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Natural regeneration pattern of the wild custard-apple, *Annona senegalensis* Pers. in the semi-arid area of Burkina Faso, West Africa

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***Annona senegalensis* Pers. (Annonaceae) is a multipurpose shrub species, but threatened in Burkina Faso. Therefore, understanding its natural regeneration is a challenge for the sustainable management of the species resources. Our study examines the regeneration potentials of *A. senegalensis* across two phytogeographic zones. The structure of Weibull showed that the distribution of the regeneration individuals based on height classes was inverse J-shaped in the two phytogeographic zones. The structure reveals a relative predominance of individuals in small size classes. A log-linear adjustment test of Weibull's confirmed the observed distribution and Weibull distribution were not conformed (p<0.0001). A generalized linear model (GLM) and an ANOVA showed that the density of the natural regeneration of *A. senegalensis* was significantly higher in the south-sudanian zone. The density of the regeneration stratum 1 was 2.46 times higher in the north-sudanian than in the south-sudanian zone. The Green Index (GI) confirmed that the spatial distribution of regeneration individuals was random (GI=0). *Annona senegalensis* reproduces mainly by seed germination. *Annona senegalensis* faces difficult natural regeneration, worsened in the north-sudanian by the climate pejoration and a stronger anthropogenic pressure. The study suggests assisted natural regeneration, which should contribute to better conservation of the species.**

Key words: *Annona senegalensis*, ontogenetic stage, population structure, spatial distribution, regeneration mechanism.

INTRODUCTION

Woody species regeneration is a major component of the renewing process of forest ecosystems (Assede et al.,

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2015). In a given ecosystem, the development stage succession of plant species and maintaining natural woody species vegetation are driven by the regeneration capacities of occurring species. Indeed, forest dynamics are based on three fundamental biological principles: recruitment, growth, and mortality (Chagneau et al., 2009). Moreover, the concept of sustainable management of natural resources suggests that priority should be given to the most vulnerable species, regarding environmental disturbance (Ouédraogo et al., 2009).

Juveniles' demographic state parameters determine the woody species population's dynamics. The ability to ensure continuity of recruitment is a key condition to maintain species in the ecosystem (Tardif, 2019). However, human disturbances and climate deterior affect many species recruitment in semi-arid regions due to the vulnerability of their regeneration individuals (Thiombiano and Kampmann, 2010; Ouédraogo and Thiombiano, 2012). According to the IUCN (2022), *A. senegalensis* is among the plant species listed as minor, but nonetheless it remains a conservation concern. Among the threatened high socioeconomic value species in Burkina Faso, there is the custard-apple, *Annona senegalensis* Pers. (Traoré et al., 2011; Zouré et al., 2021). *Annona senegalensis* is a shrub species whose size does not exceed four meters in height. It is widely distributed in fallows and savannahs of the sudanian area (Arbonnier, 2019). The species is threatened by the over-harvesting of its organs, agriculture clearing and bushfire (Hahn-hadjali and Thiombiano, 2000; Traoré et al., 2011; Zouré et al., 2021). In Burkina Faso, *A. senegalensis* is among the species with high socioeconomic value, which fulfill various needs of local populations (APFNL, 2013). Indeed, fruits and flowers of *A. senegalensis* are consumed (Atato et al., 2011; Lamien et al., 2008; Zouré et al., 2021), while roots and stem bark are used in pharmacopeia (Suleiman et al., 2008; Konaté, et al., 2012; Zouré et al., 2021). The combined effect of human harvesting and climatic pejoration in the semi-arid environment of Burkina Faso worsens the species's vulnerability (Hahn-Hadjali and Thiombiano, 2000; Traoré et al., 2011). The lack of documentation on the species' silviculture is hampering it conservation (CNSF, 2015). It is therefore urgent to understand the natural regeneration pattern of the species, with regard to the juvenile population structure, the spatial distribution, and the mechanisms of regeneration. Such an investigation can led to identifying possible constraint and find out appropriate strategies for a sustainable management of the species' resources.

The reproduction mechanism is a key factor in both juveniles' distribution and vegetation dynamics (Pannell, 2002). However, in tropical dry lands, woody species regeneration processes are often poorly understood, even less, the recruitment mechanisms that modeling can help predict the evolutionary trend regarding environmental factors. According to Glèlè et al. (2009), characterizing the spatial distribution of a species helps to analyse the individuals' disposition in their distribution area and establish a correlation with their dissemination mode, as well as with the regeneration potentials of the species. Among the many studies on savannah vegetation and species of West Africa and Burkina Faso particularly, very few have focused on woody regeneration exclusively. Rare studies exclusively devoted to regeneration have concerned overall vegetation and individual species (Ouédraogo et al., 2006a, Bognounou et al., 2009). Nevertheless, documenting the demographic behaviour of juveniles is particularly relevant for threatened species such as *A. senegalensis,* in order to understand the ecology of the species, particularly its resilience's capacity. Adult individuals that are supposed to be more resilient are the most exploited and are therefore subject to intensive anthropogenic pressure (Zouré et al., 2021). Therefore, understanding the regeneration patterns appears as a key stage to develop an appropriate strategy to ensure the species' population renewal. This study examines the regeneration potentials of *A. senegalensis* across two phytogeographic zones corresponding to the optimal distribution area of the species in Burkina Faso (Arbonnier, 2019). Specifically, it aims to: (i) determine the juvenile population structure of A. senegalensis; (ii) assess the spatial distribution pattern of the species' juveniles in natural stands, and (iii) determine the different regeneration mechanisms of the species.

MATERIALS AND METHODS

Study area

The study was conducted in two phytogeographic sectors of Burkina Faso, namely north-Sudanian and south-Sudanian located between latitude 13°27-13° N and 12°05-10°10 N and longitude 3°28-4°10 W and 4°30-5°30 W. These phytogeographic sectors correspond to the actual optimal distribution area of *A. senegalensis* in Burkina Faso. In these phytogeographic sectors, two provinces such as Mouhoun and Kenedougou, located in the north-sudanian and the south-sudanian zones, respectively, were chosen for fieldwork based on the presence of *A. senegalensis* population (Figure 1). The two phytogeographic sectors have different environmental conditions (Table 1).

Data collection

Thirty 900 m^2 (30 m × 30 m) plots (Ouédraogo, 2006; Thiombiano et al., 2016; Agbani et al., 2018) per phytogeographical sector were performed following stratified oriented sampling (Kebenzikato et al., 2015) in fallows. The stratification criterion is the phytogeographic sector and the orientation criterion is the presence of a stand of *A. senegalensis*. For the inventory of regeneration individuals, 5 square plots, four on each side and one in the center of 25 m^2 (5 m × 5 m) were installed in the 900 m^2 plot (Figure 2). Juveniles are those with a collar diameter (Dc) of less than three centimeters (Dc<3 cm). Individuals considered as adults are those with a diameter > 3 cm at 20 cm from the ground (Schreckenberg, 1996; Ouédraogo, 2006). The collar diameter and the height of each juvenile were measured. The total number of individuals of the regeneration was counted and their total height was measured

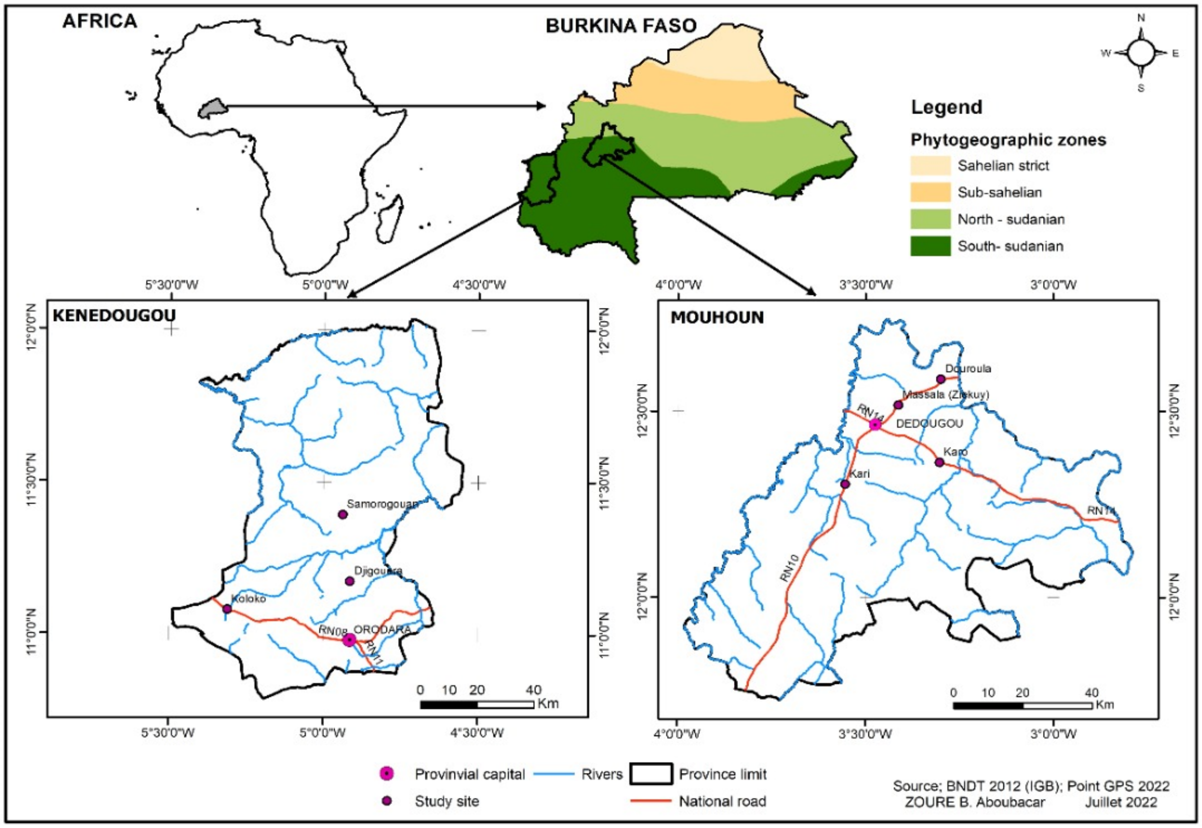

Figure 1. Map showing the study area.
Sources: Authors

Table 1. Environmental characteristics of the study area.

Parameter	North-Sudanian	South-Sudanian
Climate type	Sudano-sahelian	Sudanian
Rainfall (mm)	600-900	>900
Rainy season period	May to October	April to October
Temperature (°C)	18-39	17-37
Main vegetation	Savannas and woodlands	Mosaic of dry and riparian forests, savannas and woodlands
Soil	Brown eutrophic, vertisols leached ferruginous gravelly, hydromorphic, ferralitic	Brown eutrophic, vertisols leached ferruginous

Sources: Fontes and Guinko (1995), Boussim (2010), BUNASOLS (1997), Traoré and Anne (2010), and ANAM: National Agency of Meteorology (1989-2019).

(Stevens, 1994).

Thirty plots of 100 m² (10 m × 10 m) were used in each phytogeographic sector to determine the spatial distribution by the Green Index. Two juveniles randomly mapped out per plot was excavated, to determine the mechanism of regeneration: Vegetation (stem sprouts, stump rejection, suckers) or generative (seedling).

Analysis

The height class structure of juveniles was performed by considering 20 cm amplitude classes from 0 to 100 cm. Juveniles were ranged in three stage categories based on their height to analyse the regeneration potentials: Stratum 1, stratum 2, and stratum 3 (Ouédraogo et al., 2009; Gaoue et al., 2013) (Table 2 and Plate 1).

Analysis of variance (ANOVA) following by student Newman and Keuls test was performed to compare and structure mean heights by stage of development per phytogeographic zone after checking for the normality and equality of variance using Shapiro-Wilk test and Levene test, respectively. A generalized linear model (GLM) was used to compare the densities between the stratum (Table 3). All analyses were performed in R software version 3.5.1 (R core team development, 2018).

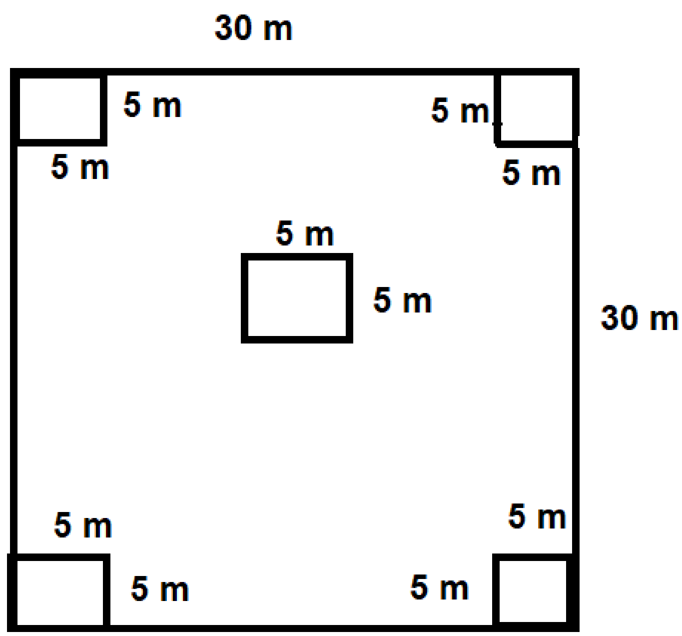

Figure 2. Plot of the dispositive.
Sources: Authors

Table 2. Ontogenetic stages of *A. senegalensis*.

Height classes (cm)	Stage of development	Descriptions
0-50	Stratum 1	Vulnerable individuals corresponding to recruitment (initial step).
50-100	Stratum 2	Individuals corresponding to postage (second step).
>100	Stratum 3	Individuals at the beginning of sexual maturity, corresponding to the installation of the regeneration (thirty step).

Source: adapted from Ouédraogo et al. (2009).

The distribution structure of juveniles based on height classes was established to estimate the demographic tendency of the regeneration. The observed distribution was adjusted to the theorical distribution of Weibull. The function of the density probability of Weibull is (Johnson and Kotz, 1970):

$$f(x) = \frac{c}{b}\left(\frac{x-a}{b}\right)^{c-1} \exp\left[-\left(\frac{x-a}{b}\right)^{c}\right]$$

In this equation, *x* is the tree height; *a* (threshold parameter) = 0.1 cm; *b* is the scale parameter linked to the central value of heights; and *c* is the shape parameter of the structure. Observed data were used to estimate parameters *b* and *c* based on the maximum likelihood method.

These values were used to establish the theoretical distribution following Glèlè et al. (2016). Log-linear analysis was performed in SAS (2009) to test the adequacy of the observed structure to the Weibull distribution. The hypothesis of adequacy between both distributions was accepted if the probability of the test value was higher than 0.05.

The Green Index (GI) was used to assess the global distribution pattern of juveniles in each plot (Table 3).

RESULTS

Population structure of *A. senegalensis* regeneration

The height class distribution structure of the regeneration of *A. senegalensis* appears in J reverse shape in both north-sudanian and south-sudanian zones (Figures 3 and 4). The values of the shape parameter "c" from Weibull's distribution that were 1.28 and 1.26 for the north-sudanian and the south-sudanian, respectively (Figures 3 and 4) reveal the relative predominance of individuals in small size classes. The class 0-20 cm recorded a higher density of individuals in both phytogeographic zones. Generally, the density decreased from the small height classes to the high ones, with observed irregularity in the south-sudanian zone (Figures 3 and 4). The tree-density of the height class (60-80 cm) is higher than next and previous classes. The transition irregularity indicates transition difficulties between the stages of development.

The log-linear analysis revealed a significant difference

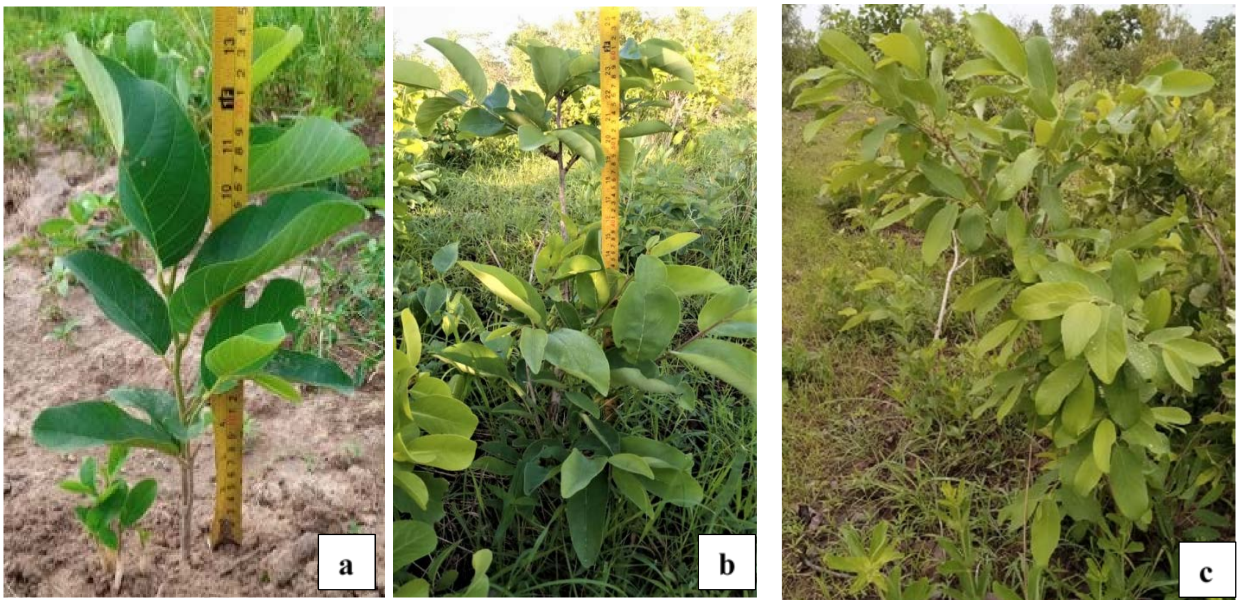

Plate 1. Juveniles of *A. senegalensis* corresponding to different regeneration stages: **a**: stratum 1; **b**: stratum 2; **c**: stratum 3.
Sources: Authors

Table 3. Structural and distribution variables used.

Names	Formula	Descriptions	References
Density of the regeneration	$D\_obsi = \frac{n_i}{n_p S}$	$D_{\_obsi}$= observed density (individuals/ha) of the class *i*; n_i= number of individuals in class *i* n_p= total number of plots S= area of a plot (125 m^2)	Glèlè et al. (2016)
Punctual transition rate	$Ptr = \frac{N_{si}}{N_{sp}} x\ 100$	Nsi= number of individuals in stratum i Nsp= number of individuals in previous stratum	Pino et al. (2007)
Regeneration rate (Rr)	$Rr = \frac{N_{s1} + N_{s2} + N_{s3}}{N_a} x\ 100$	Ns1= number of individuals in stratums 1 Ns2= number of individuals in stratum 2 Ns3= number of individuals in stratum 3 Na= Total number of adult individuals	Pino et al. (2007)
Green Index (GI)	$GI = \frac{BI - 1}{n - 1}$ $BI = \frac{\sigma^2}{N}$	IB= Blackman Index N= average density n= average number of individuals of the plots σ^2= variance on individuals' density of the plots The green index measured the spatial pattern of the regeneration GI=0, the distribution is random. It aggregated with a GI >0 and repulsive for GI<0	Green, 1966

Sources: Authors

between the two phytogeographic zones (p<0.001). The interaction between individuals' densities and height classes is also significant (p<0.001) for each phytogeographic zone. This confirms the good fitness of

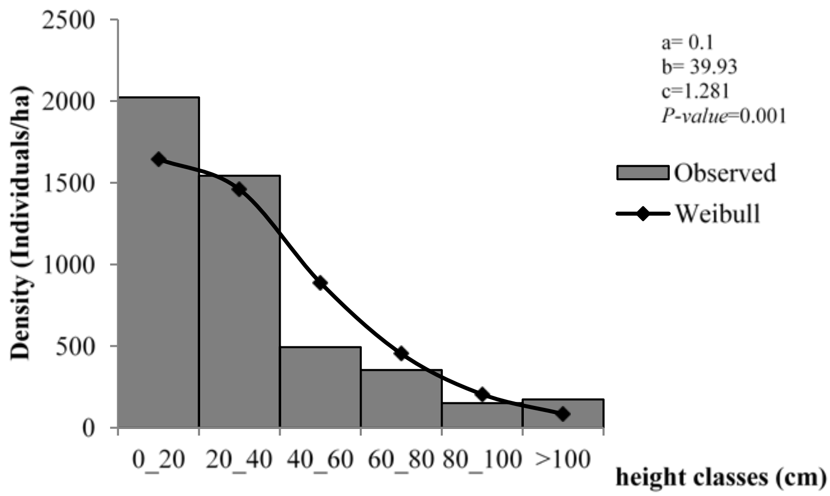

Figure 3. Height class distribution structure of *A. senegalensis* regeneration in the north-sudanian zone.
Source: Author's analysis data collection.

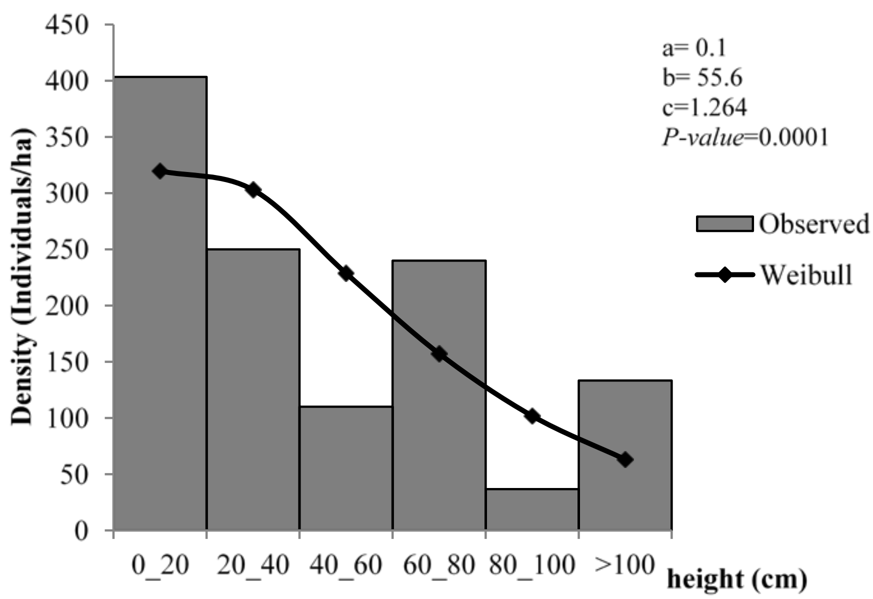

Figure 4. Height class distribution structure of *A. senegalensis* regeneration in the south-sudanian zone.
Source: Author's analysis data collection.

the observed structure to the Weibull distribution.

Capacity of regeneration of *A. senegalensis*

The regeneration rate of *A. senegalensis* population was 4 times lower in the south-sudanian zone than in the north-sudanian (Table 4). Otherwise, the transition rates between the different stratum were higher in the south-sudanian (Table 4).

In stratum 1 and 2, the density of the juvenile population was significantly higher ($p<0.05$) in the north-sudanian sector than in the south-sudanian sector (Table 5). In both the phytogeographic sector, the density of the individuals of regeneration was significantly higher in stratum 1 compared to stratums 2 and 3 (Table 5). As far as the individual's height is considered, a significant difference ($p<0.05$) in the stratum 1 between the two

Table 4. Transition and regeneration rates of *A. senegalensis.*

Phytogeographic sector	Height classes (cm)	Stage of development	Transition rate	Regeneration rate
	0-50	Stratum 1		
North-sudanian	50-100	Stratum 2	29.21	294.04
	≥100	Stratum 3	20.14	
	0-50	Stratum 1		
South-sudanian	50-100	Stratum 2	40.21	67.53
	≥100	Stratum 3	32.67	

Source: Author's analysis data collection.

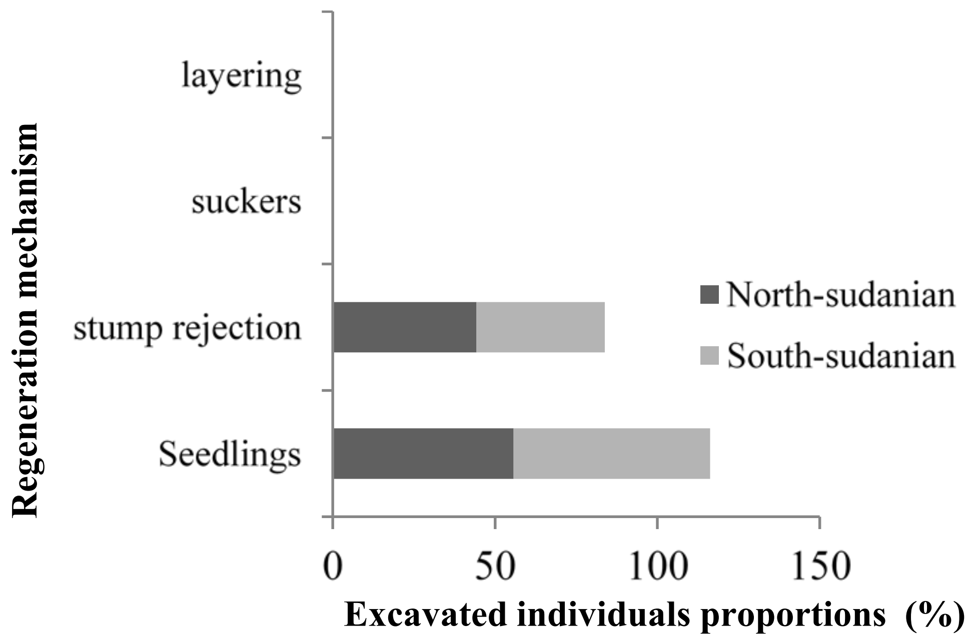

Figure 5. Proportion of the regeneration mechanisms of *A. senegalensis* in the two phytogeographic zones
Source: Author's analysis data collection.

phytogeographic sectors (Table 5) was noticed.

Spatial distribution and mechanism of the natural regeneration of *A. senegalensis*

The Green Index values (GI<0) indicated a repulsion between adult individuals in both phytogeographic zones.

The distribution was random among juvenile individuals and between juveniles and adults (GI≈0).

The results of individuals mapped out showed regeneration mostly derived from seeds (Plate 2a) and scarry from stump rejection (Plate 2b). Seedling represents 60.47 and 55.74% of regeneration respectively in the south-sudanian and north-sudanian zones (Figure 5).

DISCUSSION

Demographic characteristics of *A. senegalensis* regeneration

The regeneration of *A. senegalensis* in natural stands is dominated by the seedlings of stratum 1 compared to stratums 2 and 3 in both phytogeographic zones. The abundance of seedlings of stratum 1 traduced a good potential of recruitment in woody species (Sabo et al., 2021). The seedlings in stratum 1 are less lignified and therefore vulnerable to environmental disturbances such as livestock grazing, drought, and fire, especially in the north-sudanian zone dominated by savannahs (Savadogo, 2007). Gaoué et al. (2013) also reported that juveniles are vulnerable to fire and dryness.

Table 5. Demographic parameters according to the development stages of *A. senegalensis*.

Phytogeographic sector	Density (individual/ha)							Height (cm)						
	Stratum 1		Stratum 2		Stratum 3		P-value	Stratum 1		Stratum 2		Stratum 3		P-value
	m	se	m	se	m	se		m	se	m	se	m	se	
North-Sudanian	2629.33^{a}	2687.33	822.86^{a}	716.15	272.94^{a}	198.11	**<0.05**	23.86^{a}	1.52	59.82^{b}	1.87	125.79^{a}	19.36	**<0.05**
South-Sudanian	1065.7^{b}	677.09	500^{b}	346.91	206.32^{a}	125.97	**<0.05**	20.12^{a}	1.34	67.62^{a}	1.92	109.05^{a}	2.37	**<0.05**
P-value	**<0.05**		**<0.05**		0.854			0.07		**0.05**		0.404		

Means followed by the same letter in the same column are not significantly different at Prob. = 0.05 (Student-Newman-Keuls test). m: mean; se: standard error.
Source: Author's analysis data collection.

Plate 2. Mechanism of regeneration of *A. senegalensis* by seedling (a) and stump sucker (b).

The significant difference between the height size classes for the two phytogeographical zones showed that the species has difficulties transitioning between development's stages. This could be due to bush fire and grazing, which are particularly intense and frequent in north-sudanian zone (Thiombiano and Kampmann, 2010; Hounkpèvi et al., 2020). Tropical woody species, such as *Khaya senegalensis* (Desr.) A. Juss., *Anogeissus leiocarpa* (DC.) Guill. and Perr are negatively impacted by extensive grazing (Sinsin et al., 2004; Glèlè and Sinsin, 2009).

Spatial distribution and mechanism of natural regeneration

The distribution of juveniles is aggregative around the adult shrubs and random far away. The random distribution characterizes disturbed environments (Arbonnier, 2019) with strong anthropic actions such as fallows that *A. senegalensis* colonizes.

The aggregative distribution tendency around adult individuals traduced the dissemination capacity of the species. The aggregative distribution is a characteristic of a sexual reproduction (Idohou et al., 2016). The fruits of *A. senegalensis* are relatively heavy berries that fall at maturity under the mother-shrub. In the absence of predators, the seeds remain there and germinate around the mother-tree. The reproduction by seeds explains the aggregative distribution around the mother-tree (Hsieh et al., 2000; Bellefontaine, 2005b; Tolédo et al., 2012; Sanou et al., 2018). Seedlings are assumed to be better adapted to the environmental conditions compared to stump rejection. The proportion of juveniles resulting from the stump rejection in north-sudanian zone is higher while in south-sudanian zone, the proportion of seedlings is higher. The abiotic conditions are suitable for regeneration by seed in south-sudanian. On the other hand, in the north-sudanian, the anthropic actions induce a stress, which explains the abundance of the rejections. Thus, species from savannahs and disturbed environments such as *A. senegalensis*, faced with anthropogenic actions have developed a resilience strategy (Ky-Dembélé et al., 2007; Nzunda et al., 2007) by vegetative propagation. The ability to reject could be linked to the ecology of *A. senegalensis* (Bellefontaine, 2005b). The tuberous taproot is an ecophysiological phenomenon that explains programmed abscission (Bationo et al., 2001) but also the rejection phenomenon in *A. senegalensis*. Indeed, vegetative propagation is often response of woody species to environmental disturbances such as drought, bush fire, livestock, and grazing (Teketay, 1997; Hoffmann and Solbrig, 2003; Ouédraogo and Thiombiano, 2012).

Implications for *A. senegalensis* conservation

Studies on tropical species have showed difficulties in the transition from stratum 1 to stratum 2 (Ouedraogo et al., 2009; Agbogan et al., 2017). Indeed, the difficulty of transition between stratum 1 and 2 due to environmental conditions (Hounkpévi et al., 2020). This implies that in a framework of the restoration of the degraded zones, maintenance of the individuals of stratum 1 in nursery until stratum 2. The juveniles of stratum 1 raised in village nurseries and planted in developed sites will have better growth. Assisted natural regeneration in farmlands will contribute to the better growth of juveniles and help restore the species. Addition, vegetative reproduction by shoots in seeds will allow the production of seedlings in nurseries and an important step of the species' domestication. However, the good density of regenerating individuals in both phytogeographic areas suggests that *A. senegalensis* can be used to restore disturbed areas such as farmlands left to fallow. Furthermore, according to Chazdon and Guariguata (2016), this species can contribute to landscape restoration in tropical regions through its resilience ability. Indeed, releases following anthropogenic actions and the abundance of juveniles from the seed may restore the species in its habitats and hence deforested areas. Moreover, the landscape restoration should focus on restoring the ecosystem functions (Stanturf et al., 2001) of species with high use values such as *A. senegalensis*.

Conclusion

This study showed that the structure of the regeneration's individuals of *A. senegalensis* is unstable. The quantity of the seeds in the fruits allows good dissemination by the sexual way. *Annona senegalensis* presents ecophysiological characteristics that allow it to produce offshoots and to develop resilience to multiple anthropic actions and to the degradation of climatic conditions. Moreover, it will be necessary to control the anthropic pressures by raising awareness on the endangered status of *A. senegalensis* and to practice natural assisted regeneration and vegetative propagation in order to protect the population of *A. senegalensis* for the future generations.

CONFLICT OF INTERESTS

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.

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