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Effects of Three Different Planting Techniques on Soil Water Content, Survival, and Growth of *Senegalia* Seedlings on Semi-Arid Degraded Lands in Burkina Faso

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Abstract

Land degradation exacerbates poverty and food shortages in Sub-Saharan Africa. Tree planting is traditionally used to restore degraded lands, but the tree species used are often poorly adapted to the local climate conditions. We evaluated the suitability and efficiency of three planting techniques (half-moon, standard plantation and zaï) in a semi-arid climate using seedlings from two native Senegalia species: *Senegalia gourmaensis* and *Senegalia dudgeonii*. A total of 116 nursery-grown seedlings were planted on degraded lands using these three planting techniques. Data on soil water content, seedling survival and growth rates were measured over 1.5 years. The effects of the planting techniques on these variables were significantly different ($p < 0.001$). The lowest water content was measured in the topsoil horizon (0–10 cm) and the highest in the deeper horizons (~50 cm). At the end of the experiment, the survival rate of *S. gourmaensis* was 72.2% - 62.5% and 57.5% in half-moon, standard plantation and zaï, respectively. For *S. dudgeonii,* it was 50%, 62.5% and 47.5% in half-moon, standard plantation and zaï, respectively. There was a significant difference in height and collar diameter between *S. gourmaensis* and *S. dudgeonii* using the three planting techniques ($p < 0.001$). Based on our results, we recommend using the half-moon or standard plantation for *Senegalia* species. *Senegalia* species are suitable for planting in degraded land in semi-arid areas when using the appropriate planting technique.

Keywords

tree planting techniques, degraded lands, reforestation, indigenous species, Africa

Harsh climatic conditions and inappropriate farming practices in arid and semi-arid regions of Sub-Saharan Africa have resulted in soil degradation (Zougmoré et al., 2014). This has led to a continuous decrease in crop productivity and an escalation of hunger and poverty among rural communities (Sanchez, 2002). In addition to limited access to arable land due to rapid population growth, soil degradation is a common challenge in Sub-Saharan Africa and has greatly undermined the African Union's long-term efforts to increase agricultural production, reduce food insecurity and alleviate poverty across the continent.

The extent of land degradation can be reduced through mitigation and species planting (Zucca et al., 2014).

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Several studies have shown that the most efficient restoration technique on degraded arable land is planting of carefully selected native tree species (Bayen et al., 2016; Zucca et al., 2014). Reforestation is a potential strategy to reduce soil erosion (Oscar, 2001), increase soil organic matter, improve soil structure, serve as a carbon sink and improve local nutrient cycling (Thomas, 2001). Additional economic benefits can be expected from timber and non-timber products. Reforestation with native trees has increasingly become attractive to local farmers and ecosystem managers as a result of direct and indirect effects in the short and long-term.

Reforestation has often been unsuccessful due to inappropriate species choice or insufficient knowledge about tree characteristics, e.g. their ability to withstand the stresses of a harsh climate (Wang & Meng, 2018). Successful reforestation therefore depends on the site-specific adaptation strategies of the planted species (Aronson et al., 1993). Unlike many species, the leguminous *Senegalia* and *Vachellia* (formerly *Acacia*) species have a high potential to survive and grow under arid and semi-arid conditions as a result of their morphological and physiological adaptation strategies (Ferreira et al., 2015), which include an extremely deep root systems (Thomas et al., 2006). They are therefore widely used to restore degraded agricultural lands in the Sahel region of West Africa, where water is the limiting factor for plant growth and development (Bayen et al., 2016; Kagambèga et al., 2011). Examples are *Senegalia dudgeonii* (Craib ex Holland) Kyal. & Boatwr and *Senegalia gourmaensis* (A. Chev.), which have various interesting ecological characteristics, including drought resistance, nitrogen fixation and efficient nutrient cycling and uptake of nutrients from deep soils (Kang et al., 1990).

Degraded lands are generally characterized by high impermeability and poor water infiltration, resulting in compaction of topsoil. Planting techniques must therefore include a destruction of hardpans in topsoils to reduce surface runoff and improve water infiltration rates (Casenave & Valentin, 1992). Native species, adapted to the stressful conditions of degraded lands, can be successfully used for reforestation in semi-arid and arid areas by applying appropriate planting techniques (Bayen et al., 2016; Kagambèga et al., 2011; Kagambèga et al., 2019). Planting techniques have traditionally been used by peasants in many West African countries to improve crop yield and restore fertility (Ganaba, 2005).

The objectives of this study are (1) to evaluate the efficiency of three planting techniques for improving soil water content in drylands and (2) to evaluate the performance of two dryland species (*Senegalia gourmaensis* and *Senegalia dudgeonii*) for reforestation of degraded soils in drylands.

Materials and Methods

Study Site

The research was conducted in the north Sudanian region of Burkina Faso at Namoungou (0° 36′ 53.34″ E, 12° 2′ 19.55″ N) (Figure 1). This region has a short and intense rainy season from May to September and a longer dry season. The mean annual rainfall was 822 mm over the past 30 years and the mean temperature was about 28 °C. The site was characterized by high evapotranspiration.

Species Description

Two dryland species (*Senegalia gourmaensis* and *Senegalia dudgeonii*) were selected based on their ability to survive and grow under arid and semi-arid conditions (Bayen et al., 2016). Both species are endemic to the Sudanian region and of socioeconomic value to the local people.

Senegalia gourmaensis (Leguminosae-Mimosoideae) is a shrub with many short branches, a thin, scaly, brown, cork-like bark, which is vertically fissured, a reddish slash and dark gray twigs. The species is found in the southern, central and eastern parts of the Sahel, but is also common in the Sudano-Guinean zone (Arbonnier, 2002).

Senegalia dudgeonii (Leguminosae-Mimosoideae) is a shrub with a spreading canopy, blackish, striated rough bark, reddish slash and white flowers grouped in racemes (Arbonnier, 2002). The species is widespread not only in the Sudanian region, but also in the Guinean region of West Africa. It can grow under relatively moist soil conditions (i.e., valley floors and around ponds).

Planting Techniques

The research was conducted in July 2012 in a randomized complete blocks design involving three planting techniques commonly used in eastern Burkina Faso: half-moon, zaï and standard plantation (Figure 2). Half-moon and zaï soil are traditional planting techniques used to adapt to the changing climate in the Sahel, where breaking the soil crust facilitates water infiltration and reduces water runoff due to soil ridges formed downslope of the pits (Zougmoré et al., 2014). In half-moon, a 2 m diameter half-circle was excavated. The pit was dug (10–15 cm depth) manually at the lower part of the plot (for better collection of rainwater). In each half-moon, the water retention area was about 3.14 m^2 (Bayen et al., 2016). The zaï consisted of digging 20 cm diameter and 15 cm deep pits. The excavated soil was used to build ridges around the pits. The standard plantation consisted of digging pits of 40 cm deep and 40 cm in diameter. The excavated soil was used to form a ridge

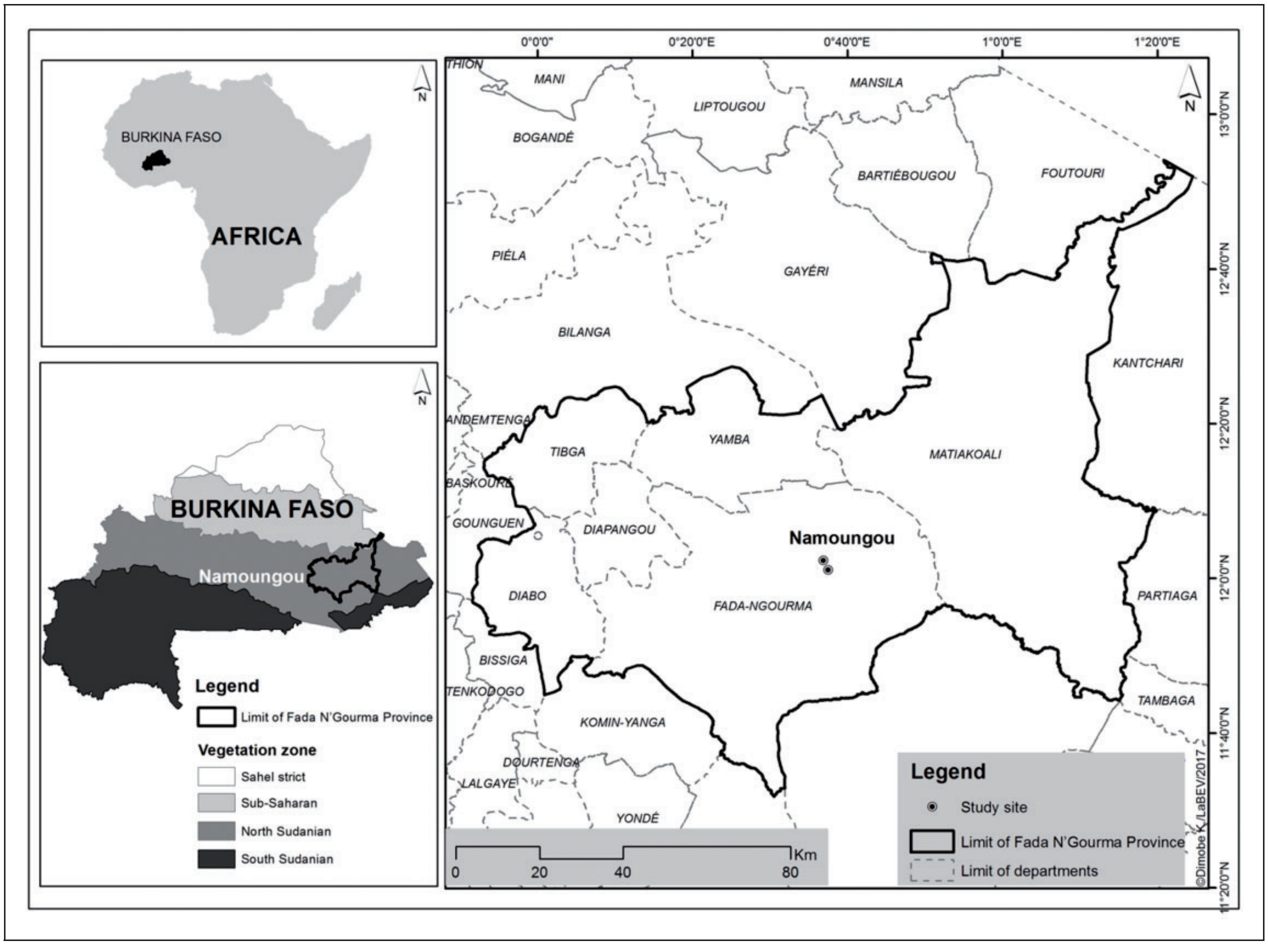

Figure 1. Location of Study Site.

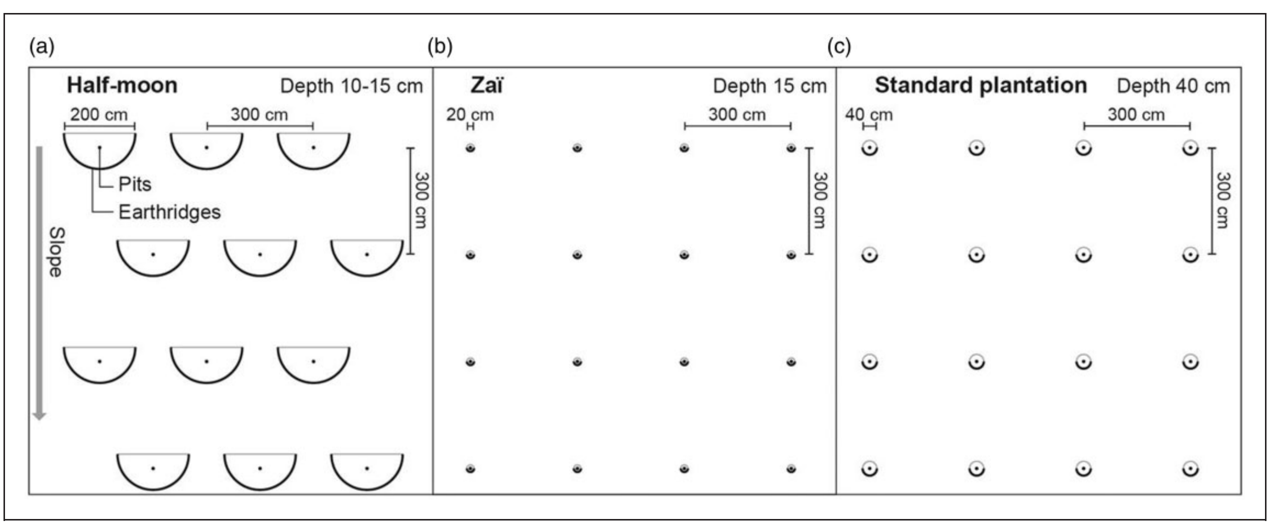

Figure 2. Planting Techniques.

around the pit. Pits were spaced at 3 m intervals within the lines and with 3 m between the lines. Half-moon is more labor-intensive than zaï and standard plantation. Blocking was done perpendicularly to the soil slope.

Three-month-old nursery-raised seedlings of the two species were transplanted. For each species, 116 seedlings were planted (36 seedlings in half-moon, 40 in zaï and 40 in standard plantation). The difference between the numbers of seedlings was due to the big dimension of the half-moon pits. After transplanting, the entire site was fenced to exclude grazing animals and human interference during the study period. The trees were neither irrigated nor fertilized.

Data Collection

Soil Water Content. The soil water content was measured gravimetrically for each of the planting technique during the dry season at five different depths (0–10, 10–20, 20–30, 30–40 and 40–50 cm). Three plots were selected randomly for each of the three planting techniques, giving a total of nine plots and 45 soil samples. Soil samples from similar planting technique types and depths were mixed, resulting in 15 pooled samples. The soil samples were weighed fresh, oven-dried to a constant mass at 105 °C and then reweighed. The following equation was used to calculate the soil water content:

$$SMC(\%) = \frac{FS(g) - OS(g)}{OS(g)} * 100 \tag{2}$$

where SMC is the soil water content, FS is the mass of fresh soil and OS is the mass of oven-dried soil.

Seedling Survival and Growth. Growth of each seedling was monitored by measuring plant height (the height of the apical meristem above the ground surface) and collar diameter (stem diameter at the ground surface) every 4 months over two years (July 2012–November 2014). Survival rates were recorded every 4 months.

Data Analysis. All statistical analyses were performed using the R version 3.4.2 (R Development Core Team, 2017). These analyses followed a protocol for data exploration described by Zuur et al. (2010) and protocols for conducting and presenting statistic analyses output (Stasinopoulos et al., 2017; Zuur & Ieno, 2016; Zuur et al., 2010). The marginal distribution of key response variables (water content, seedling survival, seedling height and collar diameter) were analyzed with the fitdistug package (Delignette-Muller & Dutang, 2015) to get the theoretical distribution that came closest to the empirical ones (Figures S1-S4). The best fit to the marginal distribution (based on the AIC of the different fitting attempts) was selected among a list of distributions adapted to real number data available in the gamlss.dist package (Stasinopoulos & Rigby, 2019). The Inverse Gaussian distribution (IG) has the best fit for water content, Log Normal distribution (LOGNO) for seedling survival and Generalized Gamma distribution (GG) for both seedling growth in height and collar diameter.

To model the response variables (water content, seedling survival, seedling height and collar diameter) as function of the explanatory variables (planting technique, species, soil depth and date), we used the Generalized Additive Model for Location, Scale and Shape (GAMLSS) (Rigby & Stasinopoulos, 2005) with the best fit family mentioned above for each response variable. GAMLSS is a modern distribution-based approach to regression analysis that expands the traditional approach to accommodate distribution parameters (μ, σ, ν, and τ) that are modeled as additive functions of predictor variables (Barber, 2018). The terms location (μ), scale (σ), and shape (ν, and τ) refer to these parameters and are connected, but not necessarily equal, to the four moments of a distribution, namely mean or median (μ), variance (σ), skewness (ν) and kurtosis (τ). GAMLSS offer a large variety of distributions with 1, 2, 3, or 4 parameters (μ, σ, ν, or τ). The IG (μ, σ) and LOGNO (μ, σ) model the means and the standard deviations of water content and seedling survival, while GG (μ, σ, ν) models the mean, the standard deviation and the shape skewness of seedling growth in height and collar diameter.

The model selection followed a stepwise approach (a combination of forward and backward selection) using the Akaike information criterion (Stasinopoulos & Rigby, 2008) by fitting the full linear models for μ. The full model for water content contains the main terms and the two-way interactions terms of the explanatory variables "planting technique" and "soil depth". The full model for seedling survival, height and collar diameter contains the interaction of the variable "species" and "planting technique". After the selection of the optimum model for μ, the same model selection procedure was followed for the selection for σ and ν (depending on the considered family distribution) to give the final optimum model. Once the optimum models were determined, the model validation test was carried out by: (1) plotting the residuals against the fitted values to assess homogeneity; (2) making QQ plots and computing filliben correlation coefficients to verify normality; and (3) using worm plots to visualize the model fit to the data. A likelihood ratio test (LRT) was conducted to evaluate the influence of the remaining explanatory variable in the optimum model. When the p-value of a given term was <0.05, the term was considered to have a significant influence on seedling performance (survival and growth).

Results

The model explaining the variation of soil moisture content as function of planting technique and depth (Table 1, Table S1, Figures S5 & S6) contains the main terms and their interaction for the mean parameter (μ), indicating that there is a difference between planting techniques, which varies depending on soil depth.

Soil moisture content increased from the top to the bottom and was significantly (LRT, $p < 0.001$) higher in half moon (ranging from 9 to 14%) than in standard plantation (6 to 9%) and zaï (1 to 4%). The standard deviations was significantly higher in half-moon than in standard plantation and zaï (Figure 3).

Table 1. Effect of Planting Technique and Soil Depth on Soil Water Content Tested by Likelihood Ratio Tests (LRT) for the Predictors of the GAMLSS Model With an Inverse Gaussian Distribution (IG, μ and σ).

	DF	LRT	Pr(Chi)
μ			
Planting technique	2	330.55	<0.001
Depth	4	191.18	<0.001
Planting technique: Depth	12	185.37	<0.001
σ			
Restoration technique	3	71.31	<0.001

Note. μ is the model for the mean of distribution, and σ is the model for the variance of distribution. DF = degree of Freedom; LRT = Likelihood Ratio Test; Pr(Chi) = Chi-square p-value.

The model explaining seedling survival as a function of planting technique, species and date contained the mains terms and the standard deviation was kept constant ($\sigma = 1$) (Table S2). All three variables and their interactions were highly significant (LRT, $p < 0.001$).

At the end of the experiment, the survival rate of *S. gourmaensis* was significantly higher in the half-moon (72.2%) than in the standard plantation (62.5%) and zaï (57.5%), while the survival rate of *S. dudgeonii* was significantly higher in standard plantation (62.5%) than in half-moon (50%) and zaï (47.5%) (Figure 4). The survival rate of *S. gourmaensis* in the half-moon and standard plantation remained constant after about 1.5 year.

The model explaining seedling growth in height (Table 3, Table S3, Figures S7 & S8) and collar diameter (Table 4, Table S4, Figures S9 & S10) as a function of planting technique, species and date contained the main and the two-way interactions terms for the standard deviation parameter (σ) and the distribution shape parameter (ν).

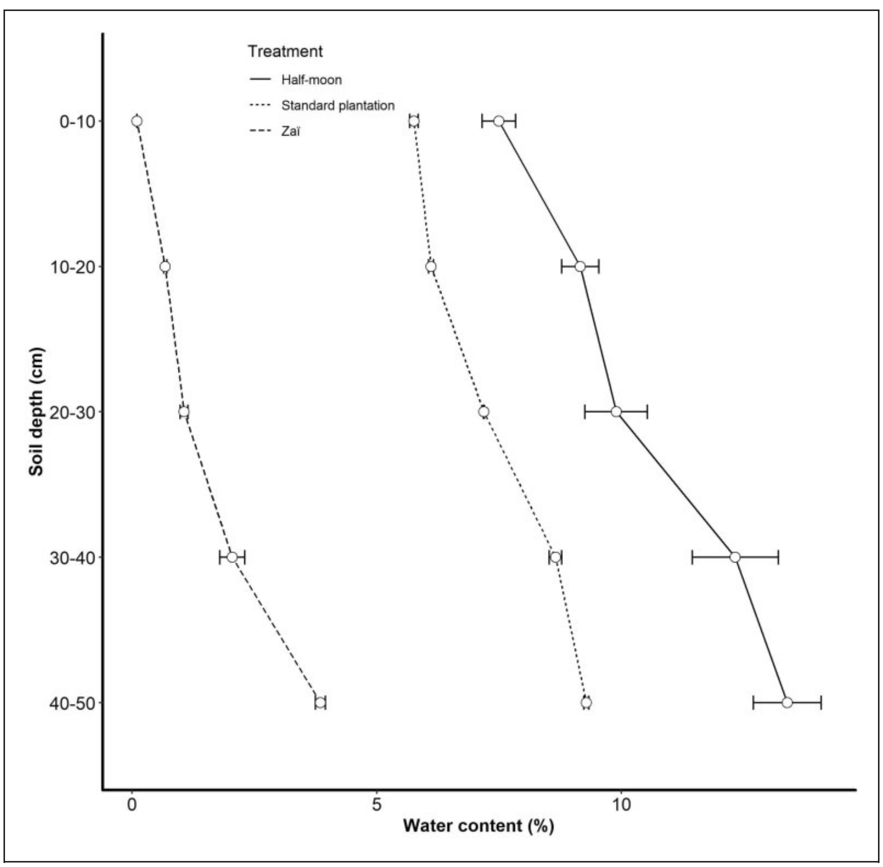

Figure 3. Effect of Planting Technique on Soil Water Content at Different Depths (Error Bars Show the Standard Error).

Table 2. Effect of Species, Planting Technique and Date on Seedling Survival Tested by Likelihood Ratio Tests (LRT) for the Predictors of the GAMLSS Model With a Log Normal Distribution (LOGNO, μ and σ).

	DF	LRT	Pr(Chi)
μ			
Species	1	28.75	<0.001
Planting technique	2	2865.55	<0.001
Date	6	2897.82	<0.001
Species: Planting technique	2	28.68	<0.001
Species: Date	6	2820.25	<0.001
Planting technique: Date	12	2834.75	<0.001

Note. μ is the model for the mean of distribution, and σ is the model for the variance of distribution. DF = degree of Freedom; LRT = Likelihood Ratio Test; Pr(Chi) = Chi-square p-value.

Regarding seedling growth in height and collar diameter, the effect of planting technique was highly significant and increased significantly over time (LRT, $p < 0.001$). Growth of *S. gourmaensis* was significantly higher in half-moon (height: from 30 to 76 cm; collar diameter: from 4 to 22 mm) than standard plantation (height: from 30 to 64 cm; collar diameter: from 4 to 16 mm), and zaï (height: from 30 to 38 cm; collar diameter: from 4 to 9 mm) (Figure 4). Growth of *S. dudgeonii* increased significantly over time without significant differences among planting technique. However, the magnitude of *S. dudgeonii* growth in collar diameter over time was significantly higher in half-moon (from 6 to 19 mm) than standard plantation (from 6 to 17 mm) and zaï (from 6 to 12 mm).

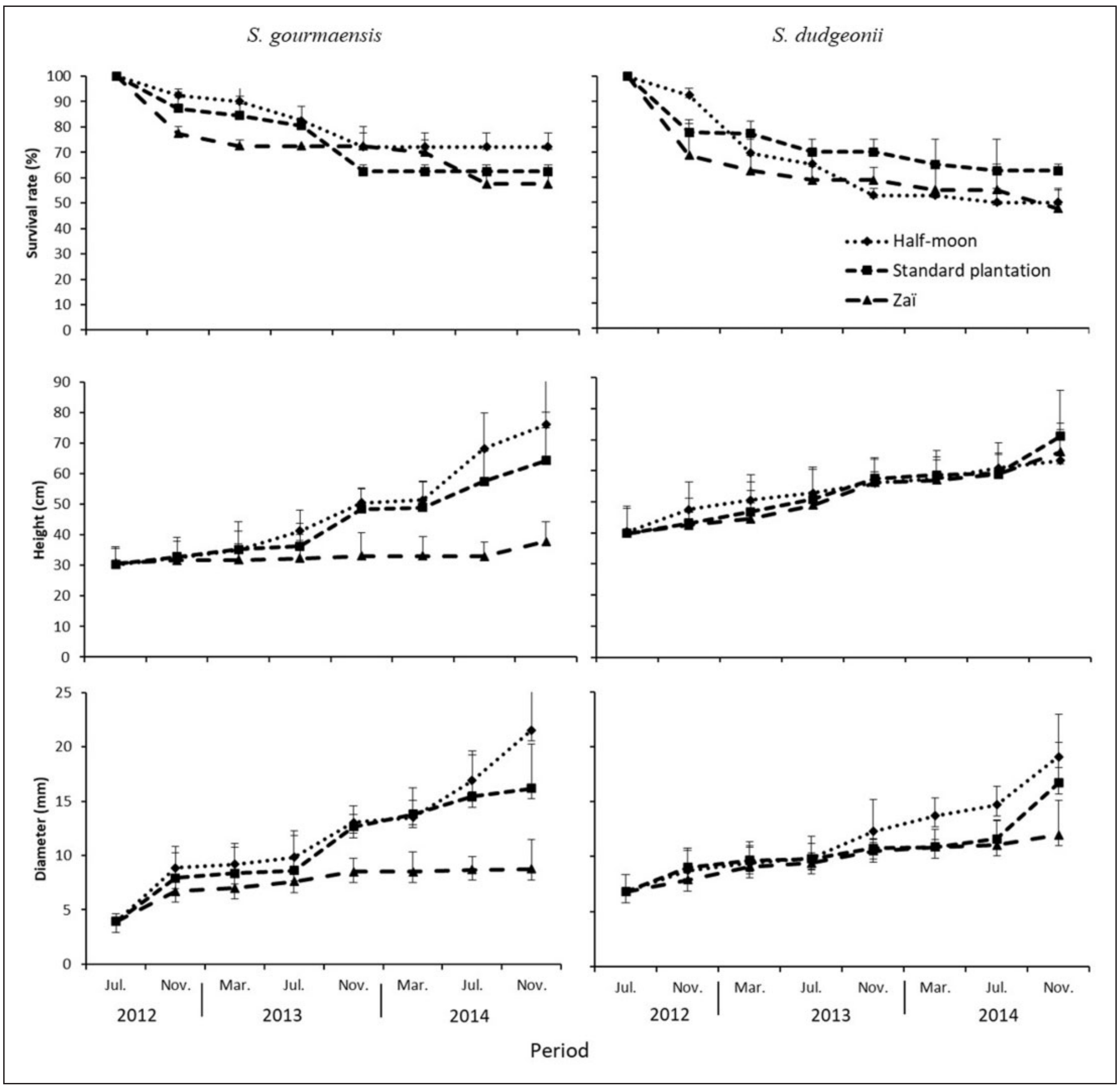

Figure 4. Effect of Planting Technique on Seedling Survival, Height and Collar Diameter.

Table 3. Effect of Species, Planting Technique and Date on Seedling Growth in Height Tested by Likelihood Ratio Tests (LRT) for the Predictors of the GAMLSS Model With a Generalised Gamma Distribution (GG, μ, σ and ν).

	DF	LRT	Pr(Chi)
μ			
Species	1	703.20	<0.001
Planting technique	2	265.80	<0.001
Date	6	502.47	<0.001
Species: Planting technique	2	215.71	<0.001
Species: Date	6	217.06	<0.001
Planting technique: Date	12	202.98	<0.001
σ			
Species	1	28.86	<0.001
Planting technique	2	50.73	<0.001
Date	6	126.94	<0.001
Date: Species	6	25.95	<0.001
Date: Planting technique	12	46.20	<0.001
ν			
Species	1	37.13	<0.001
Date	6	40.42	0.002
Planting technique	2	64.42	<0.001
Date: Planting technique	12	34.99	<0.001

Note. μ is the model for the mean of distribution, σ is the model for the variance of distribution, and ν is the model for the skewness of distribution. DF = degree of Freedom; LRT = Likelihood Ratio Test; Pr(Chi) = Chi-square p-value.

Table 4. Effect of Species, Planting Technique and Date on Seedling Growth in Diameter Tested by Likelihood Ratio Tests (LRT) for the Predictors of the GAMLSS Model With a Generalised Gamma Lopatatsidis-Green Distribution (GG, μ, σ and ν).

	DF	LRT	Pr(Chi)
μ			
Species	1	185.59	<0.001
Planting technique	2	290.82	<0.001
Date	6	414.51	<0.001
Species: Planting technique	2	130.67	<0.001
Species: Date	6	88.11	<0.001
Planting technique: Date	12	50.58	<0.001
σ			
Species	1	44.75	<0.001
Date	6	44.74	<0.001
Date: Species	6	17.02	0.009
ν			
Species	1	15.88	0.026
Planting technique	2	290.82	<0.001
Date	6	158.93	<0.001
Species: Date	6	13.16	0.041
Planting technique: Date	12	35.97	<0.001

Note. μ is the model for the mean of distribution, σ is the model for the variance of distribution, and ν is the model for the skewness of distribution. DF= degree of Freedom; LRT= Likelihood Ratio Test; Pr(Chi)= Chi-square p-value.

The standard deviations of seedling growth in height increased significantly over time with a significantly higher magnitude in half-moon than in both plantation and zaï (Figure 4, Tables 3 and 4; LRT, $p < 0.001$) and significantly higher magnitude for *S. gourmaensis* than *S. dudgeonii*. There were higher variations in *S. gourmaensis* seedling growth in height and collar diameter in half-moon than in the plantation and zaï, where the seedling growth variables were homogenous. Thus, overall, the seedling of *S. gourmaensis* had similar growth performances in both half-moon and standard plantation that were significantly higher than in zaï at the end of the experiment. The seedling growth in collar diameter of *S. dudgeonii* did not differ significantly among planting technique at the end of experiment.

The analysis of seedling growth in height and collar diameter also showed that their distribution shape (ν) in half-moon were significantly different than in standard plantation and zaï (Tables 3 and 4; LRT, $p < 0.001$). Thus, the growth performences of *S. gourmaensis* and *S. dudgeonii* were more homogenous in standard plantation and zaï than in half-moon.

Discussion

Soil moisture content increased from the top layer downwards with all planting techniques, and the half-moon retained the highest water content followed by standard plantation. The planting techniques contribute to retain runoff water and increase the water storage capacity (Chen et al., 2020). The capacity of the soil to retain water depends on the form, the depth and the size of the pits. Gravimetric variations in the soil water content are controlled by several different hydrological processes, such as infiltration (Ambouta et al., 1996) and evapotranspiration (Brandes & Wilcox, 2000). In this case, the size of the plot seems to matter. as half-moon with larger pits had larger water holding capacity than standard plantation and zaï, which had the smallest pits. The variation in soil moisture content can play fundamental role in seedling performance.

At the end of the experiment, half-moon had the best survival rate for the seedlings of *S. gourmaensis*, half-moon and standard plantation had the best growth in height and collar diameter. Standard plantation provided the best survival rate for the seedlings of *S. dudgeonii*, whereas response of seedling growth in height and collar diameter did not differ among planting techniques. These findings are consistent with previous studies that investigated the effects of water retention techniques on plant survival and growth rates (Bayen et al., 2016; Kagambèga et al., 2011; Sona & Abdel, 2016). These results can be explained by the difference in retaining soil moisture among planting techniques and the difference in plasticity between the two species. Gebretsadik (2014) argued that limited soil moisture is the primary factor controlling plant establishment and growth in dry lands. Seedling survival and growth rates depend on the availability of soil water, which can be increased by appropriate planting techniques. Applying these techniques can increase the soil water content and improve seedling survival rates.

Our results, together with those reported by Kagambèga et al. (2011) and Bayen et al. (2016) in semi-arid zones of Burkina Faso, show significant differences in survival and growth rates among the tree species. Based on the survival rates, the half-moon planting technique is the most suitable for *S. gourmanesis* seedling plantation to get an optimal survival rate, while the standard plantation technique remains the most suitable for S. *dudgeonii*. However, when it comes to seedling growth, half-moon as well as standard plantation is the most suitable for *S. gourmanesis*, while the half-moon, standard plantation and zaï are all suitable for *S. dudgeonii*. Therefore, *S. dudgeonii* has higher seedling growth plasticity than *S. gourmanesis*.

Implications for Conservation

We recommend standard plantation for *S. dudgeonii* seedlings. Zaï, providing the same growth performance, but a lower survival rate than standard plantation, is also a good alternative. The plasticity of *S. dudgeonii* seedlings along a soil moisture content gradient is higher than *S. gourmanesis*. Half-moon is not recommended for *S. dudgeonii* because it is more labor-intensive and requires more skills for installation (e.g. importance of stand slope in water catching capacity) compared to the other techniques.

Although *S. gourmanesis* had the highest survival rate in half-moon and similar growth performance compared to standard plantation, we suggest standard plantation for *S. gourmaensis*, as the difference in survival rate does not counterbalance the time and skills required to install half-moon.

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Declarations of Conflicting Interests

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Supplemental Material

Supplemental material for this article is available online.

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