3a). The mean shea tree densities in fields and fallows were not significantly different from each other ($p = 0.38$). The median density of larger shea trees was lowest in the fields, marginally higher in fallows, and clearly highest in the bushlands. An overview of the average values of the shea tree densities in the different land-use types along with the corresponding 95% confidence intervals is given in Supplementary Data (Appendix A).

Densities of minor shea trees and seedlings in fields, fallows and bushlands

The number of shea tree seedlings and saplings (< 130 cm in height) varied significantly between bushland, fallows and fields (Fig. 3b). Higher mean densities of seedlings and small shea trees were found in bushlands as compared to fields ($p = 0.005$) and fallows ($p = 0.0006$). No statistically significant difference was found between densities in fields and fallows ($p = 0.42$). The median density of seedlings and minor shea trees was four times higher in bushlands that are not used for agricultural purposes oppositely to the other land-use types. An overview of the average values of the shea tree densities in the different land-use types along with the corresponding 95% confidence intervals is given in Supplementary Data (Appendix B).

Shea tree size distribution according to land-use type
Farmers manage the lands of fields and fallows by mechanical soil preparations. In addition to this, the farmers protect shea trees from fires, cutting and other damages. These practices are not undertaken in the unmanaged bushlands.

The circumferences at breast height of trunks of a total of 682 shea trees were registered on 18.74 ha to determine distribution and tree densities in the three land-use types (Table S1). Histograms of the shea trees showed that the tree populations in the bushlands were characterised by a markedly higher density of trees in the lower diameter class (saplings with diameter less than 10 cm) while the abundance of trees in higher size classes showed a rather steep decline (Fig. 4c). In fields and fallows, the trees were more evenly distributed over the different size classes, and the highest prevalence of individuals occurred in the size classes 10-<20 cm and 20-<30 cm (Figs. 4a and b). These differences in the size class distributions were reflected in the scale parameters of the Weibull curves causing the “stretch” of the curves. The mean scale parameter for bushlands was significantly lower than the mean scale parameters for fallows (p = 0.01) and fields (p = 0.001). The similarities in the size distributions of fields and fallows were underlined by the fact that the mean scale parameters in these land-use types did not differ significantly from each other (p = 0.47).

Water retaining potential of shea trees

The predawn water potential showed that whether the trees grow in fields, fallows or bushlands, similar water potentials in the leaves were found (p = 0.085) (Table 3). The mean values of $\psi_p$ for shea trees in both fields, fallows and bushlands were ranging from $-1.03$ to $-0.88$, indicating that the leaves were not experiencing severe drought stress in any of the three land-use types.

<table>
<thead>
<tr>
<th>Field</th>
<th>Fallow</th>
<th>Bushland</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average predawn leaf water potential, $\psi_p$ (bar)</td>
<td>$-0.88$ (95% CI $[-1.68, -2.12]$)</td>
<td>$-0.92$ (95% CI $[-1.71, -2.16]$)</td>
</tr>
<tr>
<td>n = 20</td>
<td>n = 20</td>
<td>n = 20</td>
</tr>
</tbody>
</table>

Effects of shea tree canopies on microclimate

Canopies of the shea trees had a significant effect on soil temperatures beneath the canopies, relative to the soil temperature outside the canopies. The mean soil surface temperature outside shea tree canopies was high; 57.5°C as compared to mean temperatures of 33.0°C next to the trunks to 39.6°C at the periphery of the canopy (Fig. 5a). Thus, the soil surface temperatures were reduced by 31.2–42.5% underneath shea tree canopies, as compared to on open fields. The temperature difference at different distances to the trunk and the open land was significant (p = 0.0006). The random effect of trees
accounted for 51.5% of the total variance, whilst significant effects of site could not be found. The residual variance, corresponding to the within-group variance, accounted for 48.5% of the total variance.

The canopies also affected the air temperature beneath the trees. Below the canopies, the median air temperature was stable at 37°C-38°C but was 41°C outside the canopies (Fig. 5b). This corresponds to 9–10% reduction in air temperatures underneath shea tree canopies, as compared to outside on open land. Those differences were borderline significant (p = 0.06).

Effects of shea trees on PAR beneath canopies

Canopies caused a significant, gradual reduction in photosynthetically active radiation (PAR) in the different canopy zones, relative to outside the canopies. Below the canopies, the mean PAR was 421 µmol/sec, while 1,611 µmol/sec were measured outside the canopies (p = 1.69 ×10^{-5}), corresponding to a 73.9% PAR reduction relative to outside canopies (Fig. 6). The random effect of trees accounted for 34.5% of the total variance, whilst the random effect of site did not exist in this case either. The residual variance therefore accounted for most of the total variance.

Co-cultivation of yam and shea trees

Across all 3 zones below the canopies, the average yield was 2.3 kg per mound (corresponding to 11.5 t/ha), which is 44.7% lower than the yam production of 4.13 kg per mound (or 20.82 t/ha) outside the canopies. There was non-significant tendency of reduced median values of yam yields closer to the tree trunk (Fig. 7). The random effects of tree and site were found to be negligible, and the residual variance accounted for 90.33% of the total variance.

Results of the average yam yields per mound, and per hectare for the different zones determined with the linear mixed model are given in Supplementary Data (Appendix B).

Discussion

Influence of agroforestry practices on shea tree densities

This study on agroforestry systems with shea trees in the savannah region of northern Ghana demonstrated that the abundance of trees is affected by human practices and management of the land. In natural, non-cultivated bushland there was a higher density of both large and small shea trees, as well as seedlings, as compared to fields and fallows.

Since shea trees rarely are planted, the trees typically depend on natural regeneration. The options for regeneration are challenged in several Western Sub-Saharan African countries where farming activities often lead to mechanical removal of shea tree seedlings (Djossa et al. 2008; Kelly et al. 2004; Lovett & Haq 2000). Some studies show that intermissions from human disturbances, by keeping agroforestry systems fallow, support the regeneration of shea trees (Aleza et al. 2015; Elias 2013) and that higher densities of shea tree seedlings are found in fallows than in fields (Aleza et al. 2015; Raebild et al. 2012).
However, this study showed that densities of seedlings were not higher in fallows than in fields. In accordance with Djossa et al. (2008), the low densities of seedlings in fields and fallows may be explained by shortened fallow periods that decrease the supporting effects of these periods of low human-disturbance on shea tree regeneration in agroforestry systems. In the beginning of a subsequent cultivation period, seedlings will still be too small to be distinguished from weeds and they are therefore removed unintentionally by mechanical soil preparation.

A tendency of shortened fallow periods is also seen elsewhere in Western Sub-Saharan Africa due to population expansion and a higher pressure for land (Djossa et al. 2008; Lovett et al. 2018). Population expansion was also confirmed in the Nakpalli area, causing an elevated demand for farmlands and conversion of bushlands into farmlands.

Conservation and regeneration of shea tree populations

Shea tree populations of fields, fallows and bushlands were dominated by trees with lower diameters as indicated by the positive asymmetry ($1 < \lambda < 3.6$) of the Weibull curves for the size-distributions in all land-use types. Positive asymmetry is characteristic for populations with good rejuvenation and stable densities (Condit et al., 1998). Even though all land-use types demonstrated population structures with positive asymmetrical distributions, the asymmetry was more prominent for bushlands, since these lands were richer in saplings compared to the managed parklands. Given that shea trees can live up to 200–300 years, Djossa et al. (2008) suggested that reductions in shea tree sapling densities in parklands do not cause an immediate reduction of the adult population. Yet, if the practice of removing seedlings and saplings continues, there is a risk, that adult trees will die out without replacement in a few decades.

The interpretation of static information on tree size distributions is, however, not a straightforward indicator of population changes. For instance, in a population of fast-growing species with low mortality, few juveniles are not necessarily an indicator of decrease in population (Condit et al. 1998). In addition, our study does not provide any information on historical shea tree population structures to support whether there is a causal relationship between introduction of new agricultural practices and changes in shea tree population structures. Continuous historical data would have disclosed how this change in management had changed the shea tree size distributions in fields and fallows.

Threats to shea tree populations from fires and cuttings

Fire poses another potential risk to survival of shea trees around Nakpalli, either caused by lightning or by deliberate burning of farmland for preparation of land before a cultivation period. The latter was intended to be controlled but according to farmers these sometimes turned into wildfires. Around Nakpalli, there were visible indications that fire had occurred in all land types, but the landowners stated that they protect shea trees in fields and fallows against fires mainly by weeding around them (Jepsen and Stopponi 2022). However, this protection did not result in higher densities of shea trees in any size-classes in fields and fallows relative to bushlands. After surviving to the 3–5 years after germination, shea trees become highly fire-resistant (Hatskevich et al. 2011). Densities of shea tree seedlings were high in bushlands.
regardless of wildfires, suggesting that high recruitment of seedlings may have counteracted a loss of rejuvenation in these lands.

Another threat to shea trees is cutting for production of charcoal, firewood and other purposes as is locally practised in Ghana, affecting both density and size of the trees (Asare et al. 2022; Cronkleton et al. 2021; Dapilah et al. 2019). However, cutting of shea trees is uncommon and considered unacceptable in the Nakpalli area, as also reported by Hansen et al. (2012).

Climate adaption of shea trees in Nakpalli: Water balance

Values of predawn water potentials ($\psi_p$) have been used as a proxy for soil water content and have been shown to correlate with plant assimilation rates, stomatal conductance and leaf gas exchange (Williams and Araujo 2002). Low water stress is indicated by higher values of $\psi_p$ and vice versa (Ratzmann et al. 2019). The $\psi_p$ of shea tree leaves from fields, fallows and bushlands showed a similar water potential irrespective of tree location, with $\psi_p$ values varying from -1.03 to -0.88 bar. The $\psi_p$ values close to zero observed in this study indicate that the leaves were not under severe drought stress in any of the three land-use types during the studied period. The capacity of shea trees to regulate their water status was confirmed in a study of shea trees in an agroforestry parkland in Burkina Faso (north of Ghana). Here, it was found that the trees efficiently controlled the sap flow and could down-regulate the canopy transpiration (Bazié et al. 2018). Thus, a shea tree at dbh of 36 only transpired an average of 151 l water per day (ibid.). Keeping a high leaf water potential is not only important for physiology and biomass growth, it also affects the development of organs (fruits) among other biological processes in plants (Ratzmann et al. 2019) and hereby their value to the villagers.

Importance of microclimates in tree canopies

Shea trees in the Nakpalli area created a microclimate below the canopies, causing a reduced soil and air temperature, and lower PAR. Changed microclimates under shea trees have previously been assessed in Burkina Faso (Bayala et al. 2002), but this is the first study of below-canopy-microclimates of shea trees in Ghana to our knowledge. The changed physical conditions in the canopies affect the yield of understorey crops due to competition for nutrients, water and light (Bayala et al. 2002; Lott et al. 2009). Further, allelopathy and promotion of microbial plant pathogen growth may impact yields of crops negatively below canopies (Atangana et al. 2014).

Yields of a range of different crops are reduced underneath canopies of shea trees in agroforestry systems (Baziari et al. 2019; Gnanglè et al. 2013; Seghieri 2019). In Nakpalli, the observed co-cultivation of yam beneath the shea canopies yielded on average 11.5 t/ha and 20.8 t/ha outside canopies. Although the yield of yam was not measured on field-scale in Nakpalli, the yields found in this study resemble those found in other districts in Ghana, averaging 18 t/ha (Danquah et al. 2022). Even if crop yields may be affected negatively right below shea tree canopies, the effect may not occur on field-scale. For example, a study showed that shea tree densities of 12 and 36 trees/ha, which are similar to or slightly lower than the densities found in this study, caused higher sorghum yields on field scale than on
areas without shea trees (Boffa et al. 2000). Other studies found that the income from shea nuts may outweigh the downsides of keeping shea trees in the farmlands (Baziari et al. 2019; Gnanglè et al. 2013; Seghieri 2019). Co-cultivation of crops and trees also provides the benefit of diversification of subsistence and income sources, an approach that is deeply rooted in the local historical and cultural contexts (Kuyah et al. 2020; Quandt et al. 2019). Furthermore, stabilised microclimates in agroforestry systems may contribute as strategies for farmers to adapt to climate extremes (Lin 2007).

Threats to shea tree agroforestry from climate changes

The density and size distribution of shea trees in the Nakpalli region appear representative to similar areas, e.g., when compared to populations in fields, fallows and bushland in a semi-arid savanna in central-west Burkina Faso (Elias 2013), and a similar density of shea trees was recently registered in a comparable parkland area in the northern Ghana where about 30 trees at > 1 cm dbh were recorded per hectare (Lawer 2023). However, although comparison of shea tree distribution among different areas is complicated due to regional variations in soil types, precipitation and land-uses, there are signs that populations of shea trees may become reduced in the future.

Environmental threats and stressors to shea trees in northern Ghana, caused by climate changes, include drought during extended dry periods, but also occasional rainstorms that may expose the tree roots (Derbile et al. 2018). Shea trees appear less vulnerable to intense precipitation and associated flash floods (ibid). Susceptibility of shea trees to future environmental stressors seems related to age and size of the trees. The root system of shea tree includes both tap and lateral roots, which improve the ability to tolerate drought periods (More and Allars 2008). Adult trees are deep-rooted and have the capacity to store water and nutrients, making older trees less sensitive to drought periods, relative to younger trees (ibid).

Shea tree agroforestry and soil parameters

Shea trees have optimum growth in sandy, iron-rich soils with content of humus, but can also grow in heavier soils (Choungo Nguekeng et al. 2021 and references therein). The trees prefer neutral pH but do tolerate moderately acidic soils. Good water drainage is required, meaning that a high water table is not tolerated. Due to the extensive root system and tap roots in adult trees, shea trees can survive extended dry seasons (More and Allars 2008).

Our study indicated an acceptable water-holding capacity of the soils at all locations, possibly due to the content of humus, since the predawn water potentials showed that none of the trees appeared to be under water stress, even though the data collection took place in the middle of the dry season. Speculatively, this tolerance to the dry season might be caused by cultivation of selected drought-resistant tree species. During the rainy season, a high-water table might pose a periodic threat to shea trees in soils with a low-permeable subsurface horizon, but this remains to be studied.

Conclusion
Collection of shea nuts is an important supplementary household income to villagers in Nakpalli. In spite of this, the farmers do not plant the trees but rely on natural regeneration. The farming practices of short fallow periods and mechanical soil preparation may have a negative impact on the long-term regeneration and sustainability of the shea tree populations. Creation of microclimates below shea canopies allows cultivation of crops under the trees, but the yields may be reduced due to a lower PAR, as indicated for yams in this study and as observed for other crops in similar studies. Therefore, a proper balancing of the densities of trees in these systems to permit co-cultivation is needed. Trees have many benefits in cropping systems, such as improving soil structure, infiltration rates and moisture contents, and reducing run-off and erosion. Furthermore, soil fertility is improved as compared to non-agroforestry systems. The buffered microclimates in agroforestry systems may help protect crops from climate- and soil-moisture extremes and may provide economically feasible solutions as strategies for farmers to adapt to climate extremes.

The shea trees appeared not to be affected by water stress, as indicated by the high values of predawn leaf water potentials of trees on all land-uses, even in even the middle of the dry season. The thriving of shea trees underlines the benefit and importance of conserving this well-adapted indigenous tree species in agroforestry systems in Western Africa. An increasing population pressure in this area is likely to reduce the length of fallow periods, threatening the shea tree populations. However, as suggested, if care is taken to protect shea tree seedlings from removal during mechanical soil preparation, this will increase the sustainability of shea tree populations in agroforestry systems in Northern Ghana.

**Declarations**

**Acknowledgements**

The authors are deeply grateful to the people of Nakpalli, who dedicated a large amount of their time and energy to this research. This study would not have been possible without your willingness, friendliness and support. Particularly, we would like to thank the chief of Nakpalli, who allowed us to conduct this research in the village, as well as the sub chief, the assemblyman, Issah, Simple and Mma Mina for their valuable help and assistance. Also, we express our gratitude to Lantana and Zakari for their hospitality in their house We would like to sincerely thank our supervisors Dr. Mariève Pouliot, Dr. Anders Ræbild and Dr. Nerea Turreira Garcia for their guidance and exceptional support throughout the whole research process. We would also like to express gratitude to our fieldwork assistance and interpreter, Rashida, for her inestimable help, supporting us from day one of the data collection process and giving us precious advice and information.

**Author contributions**

TJ, GS designing experimental plan; TJ, GS collecting data and analysis of data; TJ designing figures; TJ, GS and NOGJ drafting and writing manuscript.

**Funding**
The study received financial support from the University of Copenhagen, William Demant Fonden and Agronomfonden.

Data availability

Data will be made available on request.

Declarations

Conflict of interest

The authors declare no competing interests of any kind.

Supplementary Information. Appendix.

Supplementary data to this article can be found online at....

References


49. Seghieri J (2019) Shea tree (Vitellaria paradoxa f.): from local constraints to multi-scale improvement of economic, agronomic and environmental performance in an endemic Sudanian


**Figures**

![Map of Ghana. The village of Nakpalli in North-Western Ghana is marked with a red pinpoint (a). Satellite image of Nakpalli and the surrounding areas and locations for measurements of shea tree size](image-url)

**Figure 1**
distributions and densities are marked (b).

Figure 2

A field with yam mounds and shea trees (a), shea trees in a three-year-old fallow (b) large shea trees in far bushlands (c).
Figure 3

Boxplots showing the densities of larger shea trees (a) and minor trees (b) according to land-use. The significance of difference between the mean density in bushlands compared to fields and fallows respectively is marked (**=p<0.01, ***=p<0.001). Trees in a total of 30 fields, fallows, and bushland were registered.
Figure 4

Histograms of shea tree populations in fields (a), fallows (b) and bushlands (c) and the fitted Weibull curves. \( \lambda \) = parameter for shape distribution, \( \alpha \)=scale parameter (determines the width and the height of the distribution).
Figure 5

Boxplots of soil surface (a) and air temperatures (b) in the different zones relative to the shea tree canopy (CR = canopy radius) and outside shea tree canopies. In the soil, significant differences between mean soil surface temperatures in zones underneath canopies and temperatures outside shea trees are shown (*=p<0.05, **=p<0.01). In for air temperatures, the difference between mean air temperatures in different zones underneath canopies and temperatures outside shea trees was not significant (ns=not significant).
Figure 6

Boxplots for visualizing the PAR in the different zones related to the shea tree canopy (CR=Canopy radius) and outside shea tree canopies. The significance of difference between mean PAR in different zones underneath canopies and PAR outside shea trees are shown (*=p<0.05, **=p<0.01, ns=not significant).
Figure 7

Boxplots of yam yield in the different zones in the shea tree canopies (CR = canopy radius) and outside shea tree canopies. The difference between yam yields of mounds in the different zones was not significant (ns=not significant).

Supplementary Files

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- SupplementaryInformation.docx