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Re-greening the Sahel? Evaluating tree cover restoration strategies in Niger

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ABSTRACT

In the Sahel, land degradation caused by climate variability and unsustainable human activities has led to soil erosion, declining fertility, and worsening food insecurity. To address this, large-scale restoration initiatives incorporating soil and water conservation (SWC) techniques and drought-resistant tree species have been implemented. This study evaluated the growth of 1564 trees from six species (*Acacia nilotica*, *Acacia raddiana*, *Senegalia senegal*, *Vachellia seyal*, *Bauhinia rufescens*, and *Ziziphus mauritiana*) on rehabilitated lands, using a Bayesian growth model to assess the effects of SWC structures, management practices, and geomorphological conditions. Among the SWC techniques studied—half-moons, trenches, bench terraces, stone bunds, and trench-bund combinations—half-moons proved most effective in enhancing tree growth (+12 %). Pediments provided the best conditions for tree development, outperforming plateaus and slopes. The absence of site management (guarding, replanting, and maintenance of plants and structures) decreased growth (−9 %). Sustainable reforestation in the Sahel requires integrating scientific knowledge with local expertise, adaptive strategies, and community involvement. A holistic approach that prioritizes effective SWC structures, suitable planting sites, and continuous management is crucial for restoring degraded lands, strengthening ecosystem resilience, and ensuring long-term success.

1. Introduction

In the Sahel, land degradation is increasingly driven by the combined effects of climate variability and unsustainable human activities (Abdou et al., 2021b; Manzo et al., 2009). Fragile climatic conditions, population growth, and poor soil fertility hinder the balance between natural resource use and their regeneration, accelerating desertification and land degradation (Ousmane et al., 2020). This degradation weakens soils, reduces productivity, and exposes many populations to food insecurity and poverty (Kagambèga et al., 2017; Abdou et al., 2021b). In Niger, as in other parts of the Sahel, pressure on productive lands is increasing due to rapid population growth (Jayne et al., 2014). Approximately 9 % of Niger's agro-silvo-pastoral lands are degraded, and over 100,000 ha of cultivable land are lost annually (Moussa et al., 2016; CNEDD, 2019). This degradation affects ecosystems, the economy, and local populations. Ecologically, it manifests through soil exposure and compaction, which exacerbate erosion, reduce fertility, and lead to the loss of plant species and their natural regeneration capacity (Bayen et al., 2016; Ousmane et al., 2020). Economically, land

degradation causes substantial losses, estimated at US \$3.535 billion in 2015, equivalent to 19 % of Niger's GDP (Nkonya et al., 2018). Socially, it results in declining household incomes, persistent food insecurity, rural outmigration, and land-use conflicts (Ousmane et al., 2020). For a country like Niger, where the economy and livelihoods heavily depend on agro-silvo-pastoral production, reversing land degradation trends is critical to restoring soil productivity and improving the well-being of its population.

Many Sahelian countries have committed to initiatives such as the Great Green Wall (GGW), AFRI100, and the Bonn Challenge to restore millions of hectares of ecosystems by 2030 through sustainable land management (SLM) practices (CNEDD, 2019; UNCCD, 2020). During COP15 on desertification, Niger and other countries increased their ambitions, pledging to restore 100 million hectares of degraded land, sequester 250 million tons of carbon, and create 10 million green jobs by 2030 (UNCCD, 2022). The Nigerien government set specific goals, including achieving land degradation neutrality (LDN), reducing degraded land from 9 % to 5 %, and increasing vegetation cover from 17 % to 19 % to sustainably improve the living conditions of its population

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(Abdou et al., 2019). To meet these targets, various land restoration activities have been implemented, including mechanical soil and water conservation (SWC) techniques—that is, physical interventions involving the use of manual tools such as pickaxes and shovels to reshape and improve soil structure—such as half-moons, bunds, stone lines, trenches, and zaï pits (Ousmane et al., 2020; Abdou et al., 2022). These measures aim to control erosion, harvest surface runoff, enhance soil moisture, and restore soil fertility. Their effectiveness has been demonstrated in several regions of Niger (Nassirou et al., 2021). The plant species used in these restoration efforts include *Vachellia seyal*, *Senegalia senegal*, *Acacia raddiana*, *Acacia nilotica*, *Bauhinia rufescens*, and *Ziziphus mauritiana*. These species were selected for their ecological and socio-economic importance. Adapted to the Sahelian and Sudano-Sahelian zones, they are drought-resistant and can grow in poor, rocky, or clay soils (Cornet and Diem, 1982). They provide multiple benefits to local populations. Leaves and pods serve as fodder for livestock, while seeds, gums, and fruits are consumed by humans. Many parts of these species such as roots, bark, leaves, and fruits are used in traditional medicine. Their wood is utilized for construction, tool-making, and is a primary source of domestic energy (Benbrahim et al., 2014). Ecologically, these species contribute to preventing soil erosion, maintaining and restoring soil fertility, and improving the microclimate (Dupuy et al., 1991; Benbrahim et al., 2014). While they may help reduce evaporation from exposed soil surfaces, they can also lead to increased water loss through transpiration.

For tree species to effectively fulfill their ecological and socio-economic functions, they must be suited to the specific conditions of the sites where they are planted (Gebrehiwot et al., 2005). It is therefore essential to study how these species behave in their environments in order to identify those that perform best and ensure sustainable productivity. According to (Olukoye et al., 2003), one of the most important criteria for assessing the suitability of species for restoration is their diameter growth. This growth is indicative of the species' adaptation to local conditions and provides insight into tree health, their potential for wood and non-timber forest product (NTFP) production, as well as the fertility of the soil (Abdou et al., 2021b). The growth and productivity of trees are influenced by environmental factors such as water, nutrients, light, and temperature, as well as the physiological traits of the species themselves (Sagar et al., 2012). SWC structures are primarily designed to harvest runoff water, and in doing so, they also accumulate mineral and organic materials in the catchment areas. This process enhances water availability, nutrient access, and soil fertility, thereby supporting the establishment and growth of trees. These structures are tailored to the geomorphological units of the restoration sites, which influence the soil's water and nutrient content (Habou et al., 2017). For sustainable management of restored sites, it is crucial not only to understand the growth performance of species but also to assess how the types of structures, geomorphological units, and management practices affect tree growth. Evaluating the growth of a forest stand, which consists of multiple species of varying ages and sizes, requires the use of growth models. Growth modeling plays an essential role in understanding, predicting, and optimizing ecosystem dynamics (Héroult and Paponot, 2018). It enables the prediction of future growth, the assessment of ecosystem services (such as wood productivity, biomass, fruits, and other derivatives), the analysis of factors influencing growth, the identification of species best suited to local conditions, and the development of optimal management practices to maximize tree productivity (Héroult et al., 2020).

In Niger, several studies have been conducted on restored sites and SWC techniques (Douma et al., 2011; Alzouma et al., 2019; Ousmane et al., 2020; Abdou et al., 2021a, 2021b, 2022; Coulibaly et al., 2022). However, to date, no study has thoroughly modeled the growth performance of planted tree species, despite this being a critical parameter for evaluating the success of restoration and the sustainable management of restored sites. The aim of this study is to address this gap by analyzing the growth performance of six tree species used for the

restoration of degraded lands through Bayesian modeling. This analysis will also estimate the impact of SWC structures, management practices, and geomorphological features on tree growth. To achieve this, we will seek to answer the following questions:

- (i) What is the growth performance of the six species after 20 years of planting?

It is hypothesized that species will exhibit varying growth performances after 15 years. Species that are more drought-tolerant and better adapted to poor soils, such as *Acacia raddiana* and *Ziziphus mauritiana*, are expected to show superior growth due to their physiological adaptations to Sahelian environmental conditions.

- (ii) What is the impact of soil conservation structures, management practices, and geomorphology on tree growth?

It is further hypothesized that tree growth is positively influenced by the presence of soil and water conservation structures, particularly half-moons and trenches, which are known to be especially effective in capturing runoff and concentrating moisture and nutrients around the root zone. In addition, effective site management (e.g., exclusion of livestock grazing) and favorable geomorphological positions (e.g., lowlands or areas of sediment accumulation) are expected to enhance overall tree development.

2. Materials and methods

2.1. Study area

This study was conducted in two villages of the Illèla municipality—Guidan Karo and Nadara II—located between latitudes 14°22'00" and 14°28'60" N, and longitudes 15°16'60" and 15°19'00" E (Fig. 1). Illèla is part of the Illèla department, situated in the southern part of the Tahoua region in Niger, covering an area of approximately 2700 km² (PDC, 2015). The region experiences a semi-arid, Sahelo-Saharan climate. Over the past 30 years (1994–2024), annual rainfall has ranged from 300 to 1020 mm, with an average of 478 mm. The average annual temperature is around 28.5 °C, with peaks reaching up to 44 °C during the dry season (<https://power.larc.nasa.gov/data-access-viewer/>). The soils in the municipality are classified into five types: glaci soils ("Foko"), plateau soils ("Dabagui"), incised valley plateau soils ("Fadama"), sandy soils ("Faska"), and lowland soils (PDC, 2015). The population of Illèla is estimated at 142,214 inhabitants (INS, 2013), with agriculture and livestock as the main economic activities. These activities are practiced by more than 90 % of the population and represent their primary source of income (Garba et al., 2017). Agricultural production is based mainly on traditional long-cycle seeds, which are increasingly challenged by current climatic variability. The main staple crops include millet, sorghum, and maize, while cowpea and groundnut are grown as cash crops (DDE, 2018). Livestock rearing, the second major economic activity, is practiced in three main forms: sedentary livestock, transhumance, and fattening systems. The animals raised include cattle, sheep, goats, camels, horses, donkeys, and poultry.

2.2. Sampling strategy

The Tahoua region is a key area for land restoration, where several techniques have been tested and promoted, particularly in the villages of Guidan Karo and Nadara II within the Illèla municipality. With support from the government and various NGOs, these villages have carried out significant land restoration activities, rehabilitating hundreds of hectares of degraded land. The study was conducted on restored sites that incorporate SWC structures and tree plantations. All of the sites studied are governed by regulations, including a ban on wood cutting and grazing, and have been protected for a period of five years. However, the

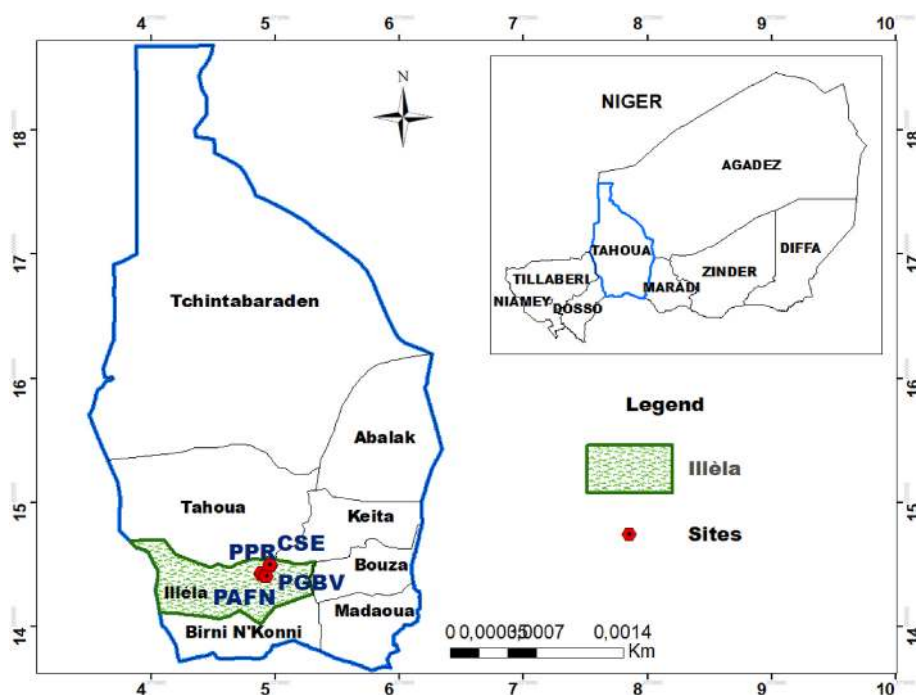


Fig. 1. – Study area and data collection sites in the municipality of Illèla.

sites differ in terms of monitoring (guarding) and maintenance (such as structure upkeep, plantation care, and replenishment). These practices, which often require financial support from projects, serve as important differentiating factors between the sites. Two types of sites were selected for this study: sites without project support, where neither monitoring nor maintenance is conducted, and sites with project support, where these practices are actively implemented. In total, nine sites were chosen, with six located in Guidan Karo and three in Nadara II (Table 1). Of these, seven sites are managed (with monitoring and maintenance), while two sites lack management (without monitoring or maintenance). Five SWC structures were studied (half-moon, bench terrace, stone bunds, trenches, and bunds + trenches). The objective of these structures is to promote the establishment of woody vegetation cover and

forage production through tree planting and herbaceous seeding (details in Table 2 and representative pictures in Appendix 1).

Between February and March 2023, a comprehensive inventory of planted species was conducted across nine identified sites. The vegetative material studied included all species planted within these sites, totalling six species: *Vachellia seyal*, *Senegalia senegal*, *Acacia nilotica*, *Acacia raddiana*, *Bauhinia rufescens*, and *Ziziphus mauritiana*. These species belong to two families, Fabaceae and Rhamnaceae (Table 3). A total of 44 plots, each measuring 2000 m² (100 m × 20 m), were inventoried. For each site, five plots were surveyed, except for the CSE site, where only four plots were established. The plots were positioned along two parallel transects oriented either East-West or North-South, depending on the topographic sequence and site accessibility. During the inventory,

Table 1

Description of the sampled sites (Name of the village, Name of the site, Planting year, number and size of plots, Soil and Water Conservation structures, Details on management, Type of geomorphology unit, list of planted species + number of individual trees).

Village	Site Name	Start	Area (ha)	Number of plots (size of plots)	SWC structures	Management Details	Geomorphology	Species planted (number of trees)
Guidan karo	PPR	2019	100	5 (2000m ²)	Half-Moon	Guarding, replanting, and maintenance of plants and structures	Glacis	<i>Acacia nilotica</i> (2) <i>Acacia raddiana</i> (10) <i>Bauhinia rufescens</i> (24) <i>Senegalia Senegal</i> (1) <i>Vachellia seyal</i> (131) <i>Ziziphus mauritiana</i> (18)
Guidan karo	PASEC	2018	150	5 (2000m ²)	Half-Moon	Guarding, replanting, and maintenance of plants and structures	Glacis	<i>Acacia nilotica</i> (11) <i>Acacia raddiana</i> (28) <i>Senegalia Senegal</i> (2) <i>Vachellia seyal</i> (200) <i>Ziziphus mauritiana</i> (3)
Guidan karo	PAC 3	2014	100	5 (2000m ²)	Bench Terrace	Guarding, replanting, and maintenance of plants and structures	Glacis	<i>Acacia raddiana</i> (29) <i>Bauhinia rufescens</i> (9) <i>Senegalia Senegal</i> (4) <i>Vachellia seyal</i> (78) <i>Ziziphus mauritiana</i> (8)
Guidan karo	PAFN	2003	60	5 (2000m ²)	Stone Bund	Guarding, replanting, and maintenance of plants and structures	Glacis	<i>Acacia raddiana</i> (6) <i>Senegalia senegal</i> (26) <i>Vachellia seyal</i> (134) <i>Ziziphus mauritiana</i> (5)
Guidan karo	Zaresse	2010	200	5 (2000m ²)	Half-Moon	/	Glacis	<i>Acacia raddiana</i> (38) <i>Senegalia senegal</i> (1) <i>Vachellia seyal</i> (26)
Guidan karo	Croix-rouge	2012	90	5 (2000m ²)	Bench Terrace	/	Glacis	<i>Acacia raddiana</i> (10) <i>Bauhinia rufescens</i> (1) <i>Vachellia seyal</i> (14)
Nadara II	CSE	2014	8	4 (2000m ²)	Trench	Guarding	Hillside	<i>Acacia raddiana</i> (48) <i>Senegalia senegal</i> (6) <i>Vachellia seyal</i> (175) <i>Ziziphus mauritiana</i> (1)
Nadara II	Nazari	2014	20	5 (2000m ²)	Trench + Bund	Guarding	Hillside	<i>Acacia raddiana</i> (1) <i>Senegalia Senegal</i> (70) <i>Vachellia seyal</i> (184) <i>Ziziphus mauritiana</i> (2)
Nadara II	PGBV	2015	/	5 (2000m ²)	Stone Bund	Guarding	Plateau	<i>Acacia raddiana</i> (20) <i>Senegalia senegal</i> (212) <i>Vachellia seyal</i> (8) <i>Ziziphus mauritiana</i> (2)

Table 2
Description of the sampled SWC structures.

Name	Shape	Length (m)	Width (m)	Depth (cm)	Spacing between SWC structures (m)	Spacing between lines of SWC structures (m)	Number of SWC structures per ha	Number of trees per ha	Spacing between trees (m)
Half-Moon	Half circle	4		30 to 40	4		312	312	8
Bench	Small dike equipped with two wings and a basin	60	10	40	10	25 to 30	5 or 6	80 to 96	5
Terrace	Alignment of rubble stones following the elevation lines	50	0.5		5	25 to 50	200 to 400 line meters	40 to 80	5
Stone Bund	Excavation equipped with two basins and a planting hole in the center	3	60	60	1	3	833	833	4 and 3
Trench									

the following data were collected: diameter at breast height (DBH, measured at 130 cm above ground), diameter at 20 cm above ground (Db), species names, type of CSW structure, geomorphological unit of the site, and geographic coordinates of each plot. Geomorphology was recorded and coded for each site as follows: Slope = 1, Plateau = 2, and Pediment = 3.

2.3. Analysis strategy

To analyse the growth of species under varying environmental and management conditions, we employed a Bayesian hierarchical model implemented in Stan (Carpenter et al., 2017). The model integrates multiple sources of variability and assesses the influence of species identity, restoration structures, management practices, geomorphological features, and other site-specific characteristics on growth. The diameter ($Diam_{i,sp}$) for each observation i of species sp is modeled using a log-normal distribution:

$$Diam_{i,sp} \sim LN(\log(\mu_{i,sp}, \sigma))$$

where $\mu_{i,sp}$ represents the expected diameter for tree i of species sp , and σ is the residual standard deviation, capturing unobserved variability.

Given that the evolution of young tree diameter over time is well approximated by a power law (Hérault et al., 2011) because growth rates scale with the tree's size, following geometric and metabolic constraints (Volkov et al., 2022), the expected diameter ($\mu_{i,sp}$) is expressed as a function of time t with:

$$\mu_{i,sp} = \theta_G \cdot \theta_P \cdot \theta_W \cdot \theta_M \cdot \theta_{POM} \cdot t_i^{\theta_{sp}}$$

Here, the components represent:

- θ_G : Effect of geomorphology.
- θ_P : Effect of the specific plot.
- θ_W : Effect of restoration structures.
- θ_M : Effect of management practices.
- θ_{POM} : Effect of the point of measurement (e.g., 130 or 20).
- θ_{sp} : Growth rate exponent specific to species.

with

$$\theta_{sp} \sim LN(\log(\mu_{sp}), \sigma_{sp})$$

where μ_{sp} is the average growth parameter across species, and σ_{sp} is the across species standard deviation and

$$\theta_p \sim LN(\log(\mu_p), \sigma_p)$$

with μ_p representing the average plot effect and σ_p its variability.

For the other Effects ($\theta_W, \theta_M, \theta_G, \theta_{POM}$), each factor is modeled using log-normal laws:

$$\theta_X \sim LN(1, \sigma_X)$$

where σ_X captures variability in the effect for each factor X (e.g., structures, management, geomorphology, or point of measurement). In this framework, the posterior value of each effect indicates its effect on diameter growth. A value of 1 means no effect, values less than 1 indicate reduced growth, and values greater than 1 suggest enhanced growth. Thus, these parameters reflect the influence of factors such as structures, management, and geomorphology on growth. Due to the limited sample size (44 plots) and the unbalanced design, interaction terms between species, SWC structures, management practices, and geomorphological units were not included in the models to avoid overparameterization and ensure model stability. Only main effects were modeled.

Table 3

Descriptive Statistics of Tree Size and Age by Species (Scientific names, Botanical family, minimum and maximum age in months, minimum and maximum Diameter at Breast Height DBH in cm, minimum and maximum Diameter at basis Db in cm).

Scientific name	Family	Age_min (month)	Age_max (month)	DBH_min (cm)	DBH_max (cm)	Db_min (cm)	Db_max (cm)
<i>Vachellia seyal</i> (Delile) P.Hurter	Fabaceae	55	247	10	120	8	121
<i>Acacia nilotica</i> (L.) Willd. Ex Delile	Fabaceae	55	67	/	/	17	94
<i>Acacia raddiana</i> Savi	Fabaceae	55	247	22	85	12	106
<i>Bauhinia rufescens</i> Lam.	Fabaceae	55	139	13	35	11	61
<i>Senegalia senegal</i> (L.) Britton	Fabaceae	55	247	17	40	10	130
<i>Ziziphus mauritiana</i> Lam.	Rhamnaceae	55	247	11	20	10	85

Lognormal laws were systematically used for inference because they ensured that both parameters and predictions are defined on R^+ . Posterior distributions of all parameters were estimated via Hamiltonian Monte Carlo (HMC), ensuring convergence and robust inference. Model codes are provided in [Appendix 2](#).

3. Results

The six studied species belong predominantly to the Fabaceae family, with the exception of *Ziziphus mauritiana* from the Rhamnaceae. Ages range from a minimum of 55 months to a maximum of 247 months across species ([Table 2](#)). Diameter values vary substantially: DBH ranges from 10 cm (*Vachellia seyal*) to 120 cm, with the highest maximum observed in the same species. *Acacia raddiana* and *Senegalia senegal* also show high maximum DBH values (85 cm and 40 cm, respectively), while *Ziziphus mauritiana* and *Bauhinia rufescens* remain below 35 cm. Basal diameter (Db) values show similar variability, with maximums ranging from 61 cm in *Bauhinia rufescens* to 130 cm in *Senegalia senegal*.

The parameterized growth model yielded the following results, with a coefficient of determination $R^2 = 0.34$, indicating that 34 % of the variance is explained.

At fifteen years, the diametric growth of the six planted species ranges between 8.84 and 13.27 cm ([Fig. 2](#)). Hypothesis 1 is not validated as among the studied species, two stand out from the group: *Bauhinia rufescens* and *Ziziphus mauritiana*. These two species are the least productive, with slower growth at 15 years, averaging 10.2 ± 1.7 cm and 9.0 ± 1.6 cm, respectively. The other species—*Vachellia seyal*, *Senegalia senegal*, *Acacia nilotica*, and *Acacia raddiana*—demonstrate faster growth,

averaging above 10.8 cm. Among all the studied species, *Acacia nilotica* is the most productive, with a growth of 12.6 ± 2.3 cm at 15 years.

The effects θ_w of the five SWC structures (half-moons, stone bunds, trenches, bench terraces, and bunds + trenches) were evaluated on the growth of six planted species ([Fig. 3](#)). Based on their impacts, the SWC structures can be classified into two categories. First, some structures promote an increase in the diametric growth of the studied species ($\theta_w > 1$). This group includes half-moons ($\theta_{w=hm} = 1.12$), trenches ($\theta_{w=tr} = 1.04$), and bench terraces ($\theta_{w=bt} = 1.03$). Among these, half-moons stand out by significantly enhancing growth (Hypothesis 2 validated), with an effect greater than that of trenches and bench terraces. The distribution of values for half-moons is highly significantly different from 1 ($P_{value} < 0.001$). Trenches and bench terraces exhibit similar positive effects, contributing comparably to the growth of the six woody species. Second, some SWC structures lead to a reduction in the growth of the studied species ($\theta_w < 1$). This group includes stone bunds ($\theta_{w=sb} = 0.91$) and bunds + trenches ($\theta_{w=bt} = 0.88$).

The effect of management (monitoring and maintenance) on the growth of planted species (θ_M) was assessed ([Fig. 4](#)), with the estimated effect of no management being $\theta_{M=0} = 0.91$. This result indicates that the absence of management is associated with reduced growth of planted species (Hypothesis 2 validated).

The effect of the three geomorphological units (pediment, slope, and plateau) (θ_G) was evaluated ([Fig. 5](#)). The results reveal a difference in impact among these units. The pediment, with an effect greater than 1 ($\theta_{G=Ped} = 1.08$), promotes an increase in growth (Hypothesis 2

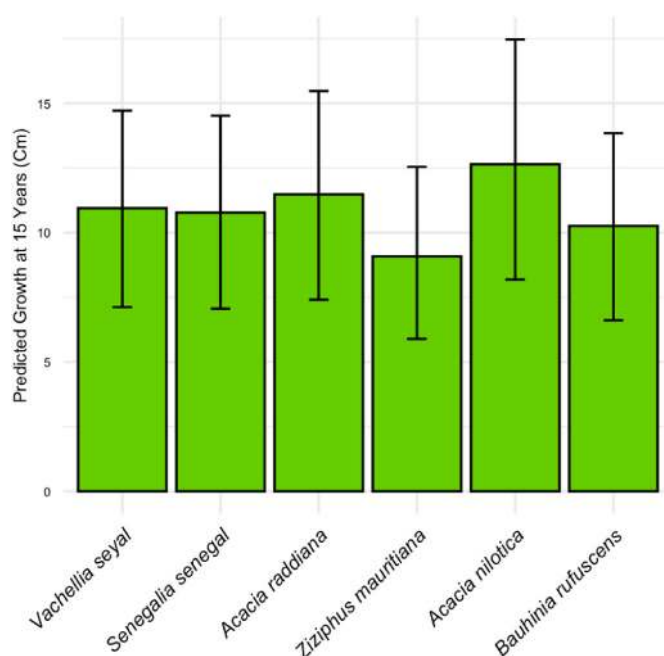


Fig. 2. – Diameter Growth of the 6 planted species at 15 years.

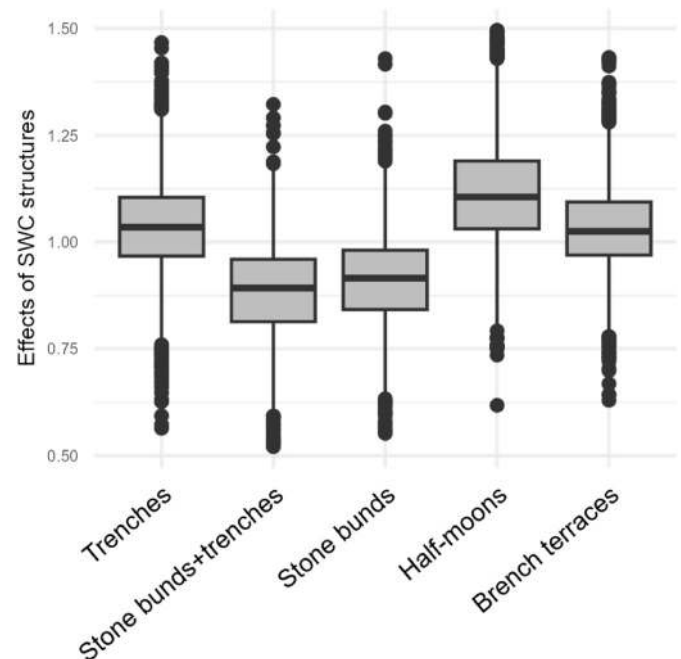


Fig. 3. – Effects of the five studied SWC structures on tree growth: A value of 1 indicates no effect, values below 1 signify reduced growth, and values above 1 represent enhanced growth.

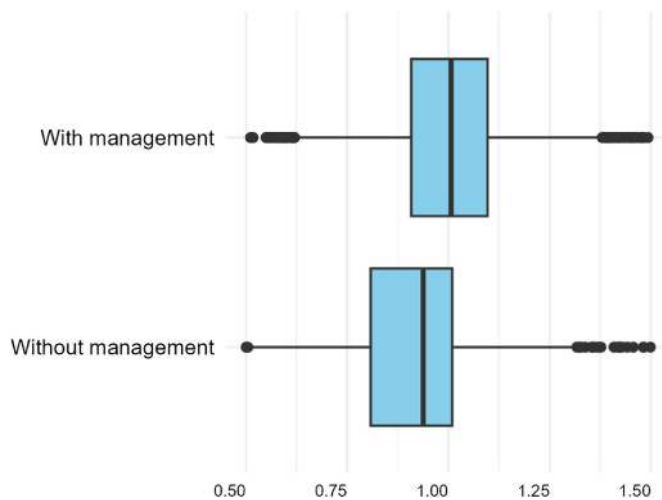


Fig. 4. – Effects of site management on tree growth: A value of 1 indicates no effect, values below 1 signify reduced growth, and values above 1 represent enhanced growth.

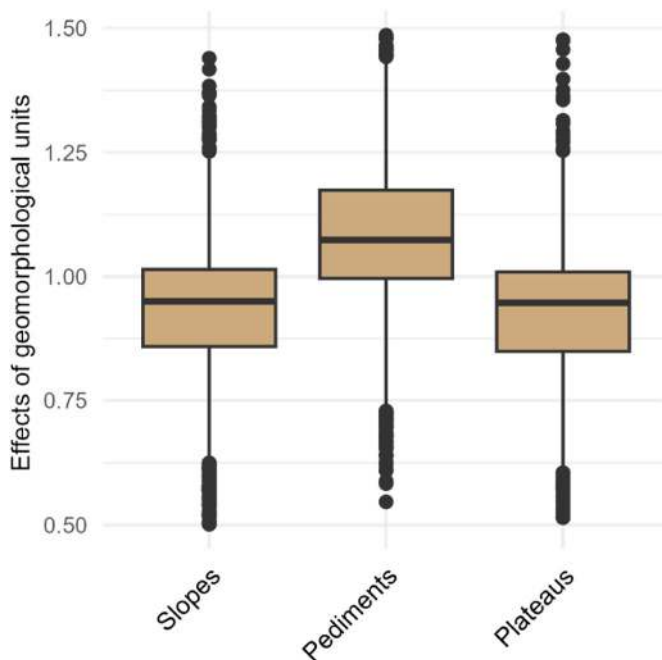


Fig. 5. – Effects of geomorphology on tree growth: A value of 1 indicates no effect, values below 1 signify reduced growth, and values above 1 represent enhanced growth.

validated). In contrast, the plateau and slope exhibit similar effects, both below 1 ($\theta_{G=Plat} = \theta_{G=Slo} = 0,93$) leading to a reduction in tree growth.

4. Discussion

4.1. Top trees for tree cover restoration in the Sahel

Growth is a key indicator for evaluating the success of afforestation projects (Héroult et al., 2020) and assessing species' adaptation to environmental conditions (Kagambega et al., 2011; Abdou et al., 2021b). Acacias (firstly *Acacia nilotica* then *Acacia raddiana*, *Senegalia senegal*, *Vachellia seyal*) demonstrated the highest growth and this aligns with observations in Niger and Cameroon, where *Acacia nilotica* was noted for its rapid growth and resilience to water stress, making it a

prime candidate for reforestation degraded lands (Manzo et al., 2009; Blaise et al., 2023). *Acacia raddiana* ranked second, and a similar growth hierarchy between *Acacia nilotica* and *Acacia raddiana* was observed in Burkina Faso (Blaise et al., 2023). However, studies from Tillabéry, Niger, indicated better growth for *Senegalia senegal* compared to *Vachellia seyal* (Douma et al., 2011), likely due to the more favorable water conditions in the Sudanian zone. These contrasting results highlight the critical role of water availability in shaping growth outcomes.

The superior performance of Acacias can be attributed to several adaptive traits. Acacias possess deep taproots and extensive lateral roots that allow them to access water from deeper soil layers, even under low rainfall conditions (Benbrahim et al., 2014). In addition, their ability to fix atmospheric nitrogen through symbiotic associations gives them an advantage in nutrient-poor soils (Cornet and Diem, 1982). Another factor that may contribute to their growth advantage is the potential role of ectomycorrhizal associations. Ectomycorrhiza can enhance nutrient and water uptake, particularly under stressful conditions, and have been reported in association with several Acacia species. These symbiotic relationships may further support their establishment and performance in degraded or arid environments (Bà et al., 2010). Together, these traits make acacias a preferred choice for reforestation and land restoration programs. In contrast, *Bauhinia rufescens* is classified as a slow-growing species (Manzo et al., 2009), although its growth can improve in wetter conditions, as observed in the Sudanian zone (Douma et al., 2011). Meanwhile, the limited growth of *Ziziphus mauritiana* can be attributed to its shallow rooting system, which restricts its ability to access water in arid environments (Logbo et al., 2013). Additionally, its rhythmic growth pattern—alternating active growth phases with dormancy—further constrains its rapid development (Boubacar et al., 2022).

In conclusion, the performance of the studied species is strongly influenced by their ability to access soil water and nutrients. Acacias stand out as the most suitable species for reforestation in the Sahel due to their resilience, adaptability, and efficient resource utilization. However, while the growth differences among species are significant, they remain relatively small in absolute terms, suggesting that all species can be used in mixed plantations. This approach would enhance ecosystem diversity and resilience, creating a more stable and adaptable reforestation strategy for the region (Héroult et al., 2020).

4.2. Pediments: optimal conditions for growth

Differences in geomorphology are associated with variations in soil water content and nutrient accessibility, both of which are critical for plant development (Habou et al., 2017).

Pediments are characterized by gentle slopes, deeper soils, and higher fertility compared to other geomorphological units (Dorlöchter-Sulser and Nill, 2012). The lower slope gradient reduces runoff velocity, thereby minimizing water erosion, which is typically more severe on steeper slopes. Studies have demonstrated that gentler slopes retain more soil moisture and nutrients, creating more fertile conditions than steep slopes (Scatena and Lugo, 1995). Additionally, the deeper soils of pediments enhance water infiltration, water storage, root penetration, and the activity of soil biota, further supporting plant development. The combined effect of these factors—improved water retention, reduced erosion, and higher fertility—makes pediments more favorable for vegetation growth compared to other geomorphological units.

In contrast, the tendency of plateaus and slopes to limit tree growth can be attributed to their shallow, rocky soils, which pose physical and nutritional barriers to root development (Vlaar, 1992; Dorlöchter-Sulser and Nill, 2012). Plateaus, in particular, are often characterized by hardened and compacted layers, low organic matter content, and poor water permeability, making them unsuitable for plant growth (Vlaar, 1992). These compacted soils restrict water infiltration and root expansion, resulting in limited access to essential nutrients. Slopes, with their steep gradients and exposed rocky surfaces, are prone to intense

runoff and significant soil erosion. This leads to further degradation, stripping the soil of nutrients and organic matter and creating harsh conditions for vegetation (Dorlöchter-Sulser and Nill, 2012; Vlaar, 1992). The combination of these factors makes slopes particularly challenging environments for the establishment and growth of plants.

4.3. Half-moons: the gold standard of SWC structures

Soil and Water Conservation (SWC) structures aim to mitigate surface runoff, enhance water infiltration, and increase soil moisture. These mechanisms are crucial for combating land degradation, supporting vegetation regeneration, and improving the fertility and physico-chemical properties of soils, especially in arid and semi-arid regions where water availability is a limiting factor. By stabilizing water dynamics and capturing sediment, SWC structures also promote ecosystem resilience and long-term soil productivity.

The crescent-shaped basins of half-moons are strategically designed to capture and store runoff while retaining nutrient-rich sediments, which enhance soil fertility (Bayen et al., 2016). These basins create favorable microenvironments with concentrated water and nutrients near plant roots, facilitating growth. Furthermore, the 8 × 8 m spacing of half-moons (312 trees/ha) minimizes competition for water, nutrients, and light, enabling trees to thrive under resource-limited conditions (Sagar et al., 2012). The superior performance of half-moons has been corroborated by previous studies. Kagambega et al. (2011) and Bayen et al. (2016) demonstrated that half-moons significantly improved the growth of species such as *Acacia raddiana* and *Acacia nilotica* in Burkina Faso. Their ability to optimize resource availability and create localized water retention zones makes them highly effective in arid environments where water stress is a primary constraint to growth.

Trenches and bench terraces are designed to retain water and maintain soil moisture for extended periods, often lasting up to a week after rainfall (Douma et al., 2011; Abdou et al., 2021b). However, certain design limitations reduce their effectiveness. Trenches, with their deeper basins, often allow water to seep beyond the reach of roots, particularly when installed on rocky soils. This reduces water availability and undermines their efficiency. Additionally, the high planting density in trench sites (833 trees/ha) increases inter- and intra-specific competition for resources such as water, nutrients, and light, potentially inhibiting growth. Bench terraces, while effective at reducing runoff and retaining moisture, can exacerbate waterlogging in soils with poor drainage, causing root asphyxiation. This may disrupt critical physiological processes such as root respiration, nutrient uptake, and photosynthesis, ultimately limiting plant development (Vlaar, 1992).

Unlike half-moons and terraces, stone bunds do not feature water basins. Their primary function is to reduce erosion and slow water flow across the landscape. However, plants at these sites rely solely on infiltrated water, which is often insufficient due to reduced infiltration capacity caused by sediment deposition upstream of the bunds (Vlaar, 1992; Yameogo et al., 2011). Furthermore, bund sites are often seeded with perennial forage species that compete aggressively with trees for limited water resources, exacerbating water stress (Durand, 2007). This competition is particularly pronounced in combination structures, where forage grasses are sown both along bunds and within trenches, intensifying resource scarcity across the site.

4.4. Growing together: the power of management in reforestation

The reduced growth in absence of management aligns with Douma et al. (2011), who compared the growth of similar species (excluding *Acacia raddiana*) on managed and unmanaged sites. Their study demonstrated significantly higher growth on managed sites, underscoring the positive influence of management practices. Management encompasses not only physical interventions such as guarding and maintenance but also a fundamental shift in the relationship between

humans and nature. It reflects a commitment to fostering coexistence and stewardship of the environment, often requiring collective action and long-term dedication from local communities and stakeholders. This willingness to actively engage in the care and protection of Sahelian woody ecosystems is as critical as the physical measures implemented (Tiétiambou et al., 2020).

Physical management plays a vital role in mitigating external stressors, creating a more stable environment for tree growth by reducing disturbances such as grazing, trampling and debarking (Amahowe et al., 2018), which are common in unmanaged sites. Factors directly influencing growth—such as light availability, water and nutrient access, soil temperature, and the biological characteristics of species (e.g., photosynthesis and nutrient absorption)—are inherently environmental and independent of human presence (Liboum and Bobo, 2018). However, human-led management shields planted trees from external threats, indirectly enabling these natural processes to occur more effectively. Indeed, in unmanaged sites, planted trees are vulnerable to browsing, cutting, and trampling by livestock and humans, leading to physiological stress and physical damage (Leriche, 2001). Such disruptions impair the trees' internal functioning, slowing their development. Tchigankong et al. (2018) identified wandering livestock as a major barrier to successful reforestation in arid zones. Similarly, Ganaba (2005) emphasized that protecting young plants from animals is essential for the effectiveness of anti-erosion structures.

Management also involves a proactive commitment to maintaining infrastructure and ecological balance. Beyond guarding, regular maintenance of SWC (Soil and Water Conservation) structures—such as repairing breaches and ensuring proper functionality—is necessary to preserve their efficiency in controlling erosion and retaining soil moisture (Ganaba, 2005; Tchigankong et al., 2018). Neglecting such infrastructure diminishes its capacity to support plant growth and long-term environmental recovery. In this way, management reflects a broader willingness to prioritize environmental sustainability and invest in the future of the land. This often involves integrating local knowledge and practices, fostering community participation, and aligning environmental goals with socio-economic benefits (Tiétiambou et al., 2020). Without this foundational human commitment, even well-designed interventions risk failure due to neglect or competing land-use priorities.

4.5. Conclusions

This study highlights the critical role of species selection, geomorphological context, SWC (Soil and Water Conservation) structures, and active management in enhancing tree growth and sustaining reforested lands in the Sahel. Several practical recommendations emerge:

1. Prioritize Resilient Species for Reforestation: *Acacia* species should be prioritized for reforestation in arid areas. Slower-growing species like *Bauhinia rufescens* and *Ziziphus mauritiana* can be included in mixed plantations to enhance diversity and resilience.
2. Optimize SWC Structure Selection: Half-moons proved most effective in promoting growth, especially in dry areas. Trenches and bench terraces are also useful on moderate slopes, provided soils avoid waterlogging. Stone bunds, though less effective for growth, offer valuable erosion control.
3. Tailor Interventions to Geomorphological Units: Pediments, with gentle slopes, deeper soils, and better fertility, should be prioritized. Plateaus and steeper slopes, being rockier and more erosion-prone, require soil amendments, erosion control, and targeted water retention strategies.
4. Invest in Active Management Practices: Active management—guarding, maintenance, and community engagement—is key. Young plants must be protected from grazing and trampling. Maintaining SWC structures is equally important to preserve their function.

5. Incorporate Local Knowledge and Community Participation: Local communities should be involved in planning, implementing, and monitoring reforestation efforts. Blending indigenous knowledge with science improves relevance and acceptance. Community-led guarding and maintenance can foster ownership and long-term commitment.

While these findings offer actionable guidance, it is important to note that the factors included in the model together explain only 34 % of the observed variation in tree growth, likely due to unmeasured environmental, biological, or social factors, or interactions between them. Therefore, caution is warranted: implementing these recommendations without accounting for these unknowns may not always yield the expected outcomes. These uncertainties highlight the importance of flexibility and continuous learning in restoration efforts. Success in restoration will ultimately depend on adaptive, site-specific approaches that remain open to local variability and knowledge. Placing communities at the center of efforts, while continuously monitoring and learning, is essential for building resilient and sustainable reforested landscapes in the Sahel.

Appendix 1. – Photos of the 5 studied SWC structures



Photo 1. Half-Moon with a *Vachellia seyal* tree, PASEC site (© Wourro Fatima).

CRediT authorship contribution statement

Fatima Wourro: Writing – original draft, Visualization, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Amah Akodewou:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Justin Kassi N'dja:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Conceptualization. **Bruno Héroult:** Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.



Photo 2. Bench Terrace with *Senegalia senegal* trees, Croix-rouge Site (© Wourro Fatima).



Photo 3. Stone Bunds, PGBV site (© Wourro Fatima).



Photo 4. Trenches, Colonel Papa Garba site (© Wourro Fatima).



Photo 5. Trench + Stone Bund with *Vachellia seyal* trees on the trenches, Nazari site (© Wourro Fatima).

Appendix 2. – Stan Codes used for model inference

```

data {
  //Number of observations.
  int<lower=0> n_obs;
  //Number of unique levels for each categorical variable.
  int<lower=0> n_espece; //Number of species.
  int<lower=0> n_ouvrage; //Number of SWC structures.
  int<lower=0> n_village; //Number of villages (not used in model)
  int<lower=0> n_gestion; //Number of management practices.
  int<lower=0> n_parcelle; //Number of plots.
  int<lower=0> n_geom; //Number of geomorphological units.
  int<lower=0> n_pom; //Binary indicator (1 = measured at 130 cm)
  //Data vectors.
  int < lower = 1, upper = n_espece > esp [n_obs]; //Species ID for each observation.
  real growth [n_obs]; //Observed growth.
  int<lower=0> tp [n_obs]; //Time since planting.
  int < lower = 1, upper = n_ouvrage > ouvrage [n_obs]; //SWC structure ID.
  int < lower = 1, upper = n_village > village [n_obs]; //Village ID (not used)
  int < lower = 1, upper = n_gestion > gestion [n_obs]; //Management ID.
  int < lower = 1, upper = n_parcelle > parcelle [n_obs]; //Plot ID.
  int < lower = 1, upper = n_geom > geomorph [n_obs]; //Geomorphology ID.
  int < lower = 0, upper = 1 > pom [n_obs]; //Indicator if measured at 130 cm.
}
parameters {
  //Species-specific growth exponent.
  vector < lower = 0.2, upper = 1.5 > [n_espece] theta_crois;
  //Hyperparameters for species effects.
  real < lower = 0.2, upper = 1.5 > mu_sp;
  real<lower=0> sd_sp;
  //SWC effect per type.
  vector < lower = 0.2, upper = 5 > [n_ouvrage] theta_ouvrage;
  //Management effect per type.
  vector < lower = 0.2, upper = 5 > [n_gestion] theta_gestion;
  //Geomorphological unit effect.
  vector < lower = 0.2, upper = 5 > [n_geom] theta_geom;
  //Binary effect of measuring at 130 cm height (pom)
  real < lower = 0, upper = 1 > theta_pom;
  //Plot-level effects and their hyperparameters.
  vector < lower = 0.2, upper = 5 > [n_parcelle] theta_parcelle;
  real < lower = 0.2, upper = 5 > mu_parcelle;
  //Observation noise.
  real<lower=0> sigma;
  //Standard deviations for hierarchical priors.
  real<lower=0> sd_ouvrage;

```

```

real<lower=0> sd_gestion;
real<lower=0> sd_parcelle;
real<lower=0> sd_geom;
}
model {
//Likelihood: lognormal model of growth.
for (i in 1: n_obs)
  growth [i] ~ lognormal (
    log ((theta_geom [geomorph [i]] * theta_parcelle [parcelle [i]] * theta_ouvrage [ouvrage [i]] * theta_gestion [gestion [i]]
      + theta_pom * pom [i]) * pow (tp [i], theta_crois [esp [i]])),
    sigma.
  );
//Priors for species growth exponent.
theta_crois ~ lognormal (log (mu_sp), sd_sp);
//Priors for group-level effects.
theta_parcelle ~ lognormal (log (mu_parcelle), sd_parcelle);
theta_ouvrage ~ lognormal (log (1), sd_ouvrage);
theta_gestion ~ lognormal (log (1), sd_gestion);
theta_geom ~ lognormal (log (1), sd_geom);
}
generated quantities {
//Posterior predictions for each observation.
vector [n_obs] growth_pred;
vector [n_obs] mu_pred;
for (i in 1:n_obs) {
  mu_pred [i] = (theta_geom [geomorph [i]] * theta_parcelle [parcelle [i]] * theta_ouvrage [ouvrage [i]] *
    theta_gestion [gestion [i]] + theta_pom * pom [i]) * pow (tp [i], theta_crois [esp [i]]);
  growth_pred [i] = lognormal_rng (log (mu_pred [i]), sigma);
}
//Predict species-specific growth at time = 20 using average effects.
vector [n_espece] species_growth_pred;
//Compute average effect values for standardized prediction.
real avg_theta_ouvrage = mean (theta_ouvrage);
real avg_theta_gestion = mean (theta_gestion);
real avg_theta_geom = mean (theta_geom);
real avg_theta_parcelle = mean (theta_parcelle);
for (s in 1:n_espece) {
  real mu_species = avg_theta_geom * avg_theta_parcelle * avg_theta_ouvrage *
    avg_theta_gestion * pow (20, theta_crois [s]);
  species_growth_pred [s] = mu_species;
}
}

```

Data availability

Datas are available at <https://doi.org/10.5281/zenodo.17054309>.

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