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1. EXECUTIVE SUMMARY

Deliverable 7.4 builds upon the foundation established in Deliverable 7.1, which focused on characterising the landscape and mapping the suitability of Crop, Shrub, and Livestock (CSL) or agrosylvopastoral systems for the SustainSahel sites. This deliverable presents a detailed mapping of 25 agro-environmental variables, including precipitation, altitude, soil types, soil organic carbon, and tree and shrub cover. The analysis was conducted at both regional levels (Senegal, Mali, Burkina Faso) and specific sites (Saria, Yilou, Koulikoro, Sikasso, Niakhar, Ouarkhokh, Koussanar) using geospatial databases such as WaPOR, ISRIC, and TAMSAT. The primary goal of Deliverable 7.4 is to generate a suitability map for CSL systems across the three countries and model the yield benefits of these systems under varying isohyets within the studied landscapes using the LUCIA model.

The suitability of CSL systems for the target areas was modelled using the Random Forest machine learning algorithm. The assessment of the agrosylvopastoral system's suitability incorporated agro-environmental variables obtained from freely accessible online platforms, vegetation indices derived from Landsat 8 satellite imagery, and field-collected occurrence data on agroforestry systems. All analyses were conducted using the Google Earth Engine platform.

The LUCIA model (https://lucia.uni-hohenheim.de) was calibrated and validated for key crops, including millet and sorghum, as well as shrubs and trees across the SustainSahel study sites. Simulations were conducted to estimate crop yields and biomass production potential of shrubs and trees under different isohyets at each location. The effectiveness of various CSL systems in enhancing crop grain yield was assessed by comparing their benefits under different soil amendment treatments to baseline yields (no amendment). Additionally, aboveground biomass production of trees and shrubs and yields benefits of cereals intercropped with shrubs and trees were evaluated across different landscape positions with varying isohyets.

The CSL suitability map indicates that western Senegal, central Mali, and northern Burkina Faso are the most favorable regions for agrosylvopastoralism, while northern Mali is significantly less suitable. The yield simulations conducted using the LUCIA model aligned with these suitability findings. In Senegal, higher yield benefits were observed in Niakhar (western region) compared to the northern area around Ouarkhokh and the southern zone near Koussanar. Similarly, in Mali, Koulikoro's central region showed greater yield benefits than Sikasso in the south. In Burkina Faso, Yilou in the north exhibited more pronounced yield gains than Saria in the south. The results also highlight that while higher yield benefits were generally associated with regions of higher isohyets, some areas displayed contrasting trends. This suggests that factors beyond rainfall, such as soil fertility, may also play a significant role. The integrated use of organic and mineral fertilizers was found to enhance yield benefits even in areas with lower isohyets.

Aboveground biomass (AGB) production contributes to both animal nutrition and soil fertility through the incorporation of pruned residues. In regions with 500 shrubs ha^{-1}, AGB exhibited minimal variability and remained stable across different isohyets in the three studied countries, in contrast to the 1000 shrubs per hectare density. At the higher planting density (1000 shrubs ha^{-1}), AGB was generally greater in areas with lower isohyets than in those with higher isohyets, except in certain locations. Overall, AGB production increased with higher planting densities of *Guiera senegalensis*. Intercropping cereals with *Guiera senegalensis* improved yields across all study regions, with the most significant benefits observed in lower isohyets, particularly in Saria and Yilou, Burkina Faso. Similarly, intercropping *Faidherbia albida* with cereals resulted in higher yields benefits. However, in most study regions, the yield benefits of *Faidherbia albida* intercropping were more pronounced in areas with higher isohyets than in those with lower isohyets.

2. INTRODUCTION

Agroforestry or CSL systems in the Sahel, commonly referred to as parklands, play a crucial role in enhancing food security and household livelihoods (Leroux et al., 2022). They contribute directly by providing food (Ickowitz et al., 2014) and indirectly through income diversification and fuelwood and fodder production (Diatta et al., 2016). However, these systems face significant threats due to tree aging and limited regeneration, driven by environmental factors such as climate change, socio-economic pressures like grazing and wildfires, and political influences, including forest regulations (Dieng et al., 2016; Gangneron et al., 2024). Mapping their suitability is therefore essential for understanding their structure and predicting their evolution in response to bioclimatic conditions at both local and regional scales.

This report represents the fourth deliverable of WP7 (D7.4) and builds upon the foundations established in the first and second reports (D7.1 and D7.2). Deliverable 7.1 focused on characterizing the landscape and assessing the extent and suitability of Crop, Shrub, and Livestock (CSL) systems using satellite and remote sensing data from geospatial databases such as WaPOR, ISRIC, and TAMSAT. It also provided an overview of existing crops, cropping systems, soil types, land use, and tree and shrub cover, serving as a reference for the parameterization of the LUCIA model (https://lucia.uni-hohenheim.de). In Deliverable 7.2, detailed calibration and evaluation of the model at the plot level were initiated for Niakhar (Senegal) using the Sob watershed, as well as for Saria and Kamboinse (Burkina Faso) and Koulikoro (Mali). Field and station experiments on CSL systems at these sites generated valuable data to refine simulations of water and hydrological processes, as well as above-ground and below-ground plant growth dynamics.

This report seeks to assess the suitability and benefits of CSL systems across the three countries and seven project sites of SustainSahel. It presents an overview of CSL system mapping, with a particular emphasis on CSL systems, examining their distribution and suitability in relation to key factors such as rainfall, air temperature, topography, and soil gradients. To achieve this, open data sources and machine learning algorithms integrated with GIS were utilized, along with the LUCIA model, to evaluate the suitability and benefits of CSL systems across various landscape positions with varying isohyets.

3. DATA AND METHODS

A combination of plot and landscape-level modelling, along with machine learning techniques was employed to assess the suitability and benefits of CSL systems. Given the high variability of biophysical factors, such as seasonal rainfall and its redistribution through surface runoff**,** vegetation cover and productivity differ significantly across countries and regions within the Sahel. The Random Forest machine learning approach, therefore, focused on 20 key variables, including topography, bioclimatic conditions, soil properties, and vegetation indices derived from Landsat-8 satellite imagery, to predict vegetation suitability at the national level. Meanwhile, the LUCIA model, calibrated for specific study regions within each country was used to simulate the benefits of different CSL systems under varying isohyets at each study location.

3.1. Overview of study sites and LUCIA model setup for simulation

Building on Deliverable D7.2, which focused on parameterized, calibrated, and biophysically validated models, the LUCIA model (https://lucia.uni-hohenheim.de) has been adapted for all seven SustainSahel study sites. That report, along with further model development, initiated detailed calibration and evaluations for Niakhar and Ouarkhokh (Senegal), Koulikoro (Mali), and Saria and Kamboinse (Burkina Faso). Site-specific calibration was conducted using weather records, soil data, CSL system characteristics, and management practices, sourced from ongoing SustainSahel project measurements and published literature.

For this study, six years (2018–2023) of weather data were used that includes in situ measurements of rainfall, air temperature, solar radiation, and evapotranspiration, as well as data downloaded from climate engine platforms (https://www.climateengine.org/). For missing in situ collected data of precipitation, we used simulated daily rainfall from CHIRPS (Climate Hazards group Infrared Precipitation with Stations) at a resolution of 0.25° × 0.25° (Funk et al., 2015). For daily mean air temperature, we used ERA5 data provided at a spatial resolution of 0.25° × 0.25° (Copernicus Climate Change Service (C3S), 2017). Photosynthetic active radiation (solar radiation) was downloaded from the NASA POWER platform (https://power.larc.nasa.gov/). While each study region exhibited diverse CSL systems, the simulated systems in this study represented the predominant ones.

Soils within the Niakhar region (Sob watershed) are Arenosols (IUSS Working group WRB, 2014); a typical sandy ferralitic soil (Siegwart et al., 2023). The soils in the Koulikoro region (Katibougou) are Ultisols; tropical ferruginous (IUSS, Working Group WRB, 2015). In Saria, at INERA experimental station, the soils are classified as Ferric Lixisol (FAO, 2006).

3.1.1. Simulated CLS systems and rainfall isohyets

Various CSL systems, representing dominant farming practices (baseline) and model scenarios discussed at IP meetings, were simulated under different isohyets (Figure 1) and biophysical gradients, such as soil texture and soil organic carbon (SOC). The analysis assessed the performance of these CSL systems in terms of crop grain yield production, comparing their benefits under different soil amendment strategies against baseline (no amendment) yields. Additionally, the aboveground biomass production of trees and shrubs was evaluated across different landscape positions with varying isohyets. Table 1 below outlines the simulated CSL systems, associated rainfall isohyets, and the climatological zones of the study regions.

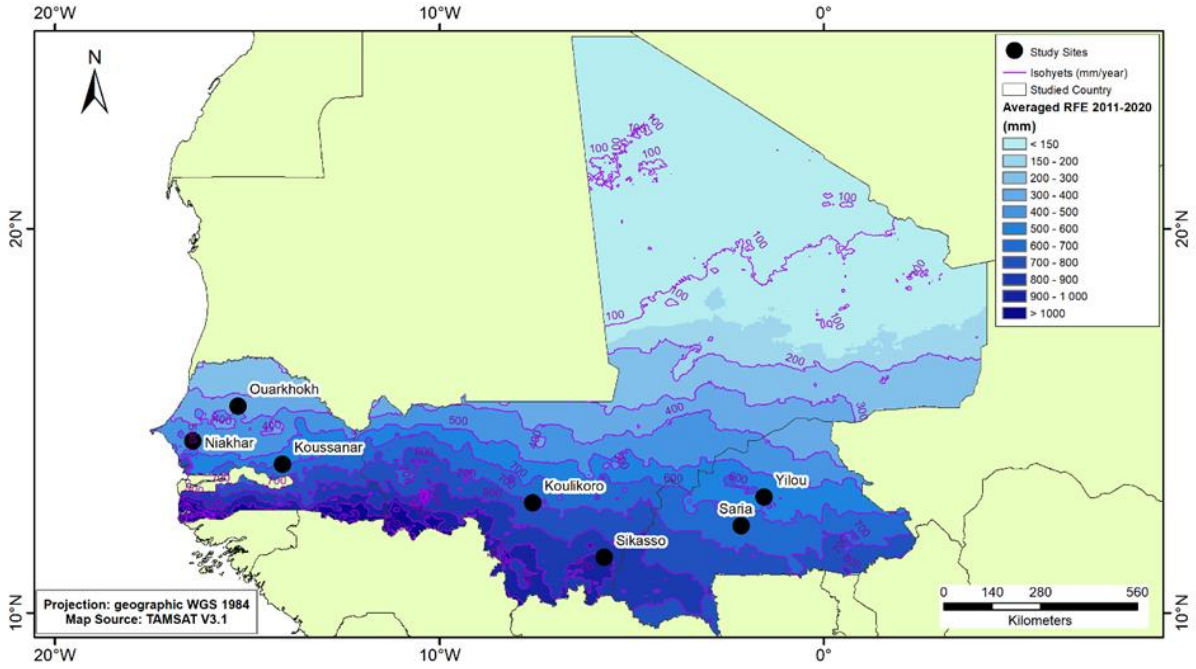


Figure 1. Average isohyet map (2011-2020) of the various study sites in Senegal, Mali, and Burkina Faso. Isohyets were computed using the TAMSAT dataset (Tarnavsky et al. 2014 ; Maidment et al. 2014).

Table 1. CSL systems, associated isohyets, and climatological zones of the study regions.

Country	Study region	Climatological zone	Isohyets tested	CSL systems simulated
Senegal	Niakhar	Sahelian (tropical semi-arid)	500 and 700 mm	1. Soil amendment study* i) No amendment ii) *Guiera s.* biomass (2.5 t ha^{-1}) iii) *Guiera s.* biomass + Min-Fert (2.5 t ha^{-1} + MF (50% RD) iv) Animal manure (2.5 t ha^{-1}) v) Animal manure + Min-Fert (1.25 t ha^{-1} + MF (50% RD) 2). Tree/ shrub and crop intercropping* i) Pruned AGB of: *Guiera senegalensis* (1000 plants ha^{-1}); *Faidherbia albida* (7 plants ha^{-1}) intercropped with Millet in Senegal, and Sorghum at Mali and Burkina Faso.
Senegal	Ouarkhokh	Sahelian (tropical semi-arid)	300 and 400 mm	
Senegal	Koussanar	Sudano-Sahelian	700 and 800 mm	
Mali	Koulikoro	Sudanian	600 and 700 mm	
Mali	Sikasso	Sudano-Guinean	800 and 1000 mm	
Burkina Faso	Saria	Sudano-Sahelian	700 and 800 mm	
Burkina Faso	Yilou	Northern Sudanian	500 and 600 mm	

* Sole millet at Senegal sites and sole Sorghum at the study sites in Mali and Burkina Faso. Pruned biomass of *Guiera senegalensis* and *Faidherbia albida* were returned to the soil as residues.

RD = recommended dose of mineral fertilizers, AGB = above ground biomass

3.2. Using machine learning to model the suitability of CSL systems

A literature review facilitated the identification of 20 pertinent variables across the three countries, encompassing various elements such as topography (30 m DEM), bioclimatic factors (temperature, precipitation, etc.), soil characteristics (organic carbon, nitrogen, pH, etc.), and vegetation indices obtained from Landsat-8 images. These datasets were resampled to a resolution of 1000 m and adjusted to align with the study area boundaries. Field data, consisting of 5183 polygons, were utilized for model calibration and validation. The selection of predictive variables was guided by a Spearman correlation matrix and a Variance Inflation Factor (VIF) test to eliminate multicollinearity. The final chosen variables are listed in Table 2 below.

The Random Forest algorithm, with optimal parameters set at mtry = 28 and ntree = 1500, was used to model the suitability of areas in Senegal, Burkina Faso, and Mali. Each sample of the training dataset was classified as either an agrosylvopastoral area or not. To validate the model, 20% of the data was set aside, and accuracy was assessed using a confusion matrix, a ROC curve (AUC), the F-score, and the Kappa coefficient. The predictions were produced as probability indices with continuous values ranging from 0 to 1, then reclassified into five categories, ranging from low to very high suitability, using the natural breaks method (Jenks, 1963).

Table 2. Variables used for the suitability mapping of CSL systems

Nr.	Variable name	Nr.	Variable name
1	Above ground biomass	11	Green Normalized Difference Vegetation Index (GNDVI)
2	Aspect	12	Normalized Difference Vegetation Index (NDVI)
3	Landsat Spectral Band 4	13	Total soil Nitrogen
4	Landsat Spectral Band 5	14	Soil pH
5	Landsat Spectral Band 9	15	Available soil Phosphorus
6	Landsat Spectral Band 1	16	Exchangeable soil Potassium
7	Landsat Spectral Band 10	17	Precipitation
8	Brightness Index (BI)	18	Temperature
9	Cation exchange capacity (CEC)	19	Tree cover
10	Elevation	20	Soil Water Content

4. RESULTS

4.1. Mapping the Suitability of Agrosylvopastoral Systems in Senegal, Mali, and Burkina Faso

4.1.1 Variable Importance and Model Prediction Performance

The most important variables in the suitability model for agrosylvopastoral systems are pH, biomass, temperature, and CEC. The least important variables in the model are the GNDVI and NDMI indices (Figure 2).

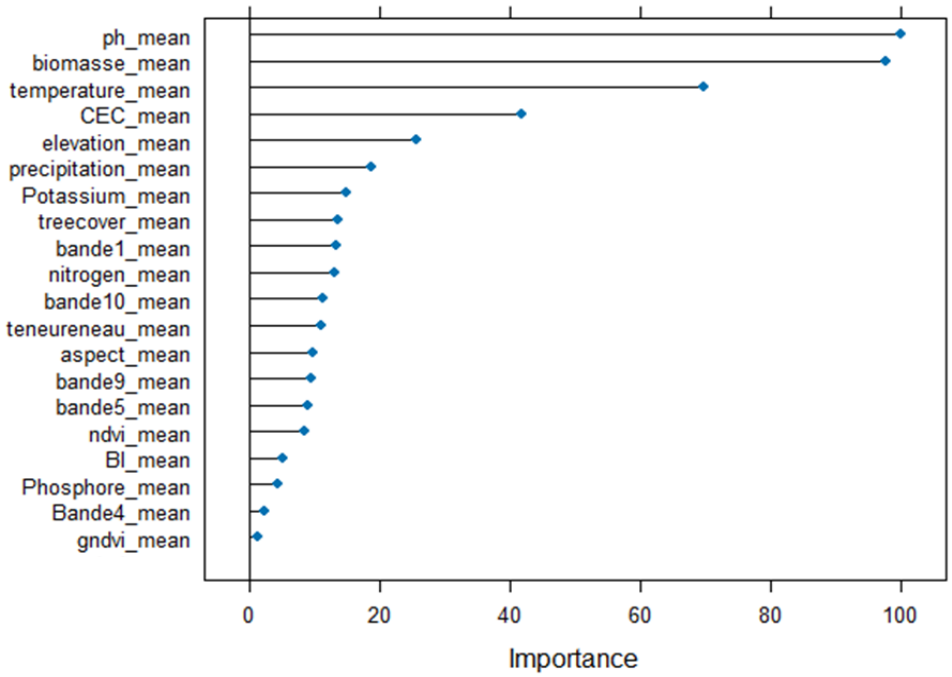


Figure 2. Predictive variables ranked by importance for the prediction of agrosylpopastoral systems in the study area

The agrosylvopastoral suitability model displays an accuracy of 96.78% and an AUC (Area Under Curve) of 0.993 for these systems (Figure 3). The models exhibit high sensitivity of 0.9283 and extremely high specificity of 0.9996. The AUC of the ROC (Receiver-Operating Characteristic) curve is 0.993 for agrosylvopastoral systems, with a kappa coefficient of 0.93.

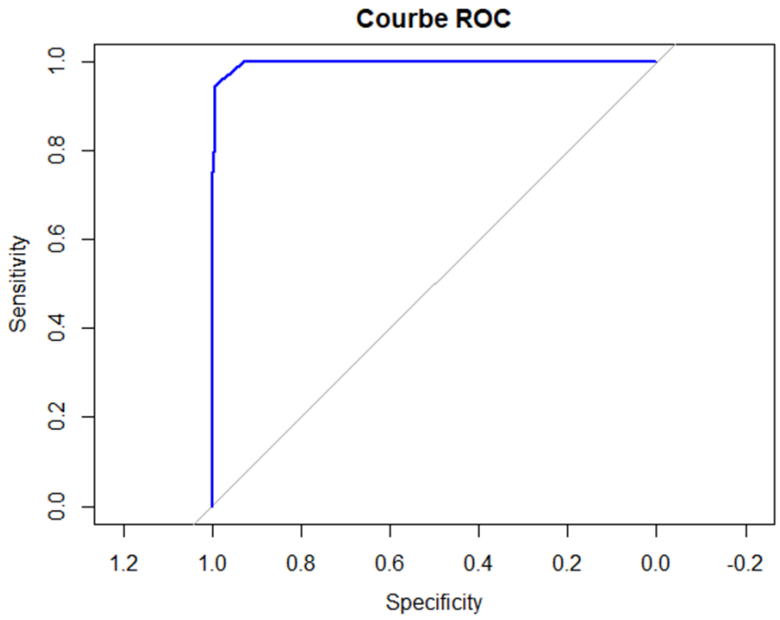


Figure 3. ROC Curve for the Agrosylvopastoral suitability model

4.1.2 Map of Agrosylvopastoral system Suitability in Senegal, Mali and Burkina Faso

The agrosylvopastoral suitability map provides a detailed view of the spatial distribution of areas suited to agrosylvopastoral systems in the regions of Senegal, Mali, and Burkina Faso (Figure 4). Note that the northern part of Mali was not covered due to unavailability of tree cover information in this region which corresponds mainly to the desert (with low suitability overall).

Areas with very low suitability, represented in pale yellow, cover 10,464,993 hectares, or 9% of the total area considered. These are mainly located in northern Mali, where conditions are least favorable for agrosylvopastoralism. The low suitability class, shown in yellow, occupies the largest area with 34,607,374 hectares, representing 29% of the total area. These zones are primarily located in northern Mali and around Niakhar in Senegal, indicating limited potential for agrosylvopastoral practices.

The moderate suitability class, represented in light green, covers 29,274,841 hectares, or 24% of the area. It is found in southern Mali, Burkina Faso, as well as in Koussanar and Ouarkhokh in Senegal, suggesting a reasonable potential for agrosylvopastoralism. High suitability areas, shown in green, cover 23,436,676 hectares, or 20%. They are mainly located in southern Mali, Burkina Faso, and around Koussanar and Ouarkhokh, offering favorable conditions for CSL systems.

Finally, areas of very high suitability, represented in dark green, cover 21,877,886 hectares, or 18% of the total area. These are concentrated primarily in southern Mali, around the sites of Sikasso and Koulikoro, as well as in parts of Burkina Faso, and are the most suitable for agrosylvopastoral systems.

In summary, areas with low suitability (very low and Low) cover 38% of the region, primarily in northern Mali, where environmental conditions are challenging. Areas with moderate, high, and very high suitability together cover 62% of the total area, concentrated mainly in southern Mali, Burkina Faso, and the north-west of Senegal, offering more favorable conditions for agrosylvopastoralism.

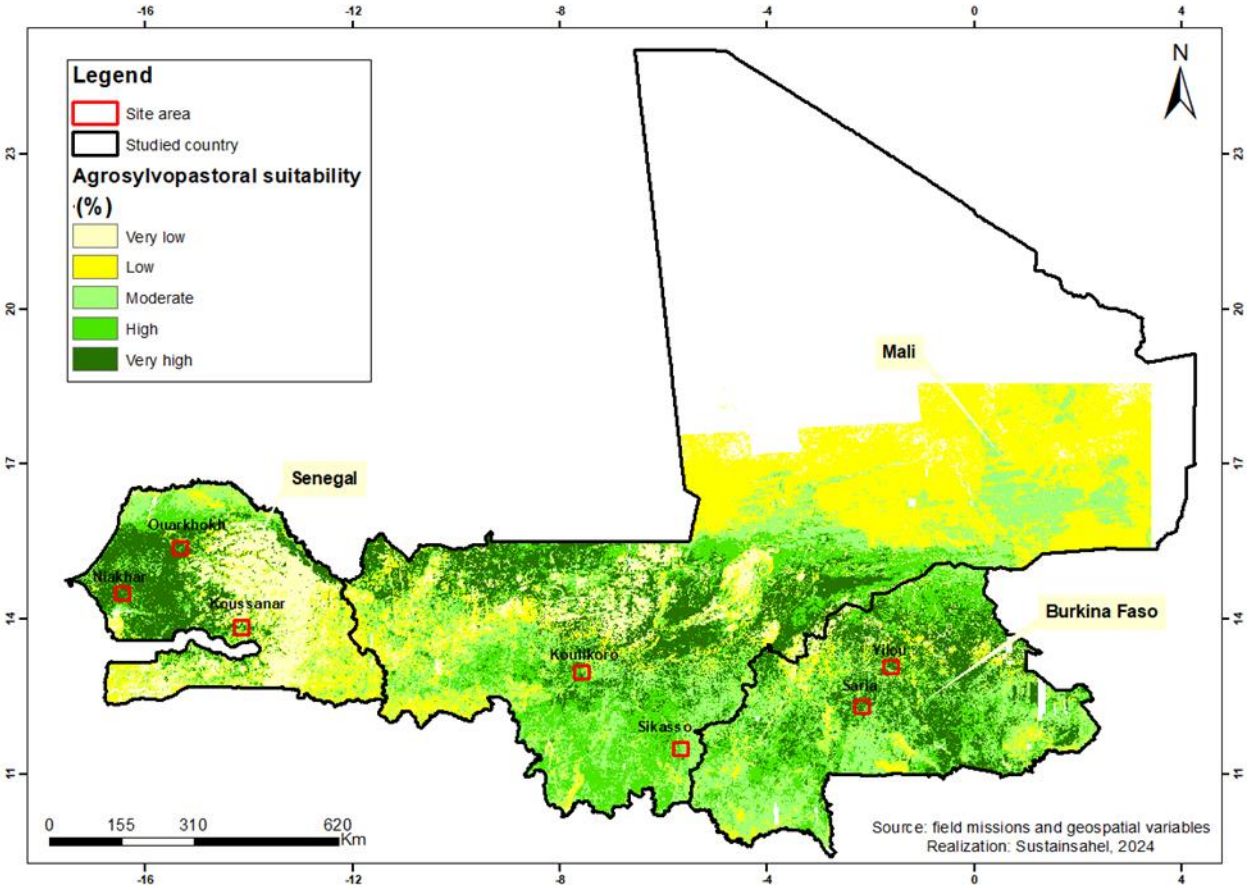


Figure 4. Agrosylvopastoral Suitability Map for Senegal, Mali, and Burkina

4.1.3 Yield benefits of different soil amendments under varying isohyets

Simulated millet and sorghum yield under a range of soil amendments relative to the baseline (no amendment) showed varied yield benefits under different isohyets and mapped CSL suitability (Figures 5, 6 and 7). Overall, most of the simulated locations within the landscape indicated potential for improved grain yield with amendments of shrub/tree pruning's or animal manure. Yield responses were generally higher at the more favourable CSL sites in the different countries. While higher isohyets suggested that increased rainfall resulted in better yield benefits, this trend was not uniform across all simulated sites. The overlapping boxes among similar soil amendment treatments compared under different isohyets indicate that yield benefits are not always strongly differentiated by rainfall. Greater yield benefits were observed under combined organic and mineral fertilizer (50% of recommended dose) applications. Lower yield benefits were observed when incorporating only *Guiera senegalensis* residues, except for a few instances in Sikasso under 800 and 1000 mm and Yilou under 500 mm isohyet.

In the low rainfall area of Ouarkhokh, the relatively small average yield benefit of millet (0.1-0.6 Mg/ha) due to CSL amendments was higher under the 400 mm isohyet than the 300 mm isohyet (Figure 5). However, yield variability was less pronounced under the 300 mm isohyet, indicating more consistent but lower yield benefits. This area corresponds with the pale-yellow regions on the suitability map (Figure 4), which indicates very low suitability for agrosylvopastoral systems. In Koussanar, at more suitable CSL sites, the average yield benefits (0.3-0.8 Mg/ha) due to amendments were larger than at Ouarkhokh; but were similar under the 700 and 800 mm isohyets, suggesting that rainfall may not be the sole factor affecting grain production in this region. Largest average millet yield benefits (0.4-0.9 Mg/ha) due to

amendments were obtained at CSL favourable sites in Niakhar, where yield benefits were more stable under the 700 mm isohyet than the 500 mm isohyet. Since Niakhar's soils are sandy, the difference in total rainfall between 500 mm and 700 mm may be less significant, as excess water drains quickly rather than being retained for plant use but rainfall distribution affects crop performance.

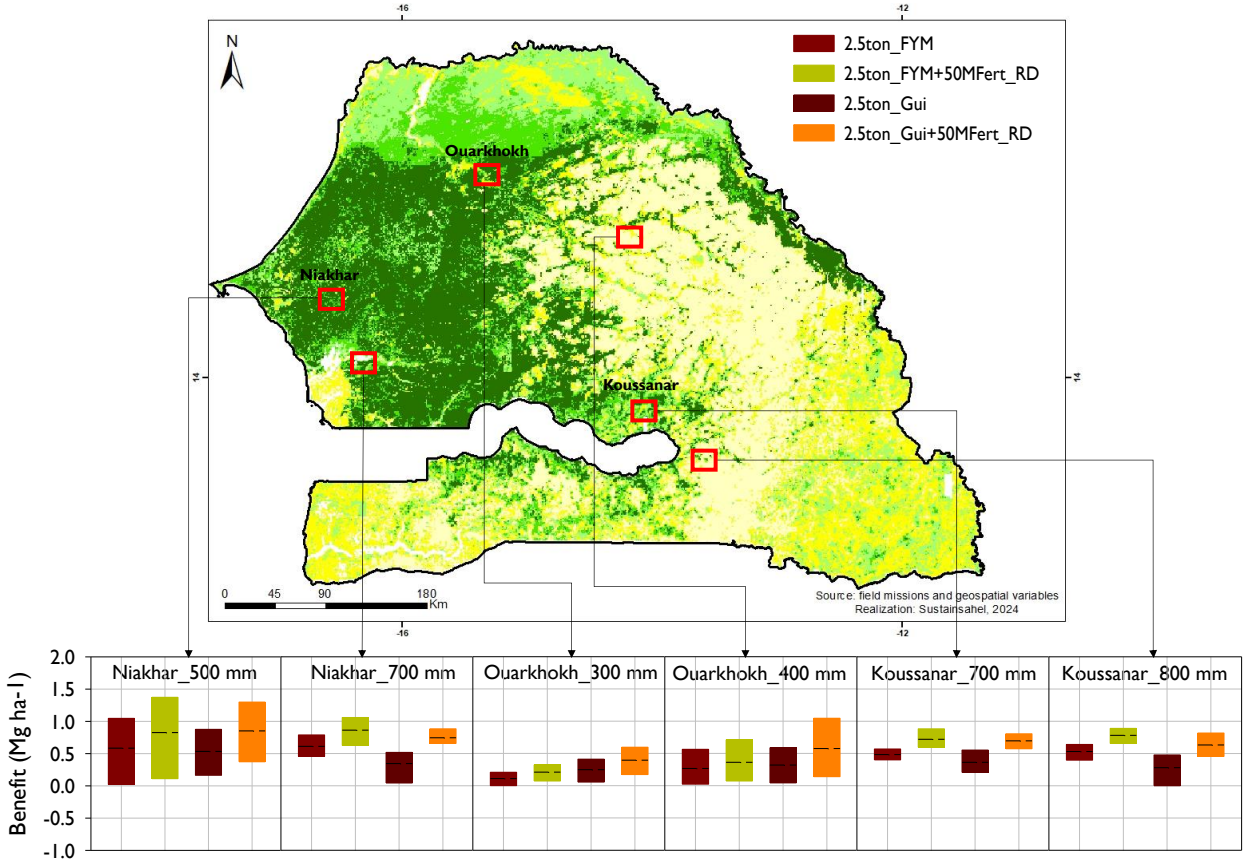


Figure 5. Map showing grain yield benefits of amendments of farm yard manure (FYM), Guiera senegalensis residues with or without 50% of recommended dose (RD) mineral fertilizer for Millet in Senegal simulated under varying isohyets. The dashed horizontal line in the box plot's middle indicates the mean of the six years of simulations from 2018 to 2023. Treatments: 2.5ton_FYM: 2.5 t ha^{-1} cow dung manure; 2.5ton_FYM + 50MFert_RD: 2.5 ha^{-1} cow dung manure plus half of the mineral fertilizer RD; 2.5ton_Gui: 2.5 t ha^{-1} *Guiera senegalensis residue*; 2.5ton_Gui + 50MFert_RD: 2.5 t ha^{-1} *Guiera senegalensis residue* plus half of the mineral fertilizer RD.

In Mali (Koulikoro and Sikasso), sorghum production yielded significant benefits due to the tested soil amendments across all isohyets (Figure 6). The 800 mm and 1000 mm isohyets in Sikasso exhibited similar yield variability. The use of farmyard manure resulted in more stable grain yield benefits compared to *Guiera senegalensis* residues, which, despite showing high variability, provided greater yield benefits in Sikasso. The more stable yield benefits under farm yard manure could be explained by its gradual nutrient release, improved soil moisture retention, and enhanced long-term soil health. The *Guiera senegalensis* residues on the other hand provided greater but more variable yield benefits due to rapid decomposition, high short-term nutrient availability under the favourable rainfall conditions (800-1000 mm). In contrast, simulation results at Koulikoro were less consistent than at Sikasso. While all amendment treatments

showed positive benefits for sorghum production, the combination with mineral fertilizer further improved yield on the farmyard manure under the 600 mm isohyet. As expected simulated yield variability in Koulikoro was greater under the 600 mm isohyet than the 700 mm isohyet, except when only farmyard manure was applied. Lower benefits in combination mineral fertilizer at the higher rainfall site in Koulikoro was likely due to reduced synchrony between nutrient availability and plant demand due to increased leaching.

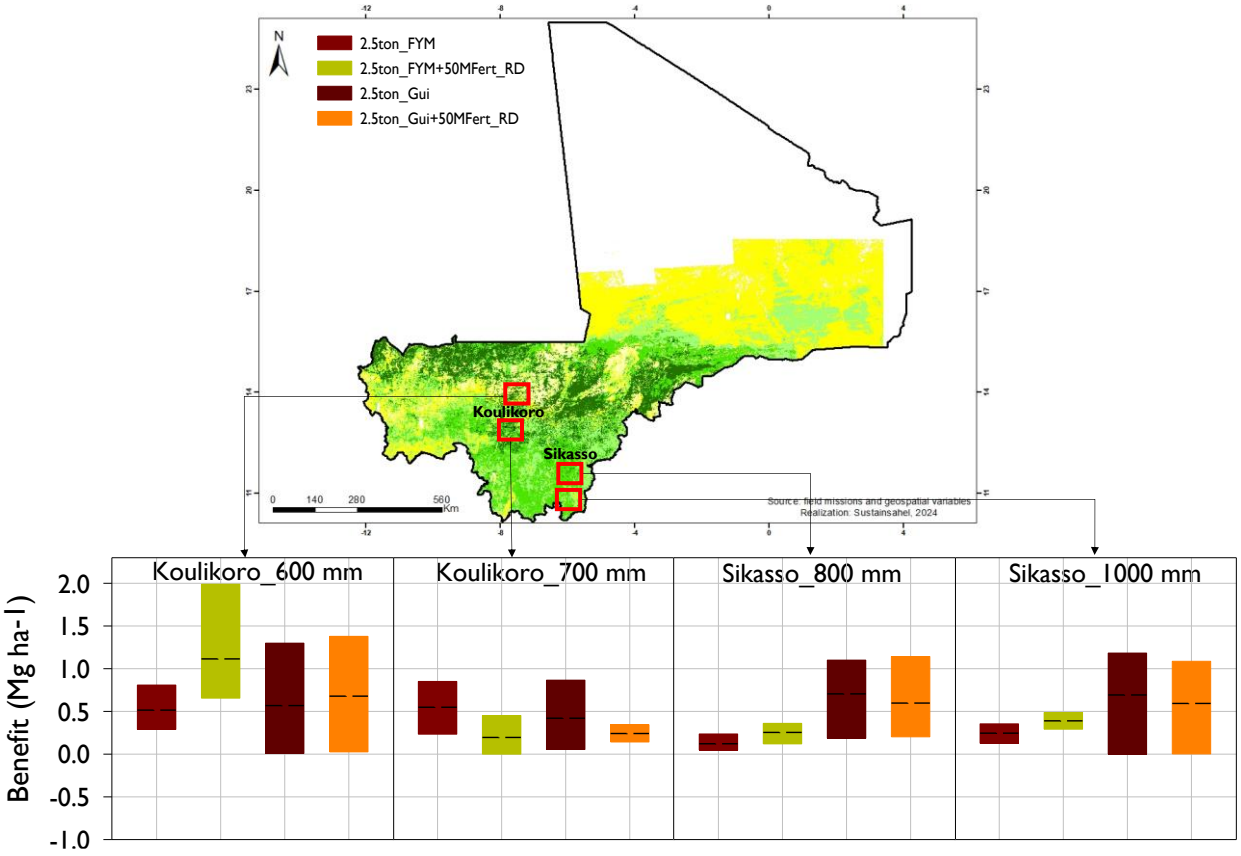


Figure 6 Map showing grain yield benefits of amendments of farm yard manure (FYM), Guiera senegalensis residues with or without 50% of recommended dose (RD) mineral fertilizer for Sorghum in Mali simulated under varying isohyets. The dashed horizontal line in the box plot's middle indicates the mean of the six years of simulations from 2018 to 2023. Treatments: 2.5ton_FYM: 2.5 t ha^{-1} cow dung manure; 2.5ton_FYM + 50MFert_RD: 2.5 t ha^{-1} cow dung manure plus half of the mineral fertilizer RD; 2.5ton_Gui: 2.5 t ha^{-1} *Guiera senegalensis residue*; 2.5ton_Gui + 50MFert_RD: 2.5 t ha^{-1} *Guiera senegalensis residue* plus half of the mineral fertilizer RD.

Sorghum yield benefits due to soil amendments were generally higher in Burkina Faso compared to Mali (Figure 7), and this could be attributed to the generally higher soil fertility (e.g. total C and N) observed in the Burkina Faso soil profile data used in the simulation. All simulated areas in these two countries were classified as high to very high agrosylvopastoral suitability zones. In Saria, yield variability was similar under the 700 mm and 800 mm isohyets, with the majority of yield benefits observed under the 600 mm isohyet, particularly from soil amendments that included organic resources combined with mineral fertilizers. In the drier Yilou area, yield variability under the different soil amendment treatments was more pronounced than in Saria. Simulated grain yield benefits from Guiera treatments under 500 mm isohyet in the northern part of Burkina Faso showed greater benefit than the other simulated locations in Burkina Faso. While

the yield benefits from the incorporation of *Guiera senegalensis* residues were greater under the 500 mm isohyet compared to the 600 mm isohyet in Yilou, the benefits from farmyard manure amendments were comparable in both conditions.

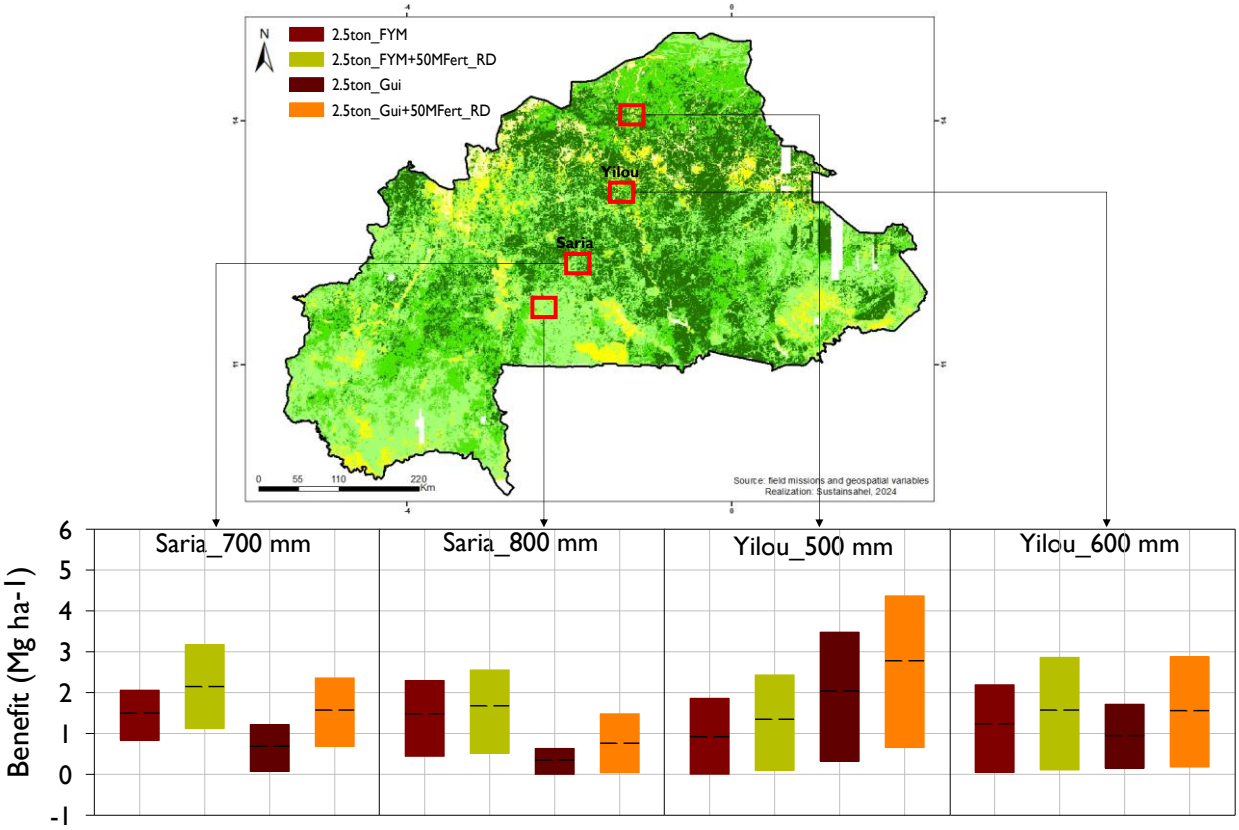


Figure 7. Map showing grain yield benefits of amendments of farm yard manure (FYM), Guiera senegalensis residues with or without 50% of recommended dose (RD) mineral fertilizer for Sorghum in Burkina Faso simulated under varying isohyets. The dashed horizontal line in the box plot's middle indicates the mean of the six years of simulations from 2018 to 2023. Treatments: 2.5ton_FYM: 2.5 t ha^{-1} cow dung manure; 2.5ton_FYM + 50MFert_RD: 2.5 t ha^{-1} cow dung manure plus half of the mineral fertilizer RD; 2.5ton_Gui: 2.5 t ha^{-1} *Guiera senegalensis residue*; 2.5ton_Gui + 50MFert_RD: 2.5 t ha^{-1} *Guiera senegalensis residue* plus half of the mineral fertilizer RD.

4.1.4 Pruned aboveground biomass of Guiera senegalensis under varying isohyets

Figure 8 illustrates the produced pruned aboveground biomass (AGB) of *Guiera senegalensis* in response to different planting densities and rainfall levels. At a planting density of 500 shrubs ha^{-1}, twice pruning a year yielded around 0.8-1.3 Mg ha^{-1} of AGB across tested sites. Increasing the planting density to 1000 shrubs ha^{-1} provided up to 2.3 Mg ha^{-1} pruning material, although this pattern was not consistent across all study locations. AGB showed less variability and remained more consistent under 500 shrubs ha^{-1} across the three countries, regardless of the isohyet, compared to 1000 shrubs per hectare. At the higher planting density (1000 shrubs ha^{-1}), pruned AGB was generally greater under lower isohyets than higher ones at Niakhar and Ouarkhokh. The soils used for this simulation in Niakhar and Ouarkhokh regions

were sandy, and under higher isohyets, more rainfall can lead to nutrient leaching, resulting in increasing nutrient limitations and potentially limiting biomass production at higher planting densities due to increased demand than the lower density. In Koussanar, pruned AGB levels were similar at both sites, though variability was higher under the higher isohyet. A similar trend was observed in Saria, but with less variability at 1000 shrubs ha^{-1}. In Koulikoro, simulated AGB production at 1000 shrubs ha^{-1} was significantly higher in the lower rainfall area (600 mm isohyet) than at the 700 mm isohyet, while in Sikasso, AGB levels were similar under the 800 mm and 1000 mm isohyets. It can be deduced from the simulation output that the AGB production of *Guiera senegalensis* was not directly related to the suitability mapping. Following the order of increasing isohyets, where a majority of the CSL systems were suitable, the AGB of *Guiera senegalensis* in most cases showed a contradictory pattern. This may be due to several reasons related to planting density and competition, water use efficiency and root adaptations, management practices, e.g. pruning, etc. Thus, higher planting densities may lead to increased competition for water and nutrients, affecting biomass production. Whereas, in lower isohyets, shrubs may allocate resources efficiently, leading to higher AGB per plant, while in wetter areas, competition might reduce individual plant biomass. *Guiera senegalensis* has a deep-root system that allows it to extract water from lower soil layers, making it less dependent on surface rainfall than shallow-rooted species. This adaptation helps maintain biomass production even in drier (low isohyets) conditions. Pruning management practices can significantly influence AGB production. Depending on the frequency of pruning (twice per year in this simulation), biomass accumulation may be limited even in high isohyet areas.

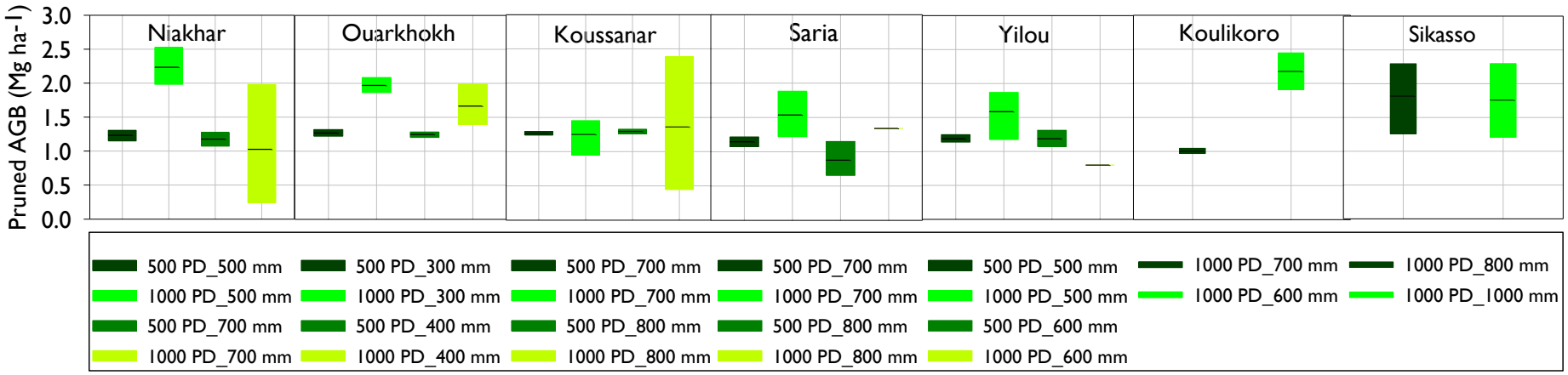


Figure 8. Simulated pruned AGB at two densities (500 and 1000 shrubs ha^{-1}) of *Guiera senegalensis* under varying isohyets. The shrubs were pruned twice in a year. The dashed horizontal line in the box plot's middle indicates the mean of the total pruned AGB over six years (2018-2023)

4.1.5 Yield benefits of cereals intercropped with Guiera senegalensis under varying isohyets

Figure 9 illustrates the grain yield benefits of intercropping millet (in Senegal) and sorghum (in Mali and Burkina Faso) with *Guiera senegalensis,* incorporating pruned residues, compared to sole cereal cultivation without soil amendments across different isohyets. Yield benefits were evident in all study regions across the three countries, but relationships to isohyets were. Intercropping Guiera (1000 shrubs ha^{-1}) and millet in Senegal provided highest crop yield benefits (around 0.4 Mg ha^{-1}) in Niakhar under the 500 mm isohyet, associated with the highest pruning yield (Figure 8) at this site. Simulated yield benefits for intercropped sorghum were higher in Burkina Faso compared to Mali, despite the higher pruning yield obtained in Koulikoro and Sikasso. This points to potential resource competition under increased shrub growth and necessitates further improvements in shrub management to balance facilitation and competition at these sites.

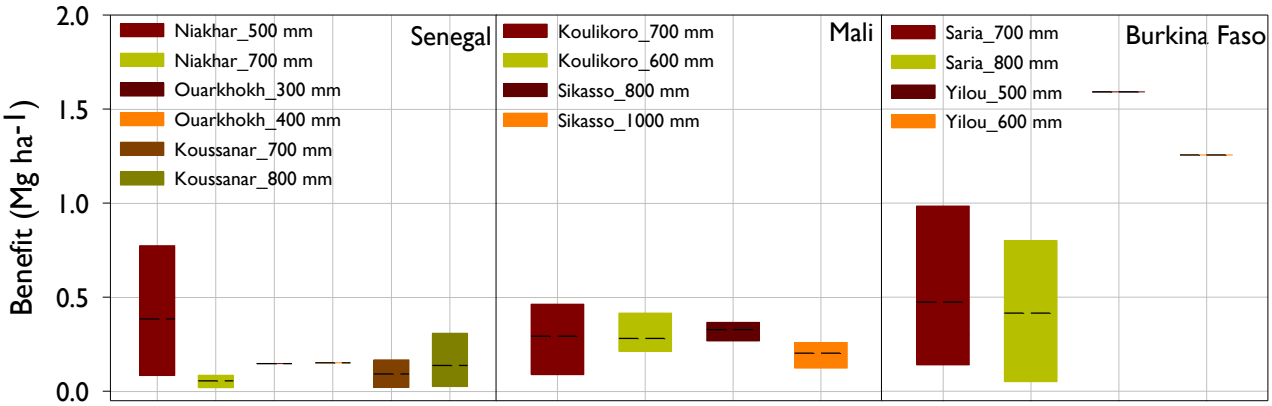


Figure 9. Yield benefit of Millet (Senegal) and (Sorghum) intercropped with Guiera senegalensis (1000 shrubs ha^{-1}) under varying isohyets. The dashed horizontal line in the box plot's middle indicates the mean of the six years of simulations from 2018 to 2023.

4.1.6 Yield benefits of cereals intercropped with Faidherbia albida under varying isohyets

Intercropping cereals with the tree *Faidherbia albida*, which has an inverse phenology, at the commonly found low planting density of 7 trees ha^{-1} resulted in positive yield gains (compared to monocrop) across all sites even without mineral fertilizer application. Simulated millet benefits in Senegal were up to about 0.4 Mg ha^{-1}, while sorghum yield improvements of up to 1.2 Mg ha^{-1} were obtained under the 600 mm isohyet in Yilou, Burkina Faso. However, the yield benefits of cereals intercropped with *Faidherbia albida* varied across different isohyets in the study regions. Specifically, higher yield benefits were observed in areas with higher isohyets compared to lower isohyets in Yilou, Saria, Sikasso, and Koussanar (Figure 10). In other areas where contradictory results were revealed (e.g. Niakhar and Ouarkhokh), this could be explained by reduced water stress in higher isohyets. Thus, in higher isohyets, water availability is already sufficient, so the additional benefits of intercropping may be less pronounced or even negligible. Whereas, in lower isohyets, the presence of *Faidherbia albida* helps improve soil moisture retention, which significantly benefits cereal crops. Additionally, increased competition for nutrients and water could also lead to this scenario. Thus, in higher isohyets, more rainfall supports greater vegetative growth of both cereals and *Faidherbia albida.* However, this can lead to higher competition for nutrients, reducing the

relative benefits of intercropping. In lower isohyets, *Faidherbia albida* can enhance soil fertility and moisture retention, leading to greater yield benefits for cereals compared to sole cropping.

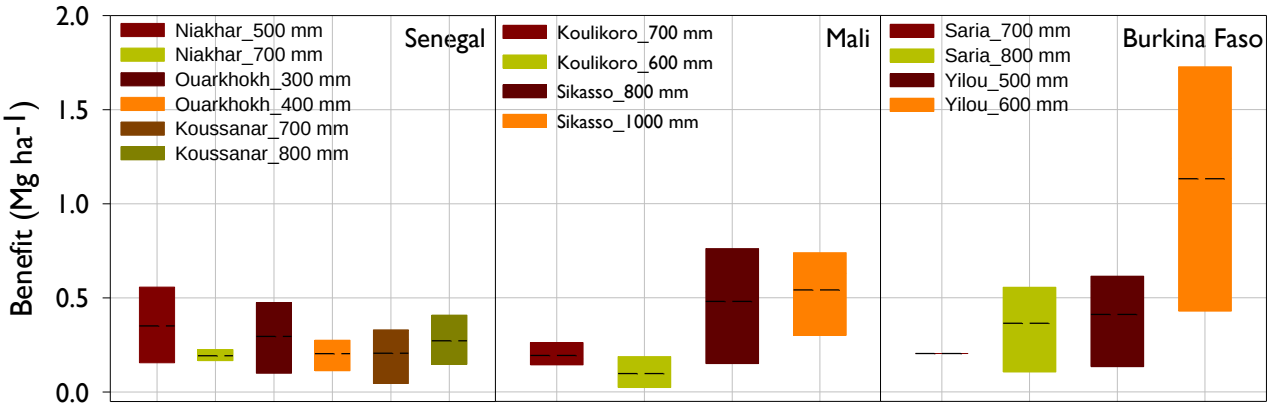


Figure 10. Yield benefit of millet (Senegal) and sorghum (Mali, Burkina Faso) intercropped with *Faidherbia albida* (7 trees ha^{-1}) under varying isohyets. The dashed horizontal line in the box plot's middle indicates the mean of the six years of simulations from 2018 to 2023.

5. CONCLUSION

This deliverable builds on previous efforts to characterise the landscape and propose a mapping of the suitability of Crop, Shrub, and Livestock (CSL) systems across SustainSahel sites in Senegal, Mali, and Burkina Faso. Through comprehensive mapping of agro-environmental variables and land use, this study has provided valuable insights into the environmental diversity and potential for CSL systems across these regions. The study highlighted the importance of accurate land use classification and the calibration of crops and tree species for effective land use change modelling. The application of the Random Forest algorithm to model the suitability of CSL systems across the three countries resulted in a detailed suitability map. This map identifies western Senegal, central Mali, and northern Burkina Faso as the most favorable regions for agrosylvopastoralism, providing critical guidance for future land management and agricultural practices in these areas. The simulated yield benefits with the application of organic resources from CSL systems using the LUCIA model largely agree with the findings of the CSL suitability mapping. Thus, in Senegal, higher yield benefits were observed in Niakhar in the western part compared to the northern zone around Ouarkhokh and Koussanar in the southern zone. Similarly, in Mali, higher yield benefits were observed in the central part around Koulikoro than in the southern part of Sikasso. Yield benefits were more pronounced in Yilou in the northern part of Burkina Faso than Saria in the southern part. The results also reveal that although higher yield benefits (1.2-2.5 Mg ha^{-1}) were observed under high rainfall amounts, the contrary was also observed in some areas, suggesting that rainfall may not be the only influencing factor in drylands. Other factors such as soil fertility, low nutrient availability, especially nitrogen and phosphorus, limit crop growth. While crop management practices, e.g. mulching, may reduce evaporation and improve soil moisture retention, climate, e.g. high temperatures can accelerate evapotranspiration, reducing soil moisture and stressing plants, etc. A combination of organic and mineral fertilizer resources generally ensured higher yield benefits even under zones with a low isohyet. The results further revealed that pruned residues of CLS systems like *Guiera senegalensis* in part can substitute for scarce farmyard manure resources and in combination with mineral fertilizer can reduce the need for expensive external inputs. Aboveground biomass (AGB) production can support animal nutrition and enhance soil fertility by incorporating pruned residues. In areas with 500 shrubs per hectare, pruned AGB (0.8-1.3 Mg ha^{-1}) showed less variability and remained consistent across different isohyets in the three studied countries compared to 1000 shrubs ha^{-1}. At the higher planting density (1000 shrubs ha^{-1}), pruned AGB was generally greater in regions with lower isohyets than in those with higher isohyets, except for a few locations. Overall, pruned AGB production increased with higher planting densities of *Guiera senegalensis* up to 2.3 Mg ha^{-1}. Intercropping cereals with Guiera senegalensis led to yield improvements across all study regions, with greater benefits observed in lower isohyets, particularly in Saria and Yilou, Burkina Faso. Some of the intercropping results with *Guiera senegalensis* point to potential resource competition with crops under increased shrub growth necessitating further improvements in shrub management to balance facilitation and competition at these sites. Similarly, intercropping *Faidherbia albida* with cereals resulted in higher yields compared to sole cereal cultivation without soil amendments. However, in most study areas, the yield benefits of *Faidherbia albida* intercropping were more pronounced in higher isohyets than in lower isohyets.

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