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Towards transdisciplinary identification of suitable woody perennials for resilient agro-silvopastoral systems in the Sudano-Sahelian zone of West Africa

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Abstract Parkland systems in the Sudano-Sahelian zone of West Africa are commonly perceived as a resilient agroforestry practice well adapted to the semi-arid climatic conditions of the region. However, there exist several knowledge gaps regarding the interplay between the different components of this agro-silvopastoral land use system. A literature review with subsequent meta-analysis was conducted to analyze the effects of woody perennials on soil, crops and livestock, for which our study found very context-specific responses. A scoring of tree and shrub species indicated a general trend of trade-off between positive impact on crops and livestock *vs.* impact on soil organic carbon content. The study further confirmed that *Faidherbia albida* (Del.) Chev. is one of the most promising parkland species, but also revealed that there are no multipurpose single species

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that should be promoted exclusively. The focus should rather shift to species mixtures that satisfy multiple human and environmental needs. The study also pointed out that information on the nutritional properties of the majority of browse species is particularly limited. Transdisciplinary modelling is suggested as a tool to assess the complex interactions between the different components that shape this agro-silvopastoral system at different scales.

Keywords Crops · Interaction · Livestock · Meta-analysis · Parkland · Integrated modelling

Introduction

There has been an increased global interest in agroforestry as one of the best food production systems to build socio-ecological resilience and alleviate the impact of climate change (Dinesh et al. 2017; Leroux et al. 2022). Agroforestry in the Sudano-Sahelian region is perhaps one of the most emblematic systems in that context, where locals use their endogenous knowledge to manage the complex interactions among the vast number of shrub, tree, crop and livestock species (Boffa 1999; Sinare and Gordon 2015). In the literature, these agroforestry systems are often called parklands, which refer to a system that is characterized by randomly scattered woody perennials (Bayala et al. 2011; Boffa 1999; Pullan 1974). Agroforestry systems in the Sudano-Sahel region prioritize croplands over trees, unlike traditional agroforestry practices where trees are the focus providing various provisioning and regulating ecosystem services. The implications of understanding and optimizing the ecological and socio-economic functioning of parklands are enormous for local and global populations (Kuyah et al. 2019; Mbow et al. 2014). Establishing climate-resilient production systems in the region and beyond involves effectively managing parklands, which requires diversifying annual plants-based croplands with trees and livestock (Bayala et al. 2014; Brown et al. 2018; Nelson and Burchfield 2021). However, such innovations in production systems and knowledge transfer can only happen when the complex interactions among the various components of parklands and their stakeholders are decoded (Do et al. 2020; Thorn et al. 2016).

Soil degradation caused by overgrazing, unsustainable use of feed resources due to increasing pressure on biomass resources and continuous crop cultivation is a common problem in the Sudano-Sahel region (Rahimi et al. 2021; Takimoto et al. 2008). Agroforestry practices have been increasingly promoted to increase the sustainability and resilience of land use systems due to the positive effects of woody perennials on soil properties and crop yields (Félix et al. 2018), and their importance for household food security and livestock feeding especially in the lean dry season (Ibrahim et al. 2020). The benefits of shrubs and trees to soil fertility, crop productivity, livestock and human uses are widely recognized and discussed in the literature. Several reviews and institutional reports (Bayala et al. 2014; Boffa 1999) have sought to measure and explain the effects of parkland systems on crop productivity (Bayala et al. 2012; Félix et al. 2018), soil quality (Félix et al. 2018), human utilization and other ecosystem services. These include soil and crop responses, as well as the provision of fodder to livestock production and health (Bayala et al. 2014; Sinare and Gordon 2015). Methodological issues (Bayala et al. 2015) and significant knowledge gaps on several processes (Sinare and Gordon 2015) to be investigated were also discussed in these publications, namely scale and productivity of parkland systems, impact of browse species on livestock performances and nutrient digestibility, crop yield response to inclusion of shrubs/trees and their management, landscape analysis of various densities and shrub/tree species composition on soil, crop, livestock and ecosystem regulation, modelling at different scales (e.g., tree-crop, field and landscape), potential quantitative biomass production of various shrubs and trees and their qualitative (i.e., mineralization rates, nutritional value) analysis, socio-cultural determinants of increasing tree cover and factors determining the survival of seedlings, beneficiaries of ecosystem services in terms of gender, age, ethnicity and occupation, trade-offs regarding labour and shrub/tree biomass availability, impact on climate change mitigation and system resilience, impact of multispecies mixtures of tree/shrub species on system productivity and performance as well as adoption and scaling pathways.

The aim of this paper is to provide an updated and more comprehensive literature review with subsequent meta-analysis on the effects and uses of shrubs

and trees on soil, crop and livestock productivity in Sudano-Sahelian parklands, with a main focus on West Africa. Despite the limited evidence base, current knowledge indicates that the key sustainable practice to produce biomass (organic matter for soil, feed for animals) in this region is through the inclusion of shrubs and trees (Félix et al. 2018) and better integration and management of livestock (Bayala et al. 2011; de Haan et al. 2016). "Feeding" soils with biomass from shrubs and trees is often the primary objective, but the importance of shrubs and trees on livestock health, nutrition and subsequently manure recycling cannot be overstated. Earlier reviews did not include a systematic evaluation of the effects of feeding shrub and tree foliage on livestock performances and nutrient digestibility. The same also applies to landscape analysis, modelling opportunities and adoption constraints, which were stated as the key knowledge gaps. As such, the current review attempts to broaden the evidence base by including these topics alongside soil quality and crop productivity responses. The following sections analyze the impact of shrubs and trees on soil quality, crop productivity, livestock nutrition and health. We identified under-utilized/appreciated species with potential, and derived recommendations and suggested future research for the sustainable integration of crops, shrubs and livestock in land use systems of the West African Sudano-Sahelian zone. Finally, we propose a transdisciplinary modelling framework to interact with key stakeholders building on local established innovation platforms.

Materials and methods

Geographical coverage

There is no uniformly used geographic definition of the Sudano-Sahelian zone. It is mostly referred to as the semi-arid zone located between the Saharan desert and the humid Guinean zone, stretching from the Atlantic coast to the Red Sea coast. The present study mainly concentrates on the Sudano-Sahelian zone of West Africa (WAS) extending from the Northern Sahel zone with annual precipitation of 150–350 mm, the Southern Sahel zone (350–600 mm), the Northern Sudan zone (600–900 mm) and the Southern Sudan zone (900–1200 mm) adapted from (Kessler and Breman 1991) (Fig. 1). The WAS encompasses major parts of Mauritania, Senegal, Mali, and Niger, and the northern part of Burkina Faso and Nigeria. The review primarily examines Burkina Faso, Mali, and Senegal, but also incorporates research from other Sahelian countries in West and East Africa.

The Sudano-Sahelian climate is semi-arid with a long dry season and a short rainy season with heavy and variable rainfall events. The vegetation in the WAS region is largely influenced by climate, as well as low soil fertility and anthropogenic factors. It is composed of grasslands with shrubs and scattered trees (Nicholson 2018). Depending on the mean annual rainfall, the range of agroforestry species, the extension of crop cultivation and livestock production, and the type of agroforestry systems varies. In areas with > 1000 mm annual rainfall, the agro-silvo-cultural system is more common, where trees are integrated with cultivation of annual crops. Trees are more frequently integrated with crop cultivation and livestock production in areas with 400–1000 mm annual rainfall (agro-silvo-pastoral) or only with livestock in areas with < 400 mm annual rainfall (silvo-pastoral) (Weber and Hoskins 1983). The most common agroforestry tree species in agro-silvo-pastoral systems of this region are *Faidherbia albida* (Del.) Chev., *Vitellaria paradoxa* Gaertn. F., *Parkia biglobosa* (Jacq.) R. Br. ex G. Don, *Adansonia digitata* L. and *Tamarindus indica* L., whereas *Acacia senegal* (L.) Willd., *Acacia tortilis* subsp. *raddiana* (Savi) Brenan, *Balanites aegyptiaca* (L.) Del., *Piliostigma reticulatum* (DC.) Hochst. and *Borassus aethiopum* Mart. are popular in silvo-pastoral systems in the 'true' Sahel climatic zone (Pullan 1974 in Boffa 1999 and Weber and Hoskins 1983).

Literature review

Independent literature searches were conducted in relevant databases (electronic catalogues and databases, search engines, scientific journals) on the sections "soil fertility", "crop productivity" and "livestock nutrition and health". Search terms that were used can be found in Online Resource 1. The literature search considered publications that were published between 1995 and 2020 (1990–2020 for the section on crop productivity) and was conducted in both English and French. Papers considered eligible to be included in

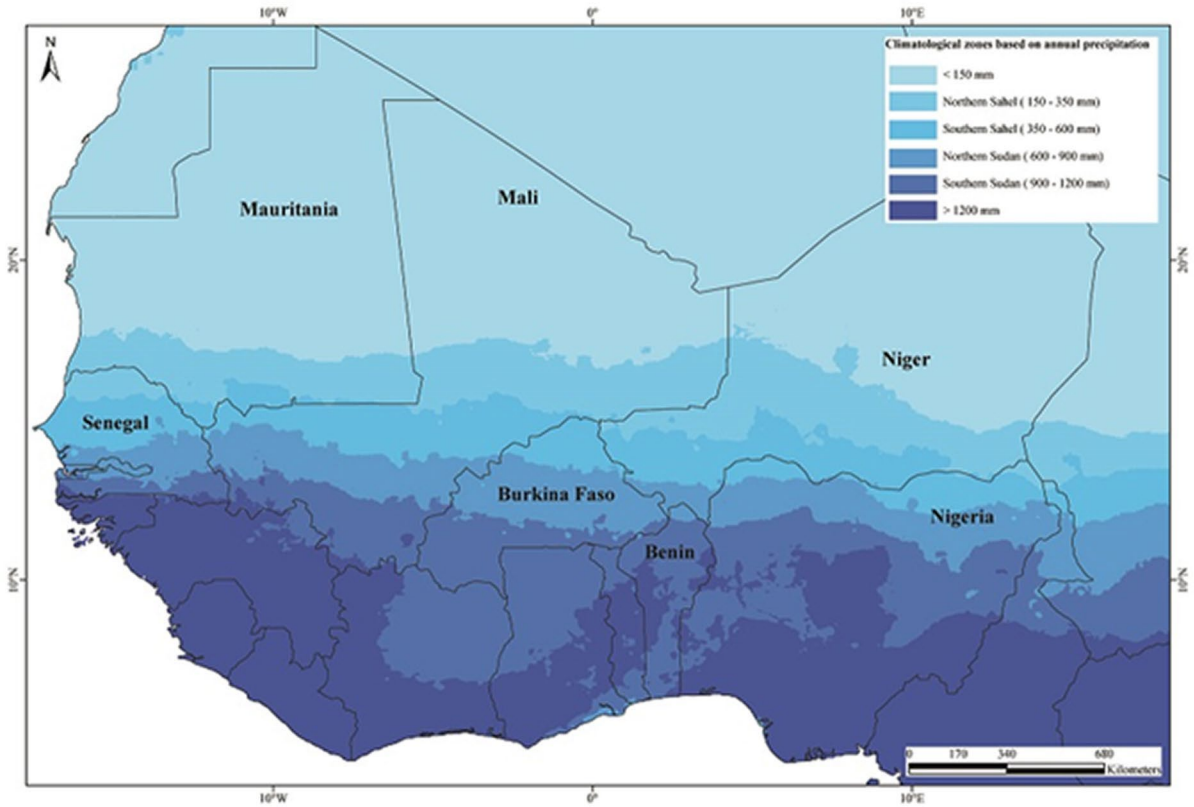


Fig. 1 Map of West Africa showing climatological zones

the study were peer-reviewed journal articles, as well as grey literature in English and French on research activities from research stations, farmer fields and the laboratory. Studies of interest were those conducted in the Sahelian and Sudanian zones.

For the section "soil fertility", only studies that contained quantitative assessments of soil parameters, as well as suitable comparisons of tree/shrub influenced situations *vs.* control situations, for which effect sizes can be calculated, were considered for further analyses, resulting in 92 studies that were published between 1965 and 2021. Further, in the figures below to illustrate species-specific effects on soil parameters, we retained species for which at least 3 different studies were performed. For the section "crop productivity", only studies fulfilling minimal experimental standards were included, having at least three independent replicates (50 studies in total). Studies without control yield were excluded from the database. If data was only represented graphically, the online tool WebPlotDigitizer (WebPlotDigitizer—Copyright 2010–2021 Ankit Rohatgi (automeris.io)) was used for data extraction. We employed the same criteria detailed in the review by Félix et al. (2018) to select suitable publications for further analysis. A total of 22 different species of woody perennials were tested, out of which 16 were tree species (with k = 252 pairwise comparisons), four shrub species (k = 101 pairwise comparisons), and two palm species (k = 2 pairwise comparisons). Among the species, 17 were from the Leguminosae family. *P. reticulatum* (n = 11), *F. albida* (n = 11), *P. biglobosa* (n = 9) and *V. paradoxa* (n = 8) were the species most often studied.

The section "livestock nutrition and health" included studies that analyzed the effect of trees/shrubs on livestock performances and feed intake, as well as the chemical composition, anti-nutritional factors, digestibility and degradability of trees/shrub foliage. Additionally, studies were considered that evaluated farmers' preferences of certain species for livestock feeding and/or animal health care; inventories determining the distribution and composition of

trees/shrubs; reviews on agroforestry systems and the use of trees/shrubs for livestock feeding and/or animal health care. This resulted in a total of 141 studies for the livestock nutrition section. For species and family names that were not specified or differed between publications, Arbonnier (2002) was used as a reference. Online Resource 2 summarizes the information that were extracted from the publications for all sections.

Statistical analysis

For the section on soil fertility, mean and SD values for all measured parameters were extracted if available in a publication, separating control and tree/shrub-based treatments. A random effect model for each treatment was fitted in R version 4.2.2 (R core team 2022) with the rma() function within the *metafor* package (Viechtbauer 2010) to estimate means and 95% confidence intervals of effect sizes. We used log ratio of means (ROM option) as effect size in our meta-analysis. In this publication, we particularly focused on identifying species-specific effects. For this purpose, we selected species for which at least three independent data were recorded.

For the section on crop productivity, many studies did not provide standard deviations and/or p-values, therefore it was not possible to calculate effect sizes along with SD or confidence estimation. For this reason, descriptive statistics were applied in R. To display the effects of the treatment on the crop yields, the relative yield change of the treatment yield in comparison to the yield of the control was calculated by Eq. (1)

$$RelativeYieldChange = \frac{Treatmentcropyield - Controlcropyield}{Controlcropyield} \times 100 \quad (1)$$

The dataset was further grouped based on the annual precipitation gradients according to Kessler and Breman (1991):

Northern Sahel zone: annual precipitation 150–350 mm.

Southern Sahel zone: annual precipitation 350–600 mm.

Northern Sudan zone: annual precipitation 600–900 mm.

Southern Sudan zone: annual precipitation 900–1200 mm.

For the section on livestock nutrition and health, descriptive statistics (mean, standard deviation, median, minimum and maximum) were computed. A random effect model for each treatment was fitted with the rma() function within the *metafor* package (Viechtbauer 2010) of R software to estimate effect size, 95% confidence intervals and statistical significance of effect sizes. We used Hedge's g as the effect size of our meta-analysis, which is based on the raw mean difference between the mean of the treatment groups fed foliage-containing diet and the mean of the group fed the control diet. Cochran's Q-values were calculated to identify the presence of heterogeneity of effect sizes among studies. Because of the significant Q-values and the low number of studies ($n < 10$ studies) that reported the response variables of interest, we did not perform any publication bias analysis or meta-regression analysis. R software package was used to create the graphs.

Scoring of species

Finally, a scoring of browse species for their beneficial effect on crops, soil and livestock was performed. For the effect on crops, the scoring was based on the average relative yield change (%) related to the control. In total $n = 19$ species were included. For the effect on soil the scoring has been conducted based on the average log ratio of soil organic carbon content ($n = 12$ species). For livestock nutrition the species ($n = 15$) were scored based on their average standardized mean difference of voluntary DM intake related to the control. The species with the highest effect on crops, soil and livestock got the highest score (= 10), and the scores for the remaining species were calculated in relation to the average effect and score of the species.

Results

Soil fertility

Soil organic carbon (SOC) enrichment under the canopy of trees and shrubs was generally positive compared to the control treatment where no trees

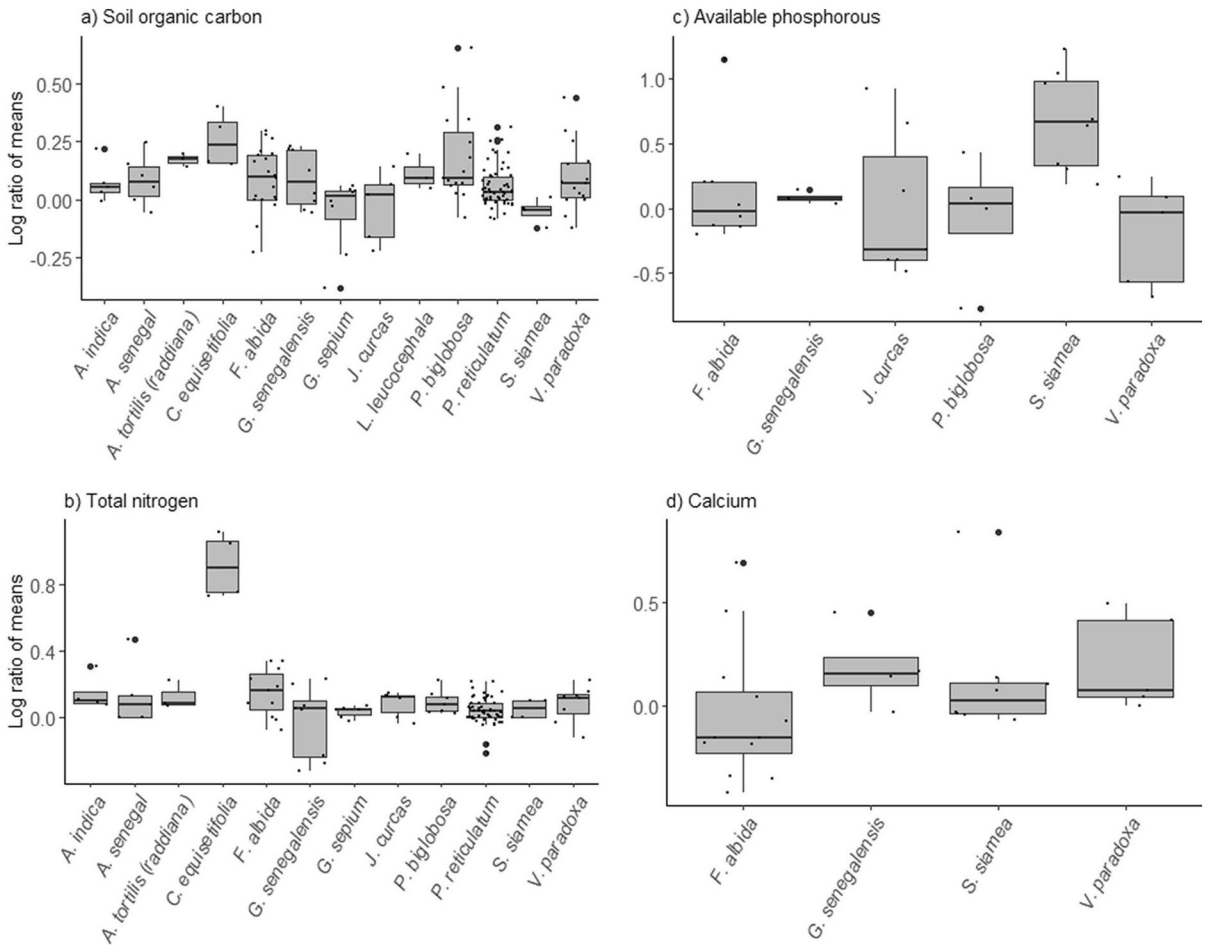


Fig. 2 Effect of tree and shrub presence on relative (to control) log mean **a** carbon, **b** nitrogen, **c** phosphorous and **d** calcium contents in soil. For N and P, only tree species for which more than three records were found are shown. For Ca all studies are shown (data less abundant). Individual effect sizes are shown as points, with distributions summarized by boxplots

or shrubs were present, with average effect size (ES) of 0.074, corresponding to 7.5% enhancement, and maximal effect of around 90% enhancement (Fig. 2a). However, there was a large variability in SOC responses, including non-significant ones and a few negative effects. In line with SOC improvements, also soil nitrogen (N) content was increased by the presence of trees and shrubs (Fig. 2b). The effect of the presence of shrubs on P availability has been documented in some studies, but the results are less consistent than those concerning SOC content, showing high variability with an average null effect except for *Senna siamea* (Lam.) Irwin & Barneby (Fig. 2c). Available cation contents, which were reported in a few studies, increased on average but in a species- and site dependent manner as well (Fig. 2d – example calcium).

Widely acknowledged is also the impact of trees and shrubs on soil pH, which increased in the vast majority of cases as expected in relation to the above observed SOC content increase (Fig. 3a). Trees and shrubs had also a beneficial impact on soil structural parameters in most studies. An integrative parameter depicting this trend is bulk density, which aggregates in situ soil structuration. Bulk density consistently decreased in the presence of trees and shrubs in a wide range of systems and regions, which depicts an improvement in soil structure (Fig. 3b).

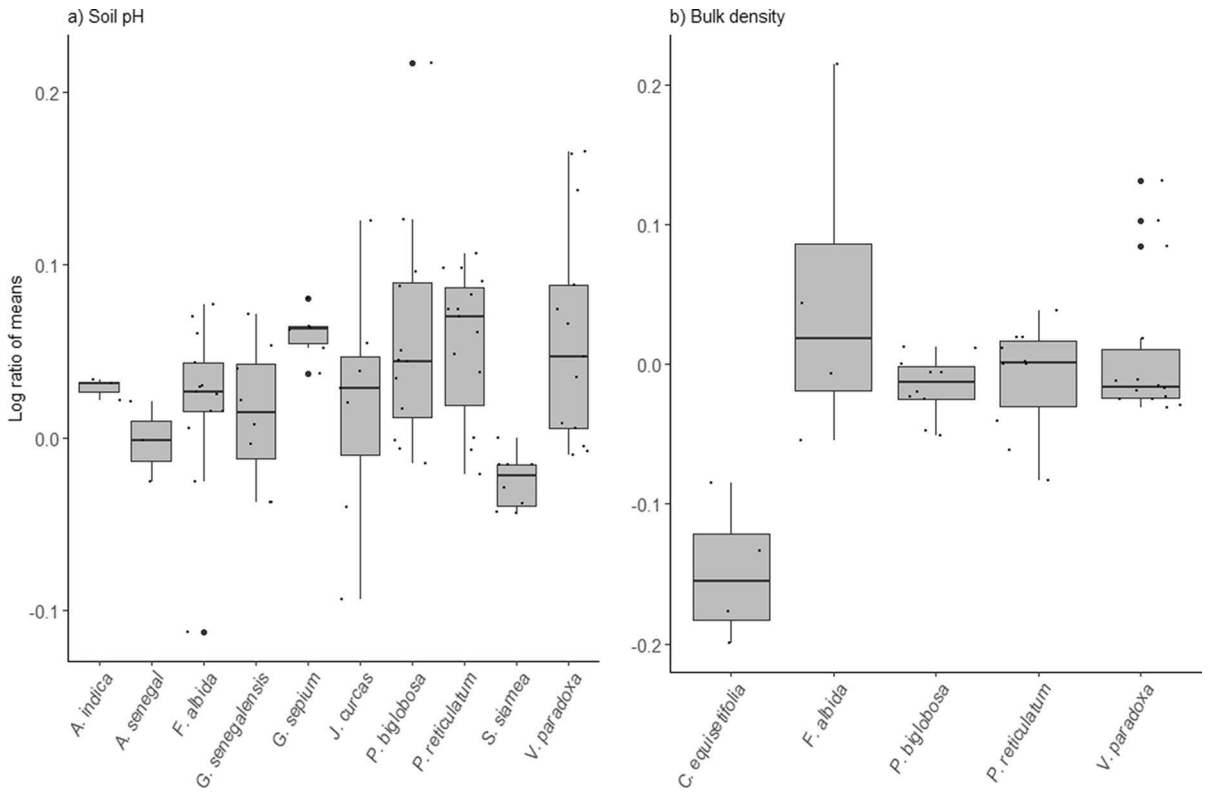


Fig. 3 Effect of tree and shrub presence on relative to control (expressed as log ratio of means) for **a** soil pH and **b** bulk density. Individual effect sizes are shown as points, with distributions summarized by boxplots

Data on soil biological parameters was scarce, which might be due to analytical difficulties or access to equipment.

Crop productivity

Overall, crop yields increased in association with trees, but there was a high variation within and between the studies. In particular, millet, peanut and sorghum productivity were evaluated across different climatic zones representing areas receiving 150 to 1200 mm of precipitation per annum (Fig. 4). In all climatic zones, except the high precipitation zone (Southern Sudan), millet and sorghum yields were greater when associated with trees or shrubs (Fig. 4). Maize and taro yields also increased when grown in association with shrubs or trees in Sudan zones.

F. albida had the greatest positive impact on millet yields, as almost all studies indicated greater yield of millet under *F. albida* than without (Fig. 5). Similarly, *P. reticulatum* had a positive influence on millet yield, particularly when mulching with tree prunings was used, but the relative yield change was slightly less than that of *F. albida*. Millet yields usually decreased when grown under or mulched with *P. biglobosa*. When grown beside *G. senegalensis* or under *V. paradoxa*, millet yields responded on average with a negligible increase, although a large variability was observed, suggesting site-/management-specific effects. When averaged across the studied ligneous species, maize and taro showed the greatest relative yield increase compared to other crops (Fig. 6). Millet and sorghum yields appeared to be greater under mulching than parkland management (i.e., grown under or around trees). Interestingly, peanut yields did not respond significantly to trees or shrubs (Fig. 6).

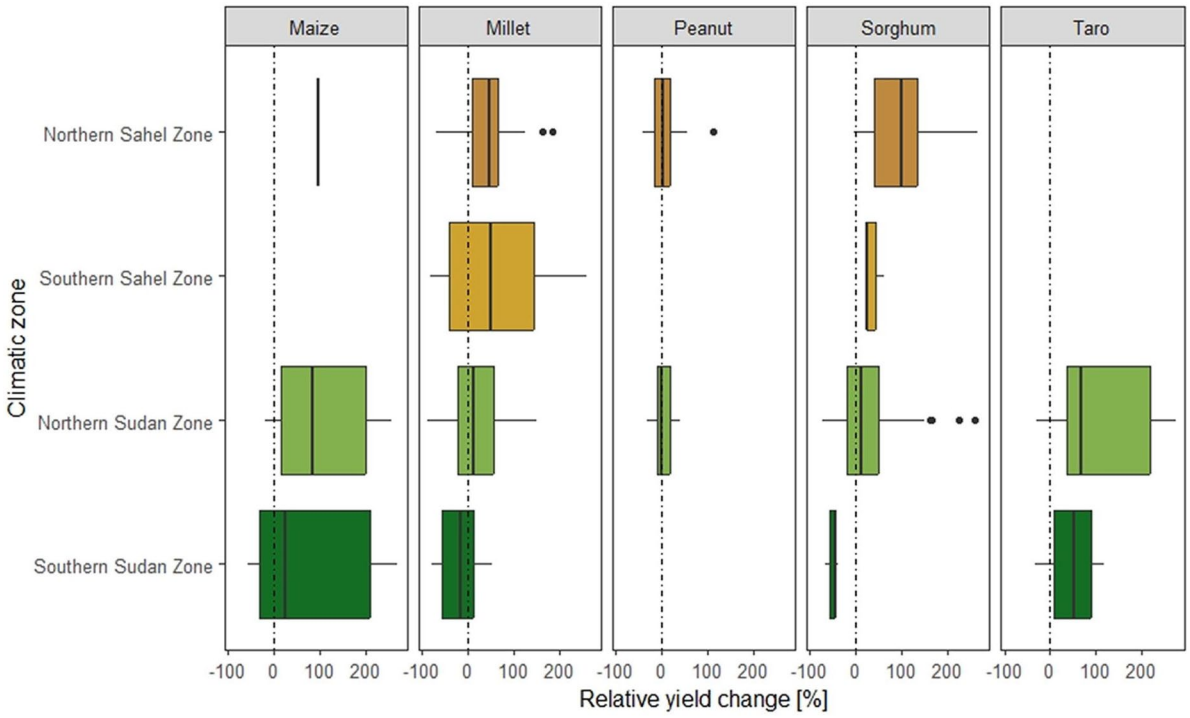


Fig. 4 Relative yield change of maize (n = 5), millet (n = 23), peanut (n = 6), sorghum (n = 22), and taro (n = 2) in different agro-climatic zones when grown in association with trees and shrubs

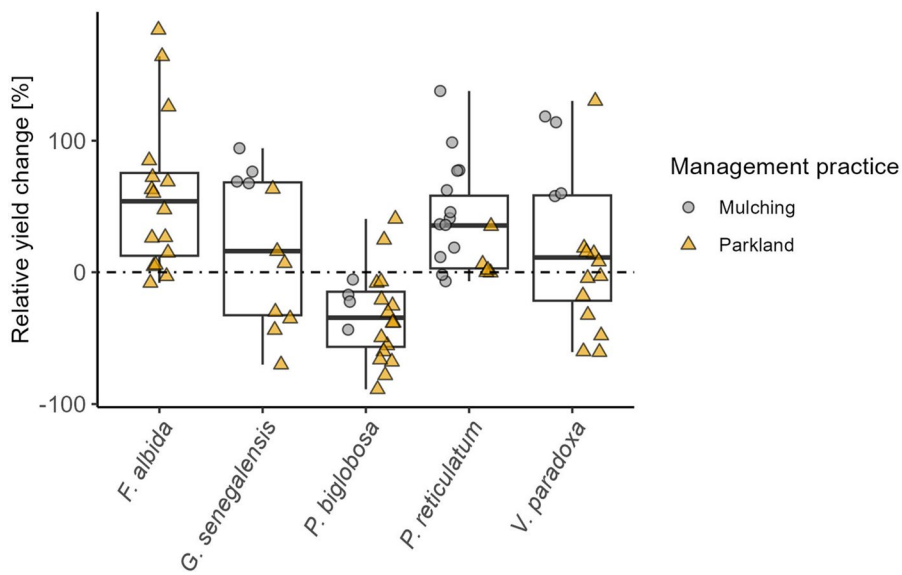


Fig. 5 Relative yield change of millet grown in association with different tree species, considering two different management practices. For each combination, the relative yield change of millet is additionally shown according to two management practices: mulching (grey dots) and parkland (yellow triangles). Only combinations with $n \geq 2$ studies and $k \geq 10$ comparisons are displayed

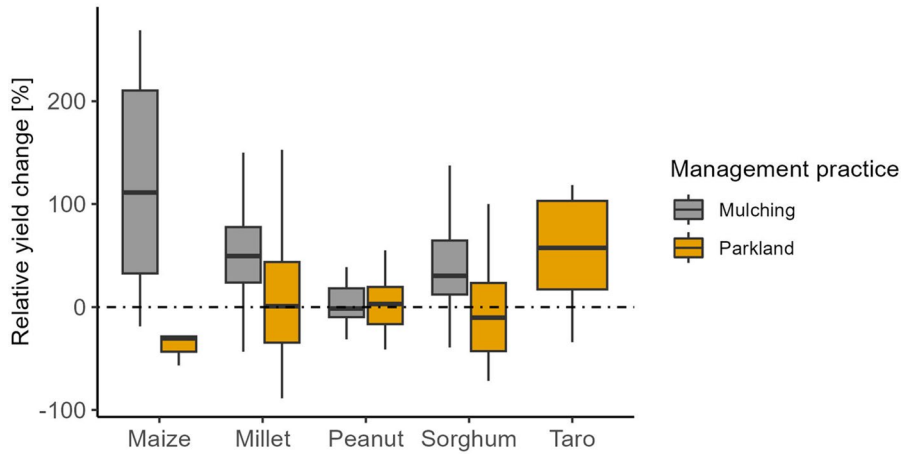


Fig. 6 Relative yield change of main staple crops grown in association with tree species, considering the two different management practices mulching and parkland. Only combinations with $n \geq 2$ studies and $k \geq 10$ comparisons are displayed

Livestock nutrition and health

Nutrient contents and secondary plant compounds

In total, 15 browse species had a favorable nutritional profile, i.e. high CP and low neutral-detergent fiber (NDF) and acid-detergent fiber (ADF) values (Table 1). *P. reticulatum*, *P. biglobosa* and *Vitex doniana* SWEET had the least favorable nutritional profile (low CP and medium NDF/ADF values); none of the studied browse species had low CP and high NDF and ADF values.

Total extractable phenolics (TEP), total tannin (TT) and condensed tannin (CT) contents for 58 shrub foliage types were extracted from 15 studies. True averages of TEP, TT and CT were within the interval of 67.6 and 134.8 g/kg DM, 41.7 and 106.3 g/kg DM and 11.7 and 26.1 g/kg DM, all in equivalent standard (probability 95%), respectively, assuming that the original random variable is normally distributed, and the samples are independent (Fig. 7).

The lowest TEP (0.1 g/kg DM) and TT values (0.06 g/kg DM) were reported for *Afzelia africana* Smith ex Pers., only one value each (Soulama et al. 2014; Zampaligré et al. 2013). In total, leaves of 15 browse species had a low CT content of < 1.0 g/kg DM, namely *Acacia gourmaensis* A. Chev., *A. senegal, A. sieberana* DC., *A. seyal* Del., *A. africana, Anogeissus leiocarpus* (DC.) Guill. & Perr., *Combretum micranthum* G. Don, *F. albida, Khaya senegalensis* (Desr.) A. Juss., *Margaritaria discoidea* (Baill.) Webster, *Mitragyna inermis* (Willd.) Kuntze, *Prosopis juliflora* (Sw.) DC., *Pterocarpus erinaceus* Poir., *Vachellia oerfota* (Forssk.) Kyal. & Boatwr., *Zanthoxylum zanthoxyloides* (Lam.) Watermann. *A. africana*, *A. leiocarpus* (Zampaligré et al. 2013) and *M. discoidea* (Aschfalk et al. 2000) contained no CT (0 g/kg DM), while lowest average CT content was calculated for *P. erinaceus* (0.14 g/kg DM) (Soulama et al. 2014; Zampaligré et al. 2013). Highest mean

Table 1 Tree/shrub foliage with favorable[a] and unfavorable[b] nutritional profile

Favorable	Unfavorable
*A. angustissima**	*P. reticulatum*
A. mellifera	*P. biglobosa*
A. senegal	*V. doniana*
A. indica	
C. procera	
C. fragrans	
C. micranthum	
*G. sepium***	
*L. leucocephala****	
M. crassifolia	
*M. olifeira*****	
P. juliflora	
S. brevispica	
V. oerfota	
Z. spina-cristi	

[a]High crude protein (CP; > 180 g/kg DM) and low neutral detergent fiber (NDF; < 400 g/kg DM)

and acid detergent fiber (ADF; < 300 g/kg DM); [b]Low CP < 80 g/kg DM; medium NDF 400–700 g/kg DM

and medium ADF 300–450 g/kg DM); ambiguous results: * Low-Medium NDF and ADF; Medium–High CP;

** Medium–High CP and Low-Medium NDF and ADF; *** Low-Medium NDF and Low–High ADF;

**** Low–High NDF and Low-Medium ADF

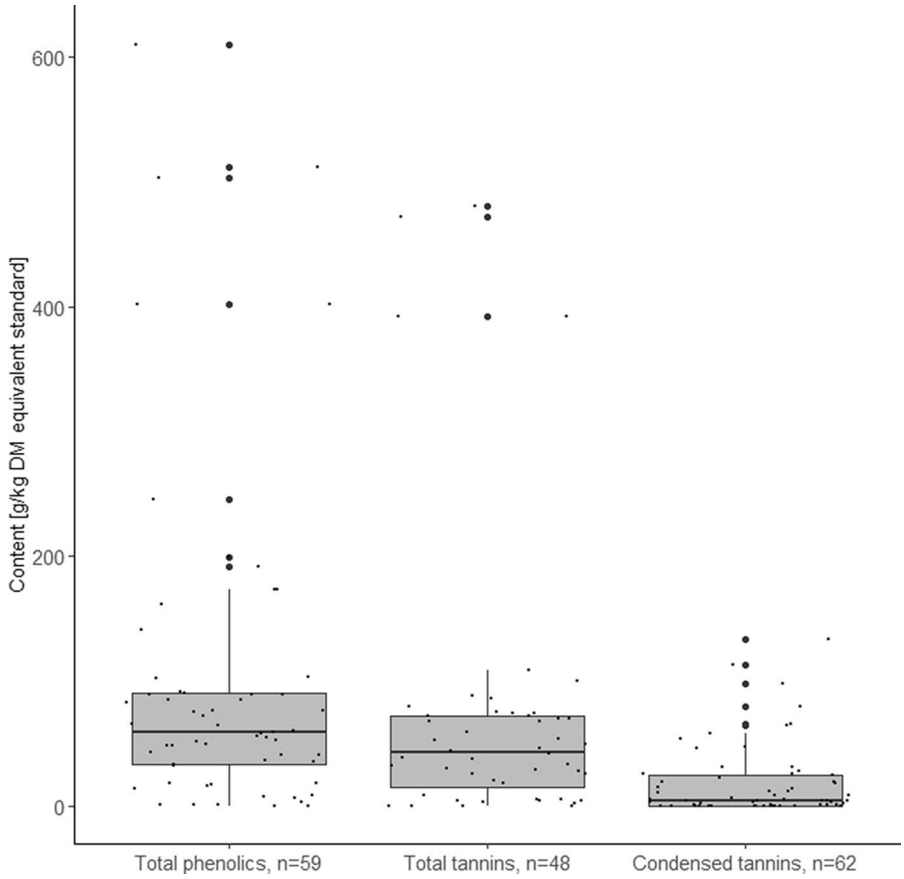


Fig. 7 Average content (with 95% confidence intervals) of total extractable phenolics and tannin fractions in tree/shrub foliage. n represents number of observations

TEP and TT were calculated for *A. seyal* (512 g/kg DM and 480 g/kg DM, respectively) (Abdulrazak et al. 2000), while the highest mean CT values were obtained for *A. digitata* leaves (113 g/kg DM) (Fall Touré et al. 1998).

Nutrient digestibility and methane emissions

Overall, nutrient digestibility of 34 browse species was assessed in 18 studies. *Leucaena leucocephala* (Lam.) de Wit had the highest DM digestibility (935 g/kg) in a study of Ikyume et al. (2018), but lowest CP (284 g/kg) (Bosma and Bicaba 1997), NDF (62 g/kg) and ADF digestibility (223 g/kg) (Hove et al. 2001). The highest OM digestibility (764 g/kg) was recorded for *Ficus thonningii* Blume (Bamikole and Ikhatua 2010) and *Moringa olifeira* Lam. (Melesse et al. 2019) leaves. Highest CP digestibility was obtained for *Ziziphus spina-christi* (L.) Desf. (910 g/kg) (Mangara 2018), while leaves of *L. leucocephala* had the highest NDF, ADF and acid-detergent lignin (ADL) digestibility (757 g/kg, 760 g/kg and 753 g/kg) (Ikyume et al. 2018). *A. tortilis* subsp. *raddiana* leaves recorded the lowest DM and OM digestibility (356 g/kg and 357 g/kg) (Nassoro 2014), while *Gliricidia sepium* (Jacq.) Walp. leaves had the lowest ADL digestibility (551 g/kg) (Ikyume et al. 2018).

The comparison of DM digestibility between ruminants fed foliage-based diets and ruminants fed a control (basal) diet showed that shrub foliage supplementation improved CP digestibility ($p < 0.05$; Table 2), while digestibility of DM, OM, NDF and ADF did not differ between the treatment and control group (Table 2). However, significant heterogeneity (Q) was observed for the effect sizes of shrub foliage feeding on nutrient digestibility ($p < 0.0001$; Table 2). Also, the forest plots of the effect of shrub foliage on apparent digestibility of DM, OM, CP, NDF and ADF revealed

Table 2 Effect size[a] and heterogeneity for the effect of shrub foliage on nutrient digestibility and ruminant performance

Response parameters	NC[c]	Effect size[b]		95% confidence intervals			Heterogeneity	
		Hedge's g	SE[d]	Lower	Upper	*p*-value	Q[e]	*p*-value
DM digestibility, g/kg	40	5.1	3.52	−1.83	11.97	1.00	225	< 0.0001
OM digestibility, g/kg DM	17	2.6	1.78	−0.91	6.09	1.00	155	< 0.0001
CP digestibility, g/kg DM	24	3.3	1.54	0.30	6.33	< 0.05	231	< 0.0001
NDF digestibility, g/kg DM	21	−0.9	2.00	−4.76	3.05	1.00	170	< 0.0001
ADF digestibility, g/kg DM	13	1.7	2.32	−2.87	6.22	1.00	106	< 0.0001
DM intake, g/kg MW	53	1.6	0.70	0.27	3.00	< 0.05	389	< 0.0001
Weight change, g/d	21	3.1	1.46	0.20	5.91	< 0.05	270	< 0.0001

[a]Multivariate meta-analysis model with Restricted Maximum Likelihood (*REML*); [b]Standardized unitless log response ratio for differences between treatment and control groups; [c]NC: number of comparisons; [d]Standard error; [e]Cochran's Q-values to identify the presence of heterogeneity among studies

a considerable variation between studies (Online Resource 3–7).

Overall, only few well documented in vitro data on the impact of these tree/shrub materials on methane production during digestion could be found (n = 3). The lowest methane production was reported for *P. juliflora* (0 ml/200 mg DM) (Melesse et al. 2019), while the highest value was reported for *L. leucocephala* leaves (18.3 ml/200 mg DM) (Melesse et al. 2019). Overall, no correlations between CT and methane production could be identified in these studies.

Animal productive performances

Voluntary feed intake (DM, OM) and average daily weight change were assessed for 20 browse species in 10 studies. Overall, DM and OM intake of foliage-based diets averaged 60.0 ± 21.95 g/kg metabolic weight and 59.7 ± 10.44 g/kg metabolic weight respectively, while weight change averaged 51.8 ± 34.60 g/d. The relationship between foliage-based diets and DM intake and weight change (g/d) of ruminant livestock species ($p < 0.05$; Table 2), respectively, significantly varied between the studies. Again, significant heterogeneity (Q) was observed for the effect sizes of shrub foliage feeding on animal productive performance parameters ($p < 0.0001$; Table 2). Like the effect sizes of nutrient digestibilities, the forest plots of the effect of shrub foliage on voluntary DM intake (Online Resource 8) and ruminants' weight development (Online Resource 9) revealed a considerable variation between studies.

Scoring of species

The highest scored species based on its positive effect on crop yield (measured as relative yield change related to control) was *Pterocarpus lucens* Lepr. ex Guill. & Perr., followed by *Azadirachta indica* A.Juss, *G. sepium* and *F. albida*. Regarding the effect on SOC improvement, highest scores were obtained for *C. equisetifolia*, *P. biglobosa*, followed by *A. tortilis* ssp. *raddiana*. For livestock nutrition, the highest scores were obtained for *A. africana* and *P. erinaceus* (Table 3).

Discussion

Overall, we found context-specific responses of soil, crops and livestock to tree and shrub foliage in the Sudano-Sahelian zone of West Africa although the small number of studies limits interpretation to some extent. Most of the studies that evaluated crop and soil responses to shrubs or trees utilized the most common species found in the region, *i.e. F. albida, P. biglobosa*, *P. reticulatum*, *G. senegalensis* and *V. paradoxa.* Exotic species such as *G. sepium* and *A. indica* have also been increasingly included in crop and soil impact studies.

Table 3 Scoring[a] of tree and shrub species based on their potential benefits for crops, soil and livestock

Tree and shrub Species	Crop yield	Soil organic carbon	Dry matter intake
A. holocericea	1.0		
A. senegal	1.9	3.2	2.4
A. tumida	1.9		
A. tortilis (raddiana)		6.6	
A. digitata	1.3		
A. africana			**10.0**
A. pentagyna			−0.4
A. lebbeck	−1.3		
A. indica	7.1	2.9	
B. ferruginea			0.6
C. equisetifolia	1.0	**10.0**	
C. pinnata	2.9		
E. guineensis	2.3		
F. albida	6.2	3.5	
F. thonningii			2.0
G. sepium	6.8	−2.4	
G. senegalensis	0.5	3.4	−0.4
J. curcas		−1.3	
K. senegalensis			−1.8
L. leucocephala			−1.0
M. oppositifolium			−0.2
M. indica			1.3
M. discoidea			0.2
M. lucida			0.5
P. biglobosa	1.4	7.0	
P. reticulatum	1.7	2.0	
P. alnifolia			0.3
P. africana	−1.3		
P. erinaceus			6.7
P. lucens	**10.0**		1.7
S. siamea		−2.0	
T. indica	−2.3		
V. paradoxa	0.4	3.7	

[a]The larger the score, the larger the benefit. Highest score = 10. Negative scores indicate that the treatment effect was smaller than the control. For details see Materials and Methods

Soil organic matter is a well-known proxy of soil fertility, associated with soil stability, retention of minerals and water, and the stimulation of biological activity. Most studies found that the presence of ligneous species led to an increase of soil C (or organic matter—OM) content in the vicinity of trees and/or shrubs. This characteristic has been well documented in the literature (*e.g.* Félix et al. 2018). For some tree species, soil carbon enrichment effect can be highly variable, neutral or slightly negative in some cases, and very positive in others. This was in particular the case for the forage tree *F. albida* (Fig. 2). In parkland systems the impact of trees/shrubs declines usually with increasing distance from the trunk, i.e. for large *F. albida* trees, Roupsard et al. (2020), and similarly Sileshi (2016), observed an influence range on millet yield parameters of about 17 m (> 2.5 times radius of the tree crown). Thus, beyond species effect, the effect of interaction between tree, tree size/density, spatial arrangement and soil management deserves further study. Changes in soil N content as a function of tree species roughly followed the same pattern as C content, which was expected, as SOM is associated with N. It is noteworthy, however, that some interesting differences in soil C *vs.* N relationships were observed in the data collected for this review. *C. equisetifolia,* an exotic species, for example had a very strong effect on soil C and soil N when compared to other species and also a proportionally higher effect on soil N than on soil C, which could partly be attributed to N inputs through its association with the N_2 fixing actinorhizal symbiont Frankia (Parrotta et al. 1996). But one must keep in mind that the use of *Casuarina* species in our records was mainly documented in very sandy areas, therefore with originally very low soil C and N contents, and with quite substantial amounts of *Casuarina* litter or compost added (Soumare et al. 2002). Consequently, the relative increments in soil C and N in this case are likely quite exacerbated. On the other hand, *G. senegalensis* showed on average a decrease in soil N content while C content was increased. This is likely linked to its inability to fix atmospheric N_2 and hence results in soil N mining. In contrast, rhizospheric soil of *S. siamea* showed the opposite effect, i.e. increase in soil N while C decreased on average, which was unexpected as this species is a non-nitrogen-fixing leguminous tree. Still, it is known to be a highly efficient nutrient scavenger (Vanlauwe et al. 2005, 2013). Despite recent progress in published studies the database is still relatively scarce to make more informed general conclusions, this is also partly due to the large number of species and systems combinations possible.

Available P and cation contents are extremely important for crop fertility, and very often depleted

in the sandy and lixiviated context that characterizes most Sudano-Sahelian soils. The phenomenon of enrichment in soil cations in tree vicinity is assumed to have two origins: (i) deep soil uplift of minerals through the root system of trees/shrubs and restitution through litterfall for instance (Isaac and Borden 2019), and (ii) wind trapping of dust and airborne particles by trees/shrub canopies and deposition (Lamar et al. 2012). Surprisingly, the effect of ligneous species on pH (amplitude of pH shift) was not dependent on the initial pH status of the soil, despite the expectation that the relative impact to be much higher on acidic soils than on neutral or alkaline ones. The improvements in soil quality were reflected in increased crop productivity, but the crop-specific responses varied according to the climatic zones.

Surprisingly, common crops such as millet and sorghum in our study seemed not respond to shrub or tree presence or mulching when the precipitation was around 1200 mm. In the southern Sudan zone, both climatic conditions and management intensity of the fields are favorable to crop performance. Intensive production of maize and cotton, common in this region is supported by subsidized fertilizers and manure application which potentially explains the limited response to the presence of trees/shrubs of these species. When cultivating millet, sorghum or peanuts, farmers often take advantage of the residual soil fertility after maize and cotton. In the drier areas (i.e. north and south Sahel), on the other hand, there is negligible input of fertilizers or manures for crop production. It could therefore be expected that biomass inputs from trees or shrubs in drier regions would have more pronounced effects than those in the wetter regions because of very poor soil fertility. However, competition for water resources by trees increases in drier areas. This often results in a reduced positive fertility effect and decreased recycled biomass productivity (Bayala et al. 2013). A lack of competition for resources by the associated tree/shrub might also explain the generally higher impact of biomass transfer (mulching) rather than the use of organic material in Parkland systems as observed in our study. Although not conclusive, there is evidence that large canopies of *P. biglobosa* and *V. paradoxa* can limit light and reduce crop yields under or in the vicinity of the tree (Bayala et al. 2015; Bazié et al. 2012) and this is reflected in our findings.

Feed consumed by ruminant livestock is digested by microbes in the reticulo-rumen that in turn are digested by the ruminant. Crude protein (CP), defined for livestock feedstuffs as nitrogen content multiplied by a factor of 6.25, serves as a source of essential amino acids for rumen microbial growth. The subsequent production of microbial protein in the rumen contributes to over two-thirds of the protein available to the ruminant (Pathak 2008). Besides, NDF and ADF are useful measures of the feeding value of leaves. They are crucial for maintaining rumen health and function, providing structural carbohydrates that promote rumination. On the other hand, NDF is negatively correlated with the voluntary feed intake of animals (Beauchemin 1996), and ADF (cellulose and lignin) constitutes the least digestible part of the feed, being inversely related to digestibility (Riaz et al. 2014). Therefore, it is crucial to achieve a balance between feeding enough structural carbohydrates to support rumen function without overfeeding and limiting feed intake and digestibility. Furthermore, tannins contained in browses may have adverse, beneficial or indifferent effects on ruminant performance and health depending on various factors including the composition and type of the diet, the source and amount of tannins and the ruminant species (Besharati et al. 2022; Makkar et al. 2007). For instance, tannins inhibit ruminal microbial growth and ruminants' feed intake, and digestibility may be reduced by high concentrations of CT, usually > 50 g per kg feed DM. These anti-nutritive effects are associated with CT's ability to bind to proteins in feed, thus retarding their digestion, along with their astringent taste that reduces ruminants' voluntary feed intake (Makkar et al. 2007). On the other hand, CT play a role in ruminant nutrition by reducing CH_4 emissions and urinary nitrogen excretions, thus impacting environmental sustainability (although no major evidence was found in the current review probably due to the limited number of studies). However, the mechanisms involved in inhibiting ruminal microbial growth and reducing CH_4 are still poorly understood (Naumann et al. 2017; McSweeney et al. 2001).

Our meta-analyses showed that in total, leaves of 10 browse species (Table 1) had a high CP and low NDF/ADF contents. Out of these 10 browse species, four (*A. senegal, C. micranthum, P. juliflora, V. oerfota*) also contained low CT in their leaves, and as such are promising alternative feedstuffs, especially

in the late dry season when other livestock feed resources are scarce and of poor nutritional quality. For many species, the late dry season coincides with the earlier development stages of leaves, resulting in the period with the highest CP content in the leaves. This correlation has been observed for example in *A. africana* and *P. erinaceus* (Ouédraogo-Koné et al. 2008). Overall, the contribution of browse biomass to the total average feed supply in the Sudanian and Sahelian zones of West Africa has been estimated to be 1% (6 kg/ha) in areas dominated by mixed crop-livestock systems in the Sudanian zone and 1.5% (1.5 kg/ha) in predominantly pastoral areas (Rahimi et al. 2021). Simulations comparing average feed supply and feed demand for ruminant livestock species in the Sudanian zones of West Africa revealed that over the past four decades, the feed demand of the local livestock population exceeded the supply from natural grasslands, crop residues and browse (Rahimi et al. 2021). Still, shrub foliage supplementation may improve CP digestibility and feed intake, and consequently also the weight gain of ruminants (Table 2). However, the optimal supplementation level largely depends on the browse species and antinutritional factors such as tannins and saponins. Accordingly, Fall Touré et al. (1998) reported a maximum diet digestibility of 47.1%, 51.3% and 60.7% for diets containing *A. digitata*, *Pithecellobium dulce* and *Calotropis procera* leaves with corresponding browse levels of 30%, 50% and 75% respectively. They also proved a negative relation between diet digestibility and CT contents of the leaves. Similar to *C. procera*, *F. thonningii* leaves can be fed in combination with *Megathyursis maximus* grass up to 75% level without detrimental effects on nutrient digestibility and animal weight gain due to their low tannin content (Bamikole and Ikhatua 2010). *A. africana* leaves, however, can be used as sole feed (Ouédraogo-Koné et al. 2008).

Our review revealed that there is limited information on the nutritional properties of most browse species, including several common species such as *A. indica, V. paradoxa and P. reticulatum*. *A. indica* is an exotic species that increased significantly in numbers during the last two decades particularly around villages, where it is mainly used as a shade for humans due to its fast growth and evergreen habit (Tropical Plants Database 2024). In conclusion, we see the need for further research to evaluate the full nutritional properties of these common species and to evaluate their effects on animal feed intake, nutrient digestibility, animal performances and environmental impact.

Scoring of species

The scoring indicates a trade-off between a positive impact on crops and livestock *vs.* soil organic carbon. The scoring of individual species, however, does not cover all three areas (crops, soil, livestock) except for a few ones, and many under-researched species are not captured due to limited/missing data. In general, the species with high mineralization rates (*F. albida, G. sepium, A. indica*) scored higher for crop production but not always also for SOC. This is partly an expected result because of the well-known need of crops for readily available nutrients from medium-fast mineralizing species in contrast to the need of SOC for slowly mineralizing species in these nutrient depleted soils, while slowly mineralizing species (i.e., *G. senegalensis, P. biglobosa* and *V. paradoxa*) can benefit SOC accumulation and reduce priming effects on native SOC (Pingthaisong et al. 2024). Thus, mixing of species, where possible, might be an option to harness such effects (Pingthaisong et al. 2024). Likewise, the relatively low CP content of *G. senegalensis* (105 g/kg DM) (Sanon et al. 2008) and *P. biglobosa* (53.8 g/kg DM) (Umutoni et al. 2015) limit their utilization for livestock feeding.

Among the species tested, this review confirms that *F. albida* is one of the most promising parkland species providing potential benefits for SOC sequestration, soil fertility, crop productivity and potentially also animal nutrition. It comes close to an ideotype of parkland species, due to its N_2 fixation capability in association with rhizobia enhancing soil fertility, and its inverse phenology that eliminates shade on crops and soil resource competition (Roupsard et al. 1999; Sileshi 2016). In return, it provides shade and high-quality feed (high CP, and low NDF, ADF and CT) (Zampaligré et al. 2013) to animals in the dry hot season. On the other hand, *F. albida* lacks a direct major human food or cash crop value and is limited to sites with shallow groundwater access (Roupsard et al. 2020). Many of the species that provide a more direct human value like *V. paradoxa* are less suited to cultivate crops under the tree, but their pruning has

a highly positive impact on soil carbon (Bayala et al. 2002).

The scoring of species for crop productivity, soil carbon and animal nutrition revealed that there is no "silver bullet" or multipurpose single species that should be promoted. For instance, despite *F. albida*'s high score for both soil and crops, its ability to produce biomass (and tolerate pruning) for feed or soil is limited (Toib et al. 2021). *A. indica*, on the other hand, is not a widespread species and appears only in and around the villages (Hänke et al. 2016). Also, neem extract and azadirachtin used as a natural pesticide may affect soil microbiology (Sarawaneeyaruk et al. 2015). The commonly occurring shrub *G. senegalensis* (Hänke et al. 2016) scored low for crops and livestock, but its availability and ease of use make this shrub an invaluable source for sustainable soil fertility management in the Sudano-Sahelian region of West Africa (Diallo et al. 2021). *G. sepium*, which scored high for crops, is also an exotic species and extremely rare. Despite the promotion efforts, its adoption was limited through grazing by free roaming livestock killing the young seedlings (Bayala et al. 2011). More research is needed on how to establish species such as *G. sepium* which can be used alongside other native species to benefit crop productivity, SOC and animal nutrition. Given the diverse species composition of agroforestry systems in this region, even at the field level (Sehoubo et al. 2023), farmers would be in a position to synergistically use the various species for different purposes when provided with proper information.

Towards a transdisciplinary assessment framework: integrated modelling as a tool to assess the interplay between different systems and actors

While our review results show the large impact of the different shrub/tree resources on soils, crops and livestock performance individually, there is still a need to better understand how the corresponding interactions among components shape ecosystem responses (Hieronymi 2013). Interactions in such savanna parkland systems occur between soils, crops, agroforestry, and livestock at different scales: i.e. (i) at plot level through grazing stubble and browsing of foliage, returning/deposition of animal feces and urine on crop fields and under trees, provision of shade to animals and crops, provision of nutrients to crop fields; (ii) at farmstead level through feeding pruned tree/crop residues to livestock in corrals through cut and carry systems; (iii) at village level through dry season grazing on communal land; (iv) watershed scale were agroforestry options might reduce the impact of over-grazing on soil erosion; and (v) landscape scale by grazing/biomass transfer of tree/shrub material for livestock feeding or by moving herds and transhumant agreements with crop farmers for manure deposition (Powell et al. 1996). Jones et al. (2017) proposed that these interactions go beyond traditional disciplinary boundaries, and hence more transdisciplinary and improved modelling approaches are needed to effectively capture such complex interactions. Consequently, there is a need to combine existing and new research approaches and couple different system component models, such as those focusing on soils, crops, trees, livestock and watersheds as well as considering farmers needs to effectively address this complexity.

The limitations in existing standalone simulation models have become apparent, particularly in sub-Saharan Africa where crop and pastoral systems are in proximity and often intimately linked. Rufino et al. (2014) highlighted the necessity of developing integrated model systems to better account for feedback mechanisms between crop and livestock components, thereby facilitating systems thinking. In addition to linking bio-physical models to simulate crop/grassland and livestock interactions, the inclusion of multi-agent socio-economic models might be necessary for assessing system responses to herd management and climate change in semi-arid areas (Marohn et al. 2022). An integrated tool of this nature should evaluate how various systems interact and assist in filling the gaps in impact assessment across various agroecosystems and climates. Marohn et al. (2022) developed such an integrated modelling framework by coupling a spatially explicit landscape-based soil-crop/agroforest model (LUCIA, lucia.uni-hohenheim.de) with a livestock model (LivSim, models.pps.wur.nl/livsim) and a multi-agent model (MPMAS, mpmas.uni-hohenheim.de) and assessed impact of climate variability and herd management on sustainability and livelihoods. Thus, integrated modelling frameworks offer the potential to strategize, execute, and assess results across diverse situations and specific contexts (Brown et al. 2023). They can thereby

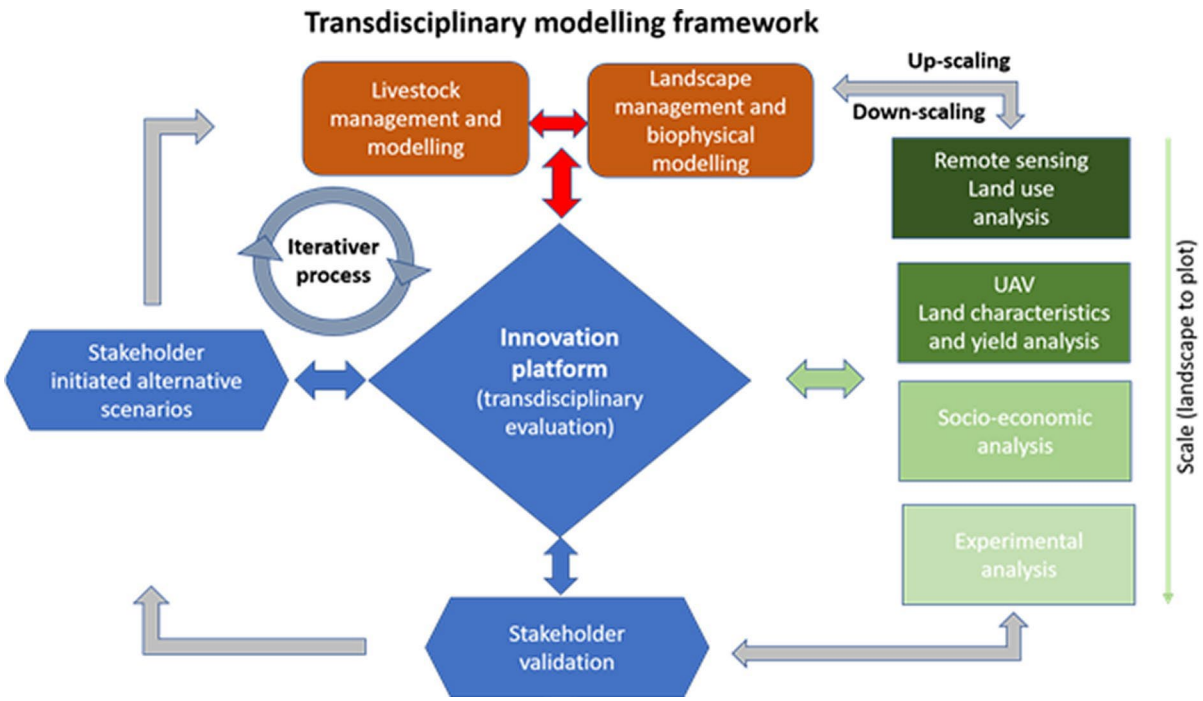


Fig. 8 Transdisciplinary modelling framework to assess the impact of integrating shrub and tree species in farming system on soil, crop, livestock trade-offs across scales (plot to landscape)

support the assessment of trade-off effects of shrubs and trees between soil, crop and livestock nutrition as well as out-scaling of results into a wider context. Remote sensing tools can provide an option to support the up-scaling of new process-model output scenarios, enabling more regional assessments, including land use change, biomass productivity, and carbon sequestration. However, the application of integrated modelling approaches is complex and often limited by data scarcity such as encountered in Sudano-Sahelian zone of West Africa. Thus, there is a need to further develop rapid cost-effective tools to obtain ecosystem variables such as spectral soil analysis (Cobo et al. 2010) and high-resolution UAV/remote sensing landscape and yield analysis combined with geostatistics (Roupsard et al. 2020) and machine learning.

To have a broader relevance, approaches and the tested options (scenarios) need to be co-designed, co-evaluated and finally accepted by the respective stakeholders. Thus, we propose a transdisciplinary approach to assess the resource use of shrub/tree residues by directly interacting with key stakeholders (Fig. 8). This framework builds upon locally established innovation platforms where stakeholder problems are identified and alternative management visions are taken into consideration. Throughout this process, stakeholder-preferred scenarios of shrub and tree use are developed and subsequently transferred into modelling scenarios. As mentioned earlier, models should address scale-related challenges, encompassing animal management and biomass transfer at the farm and landscape level while reflecting processes at the plot scale. After the simulations, the outputs generated by process-oriented models need to be adapted to stakeholders' understanding and incorporated into the discussion process within the innovation platform. This integration and trade-off analysis, along with stakeholder validation and feedback, coupled with new knowledge, allows for the modification of the previously defined alternative scenario settings of shrub and tree use in the respective region. Importantly, this feedback loop should be an iterative process together with stakeholders that promotes continuous refinement until an acceptable outcome is achieved. Such a transdisciplinary approach, however, needs effective communication and willingness between parties, trust (Lusiana et al. 2010), corresponding resources and time (beyond current time

frames of projects) and hence is a major challenge given the current settings in the region.

Conclusions

This study showed that the impact of certain tree and shrub species on crops, soil and livestock is not conclusive. A positive influence of these species on crops and livestock was often not reflected in the same impact on soil. As tree and shrub species in agro-silvopastoral systems must be able to satisfy multiple human and environmental needs, the focus should rather shift to the study and eventual promotion of species mixtures. Mixtures naturally occurring in the landscape, and targeted improvements of their composition and densities could be elaborated, starting from these original patterns. To support such strategies and convince policymakers, experimental trials are needed that look at crop, livestock and soil responses by combining fast and slow mineralizing as well as highly nutritious species. This should also include under-researched species, for which the data base is so far limited. Therefore, we strongly advocate shifting the research focus from the commonly found approach on single species to species mixtures, which should be combined with transdisciplinary and integrated modelling approaches to study interactions of the different components that characterize agro-silvopastoral systems of the Sudano-Sahelian region in West Africa.

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Data availability Data will be made available on request.

Declarations

Conflict of interest The authors declare that there are no conflict of interests.

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