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RELATIONSHIP BETWEEN REGENERATION OF BLACK ALDER (*ALNUS GLUTINOSA*) AND ANTHROPOGENIC FACTORS IN RIPARIAN FORESTS AT ITS LIMIT RANGE

SUMMARY

Natural regeneration is crucial for maintaining evolutionary processes in plant species. Understanding the factors that influence recruitment dynamics could shed light on the key processes governing this critical biological process. However, the relationship between anthropogenic factors and the regeneration of *Alnus glutinosa* in Morocco remains unexplored, despite significant habitat reduction due to fragmentation and human disturbance. Twelve representative populations were selected, and ten plots were established in each population. The slope of a linear regression and histograms were used to determine the status of regeneration. Principal component analysis and a linear mixed-effects model (LME) were then employed to evaluate the impact of tree cutting, agricultural practices, cover, slope, and altitude on the natural regeneration of *Alnus glutinosa* across ontogenetic stages (seedlings, young individuals, shrubs, and adult trees) within its populations. Three regeneration patterns were observed: a reversed J-shape, a J-shape, and an irregular shape. The main causes of this species' decline were agricultural activities and tree-cutting. Seedling recruitment was positively associated with slope variation. Additionally, average vegetative cover supported recruitment, and there was no significant correlation between natural regeneration and altitude. Further artificial intervention measures should be considered to promote plantation regeneration. These findings provide a solid foundation for future forest restoration and sustainable management initiatives.

Keywords: Natural regeneration, black alder, anthropogenic factors, conservation

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INTRODUCTION

Natural regeneration is a critical mechanism for generational succession in forest ecosystems (Dech *et al*. 2008; Tinya *et al.* 2009). It is essential for preserving forest sustainability in the long term (Lewis *et al.* 2019). It also enables ecosystems to recover following disturbance (Johnson *et al*. 2021; Pham *et al*. 2022). Compared to artificial regeneration, the natural regeneration of stands from seeds is a more cost-effective and ecologically beneficial approach (Zhao *et al*. 2023). However, human-induced disturbances strongly influence the regeneration success of woody species, controlling the vegetation structure and composition of forests (Tadele *et al*. 2014). This issue has been highlighted in various studies (Winter *et al*. 2017; Kidane *et al.* 2018). The overuse of resources has recently led to significant ecological changes worldwide, largely due to misguided economic policies (Mutia, 2010). Furthermore, population growth and associated factors, such as deforestation for agricultural expansion, fire, and wood collection for charcoal production, have accelerated the decline in forest resources in developing countries (Yakob and Fekadu 2016; Kidane *et al*. 2018). In addition, forest regeneration may be very challenging in areas where the natural forests are degraded and isolated. Riparian forest ecosystems are an important source of multiple ecosystem services, including ecological, socio-economic, and cultural functions (Naiman *et al*. 2005; Riis *et al*. 2020). These services are particularly important at the local level, significantly influencing the physical and chemical processes of aquatic and terrestrial ecosystems (Naiman *et al.* 2005). Unfortunately, all riparian habitats, including *A. glutinosa,* are subject to numerous anthropogenic pressures in the Mediterranean basin. These include the riverbeds cleaning, water abstraction for irrigation and industry, and agro-pastoral activities (Cooper *et al*. 2013; Fois *et al*. 2021).

The Moroccan populations of *A. glutinosa* have remained isolated since the last glacial maximum (Douda *et al.* 2014; Mandák *et al.* 2016). The distribution of these populations is scattered and patchy, and they are geographically isolated from the main distribution of continental Europe (Claessens *et al*. 2010). This represents an exceptional biogeographical situation, as isolated populations (Lepais *et al.* 2013). The range of *A. glutinosa* in Morocco has been significantly reduced due to habitat fragmentation and disturbance caused by human activities (Ennouni *et al.* 2021). Regarding the status of alder in the regional Red List (Fennane, 2021), it is clear that the current status is near threatened (NT) or least concern (LC). However, this status should be revised and replaced by the Endangered category (/EN/ B1ab+B2ab) (Ennouni *et al.* 2021). The IUCN (2012) has classified this species as endangered in Morocco, and the threat is being exacerbated by climate change (Pachauri *et al.* 2014). Therefore, restoration work should be carried out in multiple regions, including Morocco, through various efforts such as trees replanting (enrichment planting and natural regeneration). To date, no study has examined the anthropogenic effects on the natural regeneration of *Alnus glutinosa* (*A. glutinosa*) in Morocco.

To address this research gap, the present study examined the impact of environmental factors and anthropogenic drivers on natural regeneration across different ontogenetic stages (seedlings, young individuals, shrubs, and trees) in *A. glutinosa* populations. The research objectives were threefold: (i) evaluating the influence of altitude, slope, and cover factors on *A. glutinosa* regeneration dynamics; (ii) evaluating the anthropogenic factors (tree cutting and agricultural practices) on regeneration success across developmental stages; and (iii) proposing some management strategies to enhance the efficacy of natural regeneration. These findings are expected to provide critical insights into optimising *A. glutinosa* population restoration and informing sustainable forest regeneration practices in Mediterranean ecosystems.

MATERIAL AND METHODS

Study area

The populations of *A. glutinosa* selected for this study are located in the central-western Rif region of northern Morocco (Sahli *et al.* 2023; Sahli *et al.* 2025a). This species inhabits riparian habitats within a range of bioclimatic environments, from subhumid to perhumid (Table 1).

Table 1. The main characteristics of the study sites. Altitude (ALT). The average maximum temperature during the warmest month of the year (M°C). The average minimum temperature during the coldest month of the year (m°C), and the average annual precipitation (P)

Population	**Code**	**ALT-max (m)**	**Latitude (°)**	**Longitude (°)**	**P mm**	**M °C**	**m°C**	**Bioclimats**
Ain Korra	AK	1377	35.16546	-5.31642	1772,13	27	2,1	PH-F
Amlay	AM	1412	35.10789	-5.22525	1005,20	33,5	5,5	H-T
Ben Idder	BN	1377	35.22106	-5.323	1108,00	33,9	6,3	H-T
Boubiyine	BO	1412	35.12983	-5.23099	1005,20	33,5	5,5	H-T
Bouztate	BZ	1505	35.00803	-5.11503	1482,20	32,5	2,5	H-F
Khezana	KH	1562	35.03445	-5.14031	1482,20	32,5	2,5	H-F
Oued Lakhmis	OL	240	35.28634	-5.15291	464,50	28,9	8,6	SH-C
Siouana	SO	596	35.28816	-5.46806	816,80	32,0	6,1	H-T
Tanghaya	TN	1477	34.972778	-5.15222	1482,20	32,5	2,5	H-F
Tayenza	TY	1603	35.16082	-5.25836	1772,13	27	2,1	PH-F
Tifouzal	TF	390	35.06139	-5.16553	1005,20	33,5	5,5	H-T
Ketama	KT	1 308	34.878610	-4.619722	1 616,00	28	1	PH-F

Note: Bioclimates: PH=Perhumid; H=Humid; SH=Subhumid. Bioclimatic variants: Winter: F=Cool; T=Temperate; C=Warm. M°C: average of the maximum temperatures in the warmest month of the year. m °C: average of the minimum temperatures in the coldest month of the year. P: average annual precipitation in mm

From an edaphic perspective, the species settles on schistous substrates in the central Rif and on sandstone substrates in the western Rif (Table 1). The distribution of this taxon's populations of this taxon demonstrates that they are situated along an altitudinal gradient (Sahli *et al.* 2025b). The highest altitudes were observed in the Tayenza populations (1.603 m), while the lowest altitudes were observed at the Oued Lakhemis site (240 m) (Table 1) (Sahli *et al.* 2025c). Observed precipitation levels ranged from 464 mm to 1.770 mm. In terms of stand typology, most stands are classified as high forest (97.73%), with coppice stands being relatively uncommon and predominantly found in heavily disturbed sites. These stands were primarily observed in three locations: The locations in question are Tayenza, Bouztate, and Amlay. (Ennouni *et al.* 2021). Conversely, an examination of the composition of these populations revealed that they are characterized primarily by the dominance of *A. glutinosa* individuals. In these stands, the tree layer dominated by *A. glutinosa* is rarely mixed with *Prunus lusitanica*. This mixture only occurs at the upper limit of the black alder population, corresponding to the base of the *Prunus lusitanica* populations, and marking the transition zone between the two populations (Ennouni *et al.* 2021).

Sampling

Riparian vegetation sampling was conducted during the summer months. Twelve sites were selected for the study (Figure 1). A total of 120 plots were set up. The different types of *A. glutinosa* individuals were classified according to their height.

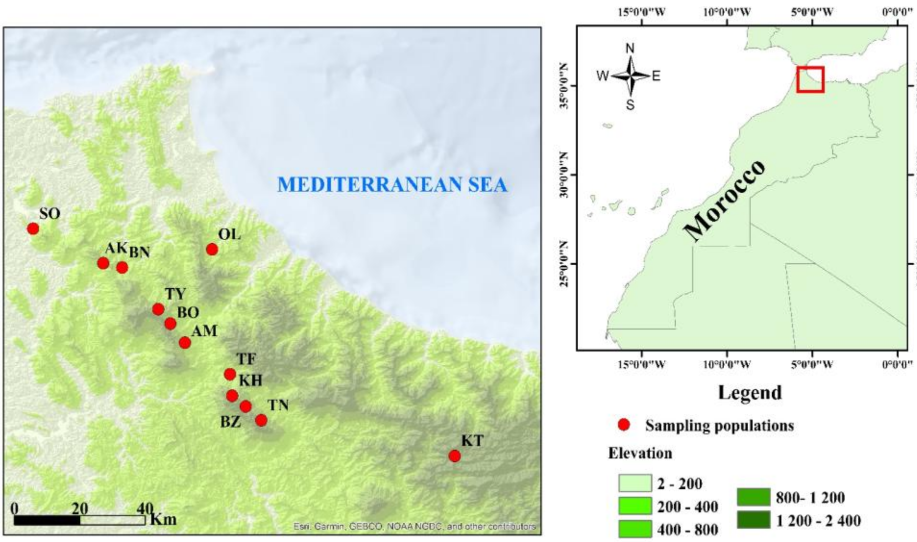

Figure 1. Geographical location of the populations studied in the central-western Rif. Acronyms of populations: SO: Siouana; AK: Ain Korra; AM: Amlay; BN: Benidder; BO: Bobiyine; BZ: Bouztate; KH: Khezana; OL: Oued Lakhmis; TN: Tanghaya; TY: Tayenza; TF: Tifouzal; KT: Ketama

Seedlings were defined as individuals with a height of 0-50 cm, young individuals (50-100 cm), shrubs (100-200 cm and 200-400 cm), and trees (height >400 cm) (Setshogo and Venter 2003; Burton *et al.* 2005; Tsheboeng *et al.* 2017). The height of *A. glutinosa* individuals identified was estimated in a 10 randomly selected 10×10 m^2 quadrat at each site. Additionally, the number of *A. glutinosa* individuals in each height class within each quadrat was recorded.

Density was standardized and expressed as the number of individuals per 10^3 m^2.

Statistical Analyses

The measured variables are presented with the following parameters: the arithmetic mean (M) and confidence intervals (CI). The nested analysis of variance (ANOVA) was performed to show the level of difference in density and height. The Tukey post-hoc test was used to determine whether there was a statistically significant difference in the density of the various types of individuals of this species across the different sites.

The graphs were conducted for this species at each site to facilitate a comparison of the regeneration structure between the studied populations (Tsheboeng *et al.* 2017). The principal parameters that define the sites, including bank slope, altitude (Debruxelle *et al.* 2004), and cover, were estimated based on available data. Additionally, the intensity of anthropogenic disturbances was assessed following the methods proposed by Debruxelle *et al.* (2004). These disturbances included the cutting of adult trees (i.e., the number of trees cut in each plot) and intensified agricultural practices (i.e., the area of land occupied by agricultural practices around the riparian zone of the species).

The regeneration status of different woody individuals was determined using Shackleton's (1993) procedures by analyzing the slope of a linear regression between height classes and the mean number of individuals per 103 m^2 in each class. A positive slope indicates a population with a greater number of individuals in the larger size classes than in the smaller ones. Conversely, a negative slope suggests ongoing recruitment, where there is a greater number of individuals in the smaller size classes than in the larger ones (Tsheboeng *et al*. 2017).

To quantify the direct impact of anthropogenic and environmental factors on the density of seedlings, young individuals, shrubs, and trees, we applied linear mixed-effects models (LMEs). This approach was chosen to explicitly account for the hierarchical structure of the data, whereby observations are nested within sites, by including site as a random effect. Using LMEs allowed us to separate local-scale variability from broader environmental and anthropogenic influences, thus improving parameter estimation and inference (Salazar Zarzosa *et al.* 2021). Linear regressions were also applied where data aggregation permitted (Sahli *et al*. 2005a). Furthermore, as many of the anthropogenic and environmental variables were expected to be correlated, we conducted a principal component analysis (PCA). This was employed to cluster correlated variables, identify the dominant factors shaping site variations, and simplify the interpretation of multivariate relationships within and between populations. Using PCA alongside LME enables both an exploratory assessment of the structure of the variables and a formal evaluation of their effects on density. Data statistics were analyzed using the R 4.1.3 software program (R Core Team 2024).

In this study, individuals with a height between 200 and 400 cm were defined as shrubs, while trees were considered to be individuals with a height greater than 400 cm (Setshogo and Venter 2003; Tsheboeng *et al.* 2017).

RESULTS AND DISCUSSION

The results illustrate a significant difference in the density between the various categories of individuals within *A. glutinosa* populations. The results of the ANOVA analysis and Tukey test corroborate the assertion that there is a significant difference in density between the various categories of individuals, which include seedlings, young individuals, shrubs, and mature trees (Table 2).

Table 2. Density for the different types of individuals in each population. Anova one-way and different letters Post-hoc test. significant (***p<0.001) between sites

Sites	Code Sites	Seedling	Young individuals	Shrubs	Trees
Ain korra	**AK**	20^{a}	7^{ab}	21^{ab}	11^{ab}
Amlay	**AM**	0^{a}	0^{a}	0^{a}	21^{b}
Beni Idder	**BN**	63^{b}	17^{b}	4^{a}	34^{b}
Bobiyine	**BO**	40^{b}	1^{a}	5^{a}	24^{b}
Bouztate	**BZ**	0^{a}	0^{a}	11^{b}	21^{b}
Ketama	**KT**	0^{a}	0^{a}	0^{a}	2^{a}
Khezana	**KH**	0^{a}	0^{a}	1^{a}	17^{b}
Oued Lakhemis	**OL**	0^{a}	0^{a}	0^{a}	20^{b}
Siouana	**SO**	31^{ab}	21^{a}	35^{bc}	50^{b}
Tanghaya	**TN**	177^{c}	4^{a}	8^{a}	39^{b}
Tayenza	**TY**	3^{a}	9^{ab}	83^{c}	5^{ab}
Tifouzal	**TF**	1^{a}	1^{ab}	0^{a}	14^{ab}
ANOVA $_{\text{inter-populations}}$		7.01***	3.03 ***	7.37***	5.88***

Furthermore, a highly significant height difference was observed between populations for each category of individual. For example, considerable variation in height was observed among seedlings, ranging from 8.06±0.86 cm in the Tanghaya population to 37.33±7.53 cm in the Tayenza population. The results of the ANOVA analysis corroborate the significant height differences observed between the populations of the different types of individuals (Table 3).

Table 3. Mean height (Mean±CI) for the different types of individuals in each population. Anova one-way and different letters Post-hoc test. significant (***p<0.001) between sites

Sites	Seedling	Young individuals	Shrubs	Trees
Ain Korra	26.45 ± 5.69^{b}	77.14 ± 0.00^{b}	159.11 ± 12.4^{bcd}	5.25 ± 0.45^{a}
Amlay	0.00 ± 0.00^{a}	0.00 ± 0.00^{a}	0.00 ± 0.00^{a}	8.88 ± 0.20^{a}
Ben Idder	28.87 ± 3.18^{b}	65.71 ± 0.00^{b}	0.00 ± 0.00^{a}	7.26 ± 0.13^{a}
Bobiyine	9.65 ± 1.30^{b}	55.00 ± 0.00^{b}	165.60 ± 0.00^{bcd}	11.11 ± 0.20^{ab}
Bouztate	0.00 ± 0.00^{a}	0.00 ± 0.00^{a}	106.98 ± 2.88^{bcd}	15.98 ± 0.21^{ab}
Ketama	0.00 ± 0.00^{a}	0.00 ± 0.00^{a}	0.00 ± 0.00^{a}	13.50 ± 2.09^{ab}
Khezana	0.00 ± 0.00^{a}	0.00 ± 0.00^{a}	40.00 ± 0.00^{b}	11.85 ± 0.29^{ab}
Oued Lakhemis	0.00 ± 0.00^{a}	0.00 ± 0.00^{a}	0.00 ± 0.00^{a}	9.00 ± 1.39^{a}
Siouana	22.97 ± 4.96^{b}	72.48 ± 23.33^{b}	221.44 ± 9.89^{d}	6.93 ± 0.12^{a}
Tanghaya	8.06 ± 0.86^{a}	55.00 ± 19.60^{b}	224.80 ± 4.3^{d}	12.54 ± 0.13^{ab}
Tayenza	37.33 ± 7.53^{b}	70.00 ± 8.12^{b}	227.82 ± 6.09^{d}	9.09 ± 0.87^{a}
Tifouzal	35.00 ± 0.00^{b}	65.00 ± 0.00^{b}	0.00 ± 0.00^{a}	8.12 ± 0.32^{ab}
ANOVA inter-populations	58.818***	2.579*	5.555**	5.582***

A comparison of the regeneration structures among populations of this species studied reveals that the population of Tayenza exhibits an irregular structure. The populations of Ain Korra, Beni Idder, Bobiyine, and Tanghaya display a reversed J-shape, indicating relatively stable regeneration (Figure 2). The remaining populations are characterized by unstable regeneration. The populations of Amlay, Bouztate, Ketama, Khezana, and Oued Lakhemis exhibit an absence of classes between 0 and 50 cm, 50 and 100 cm, and 100 and 200 cm. The populations of Siouana and Tifouzal display a J-shaped structure, indicating a disproportionate abundance of individuals in the tallest height classes (100-400 cm and >400 cm) compared to the shortest (0-50 cm and 50-100 cm) (Figure 2). This result was corroborated by the regeneration slope coefficient, which exhibited negative values, indicating that the regeneration of *A. glutinosa* in the populations of Ain Korra, Beni Idder, Bobiyine, and Tanghaya is relatively unimportant. Nevertheless, no evidence of regeneration was observed in the remaining populations (Table 4).

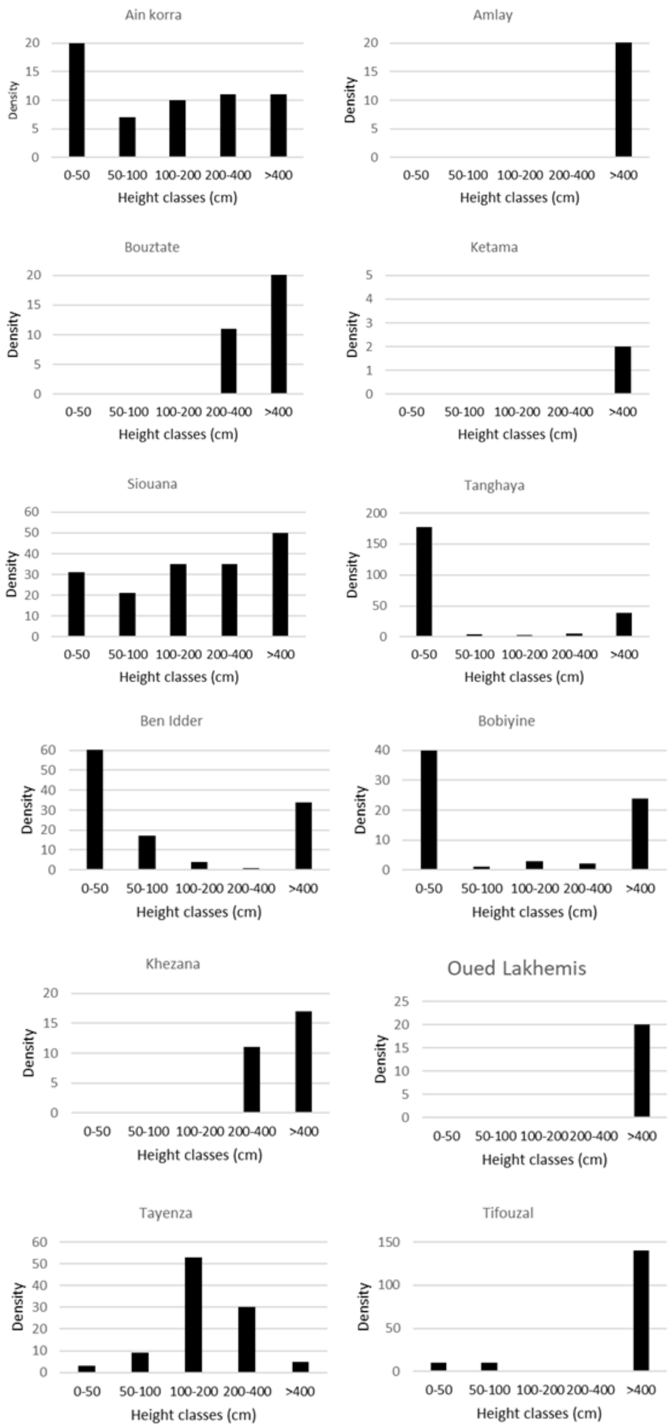

Figure 2. Regeneration structure of *Alnus glutinosa* in its representative populations

Table 4. Regression analysis slope coefficients for *A. glutinosa* in its populations

Sites	Slope coefficient
Ain korra	-0.06
Amlay	0
Beni Idder	-0.23
Bobiyine	-0.23
Bouztate	0.48**
Ketama	0
Khezana	0.96*
Oued Lakhemis	0
Siouana	0.52
Tanghaya	-0.17
Tayenza	0.46
Tifouzal	0 .35**

The Principal Component Analysis (PCA) analysis confirmed the structure of the populations and showed that this disparity in the density of the four categories (seedlings, young individuals, shrubs, and trees) could be attributed to environmental and anthropogenic factors (Figure 3). The analysis revealed that three groups within the studied populations: the first group comprises the Tayenza and Ain Korra populations, and is characterized by a high density of shrubs; the second group comprises the Siouana, Beni Idder, Bobiyine, and Tanghaya populations, and is characterized by a high density of young individuals, trees, and seedlings, respectively; and the third group comprises the remaining populations, and exhibited a level of disturbance (Figure 3).

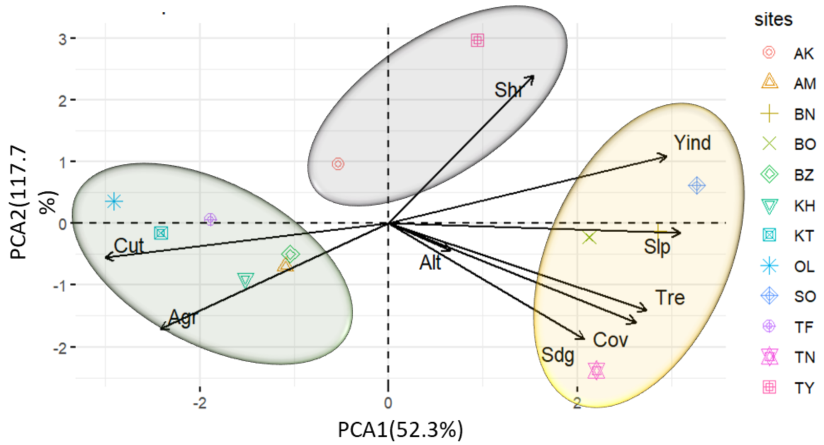

Figure 3. Principal component analysis (PCA) of density and independent factors. PCA1 and PCA2: Principal component analysis axes 1 and 2. Slp: salop. Alt: altitude. Agr: agriculture. Cut: Cutting. Cov. Cover. Sdg: seedling. Yind: young individual. Shr: Shrubs and Tre: trees. Acronyms of sites see Table 1

In addition, the PCA analysis showed that the density of seedlings, young individuals, shrubs, and trees correlates positively with the slope and cover. However, it correlates negatively with tree cutting and agricultural activities. This result was confirmed by the linear mixed model analysis (LME), which showed that tree cutting negatively affects the density of young individuals and the density of trees (Table 5, Figure 4). The slope has a positive effect on the density of seedlings, young individuals, and trees (Table 5, Figure 4). The agricultural practice negatively affects young individuals (Table 5, Figure 4). However, the altitude variation does not affect the density of the four categories (seedlings, young individuals, shrubs, and trees) (Table 5).

Table 5. Results of the LME models explaining the variation of density with anthropogenic and environmental factors. T value for each independent variable and significant correlations is indicated in bold (*P<0.05, **P<0.01, and ***P<0.001) and nearly significant (a 0.1>P>0.05) in bold.

Factors	**Variables**	**Estimate**	**Std. error**	**t value**
Cutting	**Seedling**	-0.10	0.08	-1.26
	Yong individual	-0.03	0.00	**-4.17****
	Shrubs	-0.06	0.04	-1.49
	Trees	-0.05	0.02	**-2.63***
Cover	**Seedling**	0.12	0.06	**1.95a**
	Yong individual	0.01	0.00	2.11**a**
	Shrubs	0.03	0.04	0.08
	Trees	0.05	0.01	**5.93*****
Slope	**Seedling**	0.22	0.07	**2.92***
	Yong individual	0.03	0.01	**3.22****
	Shrubs	0.06	0.05	1.14
	Trees	0.06	0.02	**2.63***
Agriculture	**Seedling**	-0.07	0.08	-0.87
	Yong individual	-0.02	0.00	**-3.24****
	Shrubs	-0.07	0.04	-1.81**a**
	Trees	-0.01	0.02	-0.64
Altitude	**Seedling**	0.00	0.00	0.71
	Yong individual	-0.00	0.00	-0.24
	Shrubs	0.00	0.00	0.43
	Trees	0.00	0.00	0.04

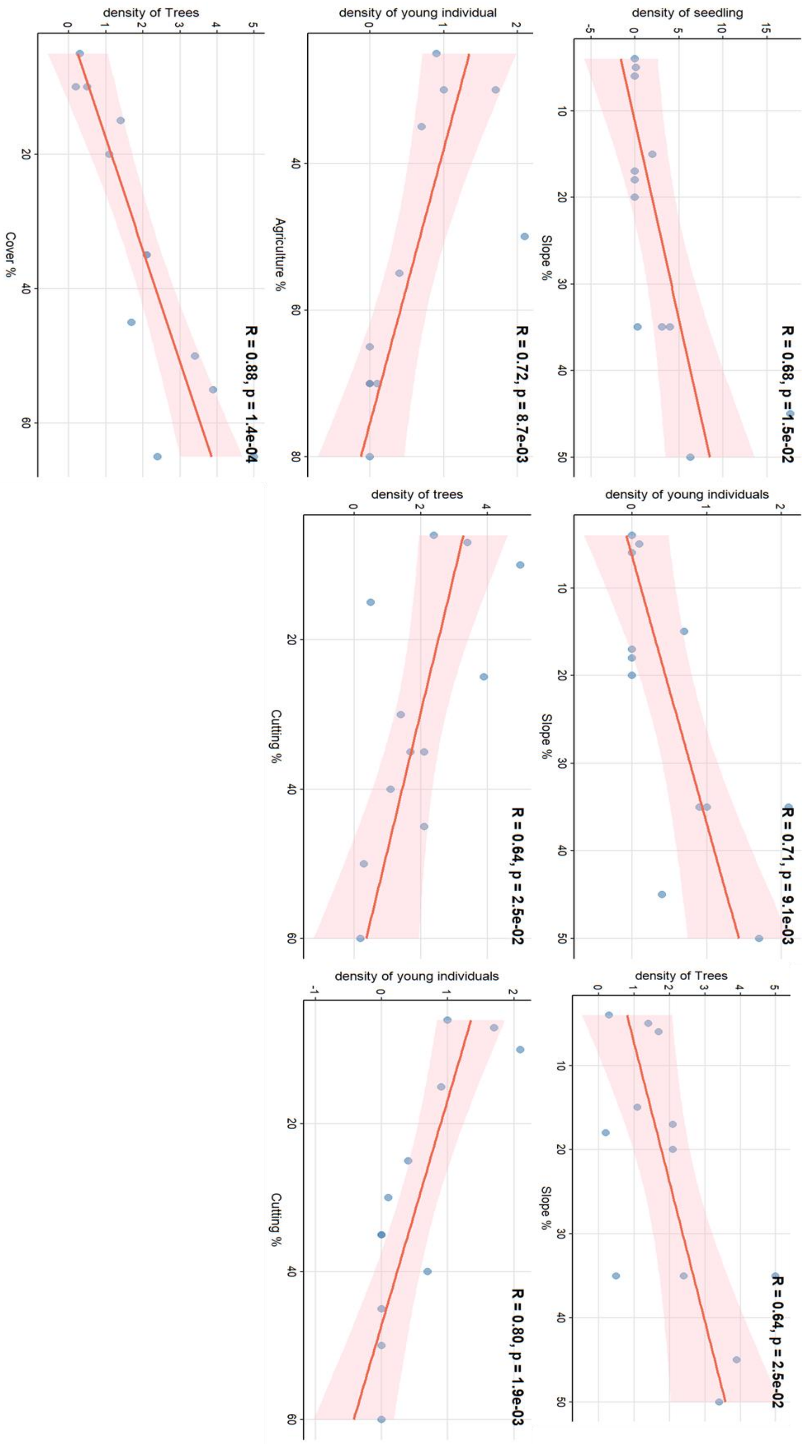

Figure 4. Linear regression analysis between population characteristics and the density of different types of individuals

DISCUSSION

Natural regeneration is a key mechanism in the generational succession of forest ecosystems (Qin *et al.* 2025). This ecological process is essential for ensuring the long-term sustainability of forests (Lewis *et al.* 2019) and helps ecosystems to recover after disturbance (Johnson *et al.* 2021; Pham *et al.* 2022). Compared to artificial regeneration, seed-based natural regeneration is a more economical and ecologically efficient method of stand restoration (Zhao *et al.* 2023). However, the overall regeneration status of the woody species at the study site was unsatisfactory at the population level, with poor regeneration observed in the Amlay, Bouztate, Ketama, Khezana, and Oued Lakhemis populations. This was evident through the absence or low recruitment of *A. glutinosa* seedlings within their natural populations, which may indicate a correlation between seedling density and population characteristics. Good regeneration of this woody species was observed at Ain Korra, Beni Idder, Bobiyine, and Tanghaya, characterized by a reverse J-shape. The linear mixed-model analysis revealed that agricultural activities such as overgrazing and tree cutting negatively impact the density of young individuals. Intensive trampling by livestock while browsing and grazing in the forest also compacts the soil, thereby reducing the germination of seeds from the soil seed bank (Gebirehiwot *et al.* 2023). This could explain the poor regeneration of the *A. glutinosa* species.

In addition, the positive correlation between seedling density and tree density (Figure 3) suggests that the cutting of trees will reduce the quantity of seeds produced and, consequently, lead to a decline in seedling density. Furthermore, well-established that *A. glutinosa* seeds have a low germination capacity (De Atrip and O'Reilly 2005; De Atrip and O'Reilly 2007; Gosling *et al.* 2009; Kaliniewicz *et al.* 2018; Gomes Marques *et al.* 2021). This is because most of the seeds produced by this species are devoid of any viable contents (McVean, 1953). The findings also indicate that an increase in tree cover is associated with an elevated tree density and moderate increases in seedling density and young individuals (Table 5). Moderate cover has been shown to reduce evapotranspiration and protect young seedlings (Gómez-Aparicio *et al*. 2005). Conversely, high canopy cover, in conjunction with a light-poor understorey, markedly restricts photosynthetic activity, thereby rendering regeneration untenable for more than one year (La Mela Veca *et al.* 2013). Additionally, low cover can impede the impact of radiation intensity reaching the soil, which may negatively affect seedling growth (Gómez-Aparicio *et al.* 2005, 2008). This is exemplified by the Amlay, Bouztate, Ketama, Khezana, Oued Lakhemis, and Tifouzal populations, which demonstrate minimal or no seedling growth. The low or zero density of height classes 0.5 to 1 m (young individuals) in the populations of Bouztate, Ketama, Khezana, Oued Lakhemis, and Tifouzal (Figure 2), can be attributed to the impact of agricultural activities and the cutting of adult trees (Table 5, Figure 5). These are the primary direct causes of the decline in young individuals. Furthermore, these populations are also subject to impact from wild herbivores (Figure 5). Their proximity to human communities has resulted in the overexploitation of water resources by riverside communities, and the diversion of watercourses for the irrigation of food crops (Ennouni *et al*. 2021). Additionally, the presence of goat herds has been observed to intensify the impact of human activities (Benamar 2005). Additionally, the disposal of garbage and the discharge of wastewater containing chemicals (Figure 5) have the potential to impede growth and cause the death of young individuals due to the toxicity of these substances. This low density could indicate a local extinction in the future, as the dying trees will not be replaced.

Figure 5. Intensive impacts on *A. glutinosa* in some populations. a: Cutting of trees (Tanghaya site). b: Grazing (Bouztate site). c: Pollution (Oued Lakhemis site) and c: Water capture for agricultural activities (Bobiyine site)

The low density of *A. glutinosa* individuals in the medium height classes (shrubs) in Amlay, Beni Idder, Ketama, Khezana, Oued Lakhemis, Tanghaya, and Tifouzal populations may be attributed to agricultural activities, as illustrated in Figure 5. For instance, raising goats along the riverbanks has been observed to result in the consumption of the leaves and young shoots of *A. glutinosa*. Furthermore, the weakening of the herbaceous layer during the summer period exerts additional pressure on the young *A. glutinosa*, not to mention the impact of overgrazing (Ennouni *et al.* 2021). The low density of shrubs may also be due to the selective removal of individuals before the onset of the next growth phase begins (Gurmessa *et al*. 2012), a process that can be facilitated by herbivory

(Bendaanoum, 1998). Herbivory can disrupt the soil structure through compaction (Hulme and Borelli, 1999; Smit *et al*. 2006), and also modify the vegetation and soil structure (Addar *et al.* 2016). Conversely, the findings indicate that the slope is conducive to the successful establishment of young individuals (Table 5). Populations characterized by a low density of young individuals are typically situated on gentle slopes. This is exemplified by the populations of Amlay, Bobiyine, Ketama, Oued Lakhemis, and Tanghaya. Indeed, a moderate slope facilitates the accumulation of nutrients in minor watercourses (Bergérs 2004). The watercourses of this species are typically narrow and characterized by weak banks. (Ennouni *et al*. 2021). However, Chhetri *et al.* (2023) posited that slope exerts no significant influence on species regeneration.

In terms of regeneration structure, populations of *A. glutinosa* Tayenza are characterized by a higher number of low-height individuals (seedlings) than medium-size individuals (young individuals and shrubs). This may be indicative of episodic recruitment (Helm and Witkowski 2012; Traoré *et al.* 2013). In episodic recruitment, there is variation in the growth of individuals in different size classes over time (Helm and Witkowski 2012), indicating that in the past, individuals from lower size classes were previously recruited. This episodic recruitment may result from the selective removal of individuals from the medium-sized classes before they are recruited into the subsequent growth stage (Gurmessa *et al*. 2012). In our study, the elimination of individuals from these classes in Beni Idder and Bobiyine may result from herbivory (Ennouni *et al*. 2021), and agricultural activities.

This species exhibits an irregular regeneration pattern in the Tayenza population, characterized by the absence of height classes of 0-50 cm, 50-100 cm, and 100-200 cm. In contrast, the populations of Siouana and Tifouzal exhibit a J-shaped regeneration structure. The presence of these two regeneration shapes suggests that the regeneration process in these populations is inherently unstable. This result was corroborated by the positive slope coefficient. The low reproduction can be attributed to the low pollen viability of this species (Sahli *et al.* 2025d). Sahli *et al*. (2026) demonstrated that the pollen development of this species is primarily influenced by the climatic factors, particularly temperature, which impacts the starch content in the pollen. Additionally, regeneration in these populations may be attributed to herbivory (Benamar 2005; Ennouni *et al.* 2021). The potential for extinction of this species is exacerbated by the scarcity of individuals in the smaller size classes, hindering the replacement of deceased older individuals. The J-shaped regeneration structure observed in riparian species may indicate local extinction in the future due to the lack of replacement for older and dying stands (Helm and Witkowski 2012).

In the Tanghaya, Beni Idder, Bobiyine, and Ain Korra populations, the *A. glutinosa* is designated as a reverse-J shape. This suggests relatively stable regeneration (Figure 2). Reverse-J shape regeneration is considered a healthy phenomenon because it enables deceased individuals from lower size classes to be replaced (Mwavu et al. 2009). This regeneration structure also demonstrates that individuals are subject to selective elimination in subsequent height classes (Senbeta *et al.* 2003; Gurmessa *et al.* 2012). As observed in these two populations, there is a scarcity of individuals within the 50-100, 200-400 cm, and >400 cm size classes. The removal *A. glutinosa* individuals may have had a detrimental impact on its regeneration structure, as indicated by a low negative regression coefficient (Table 5). Generally, a negative regression slope of height classes indicates that there is ongoing recruitment (Shackleton, 1993). The wood of *A. glutinosa* is generally used by riparian populations for various purposes, including as an energy source, fodder, and services (Ennouni *et al.* 2021).

Other factors that could influence the density of riparian species include, in particular, the construction of dams in watersheds, hydrological and climatic changes (Parolin and Wittmann 2010), and prolonged drought, which mainly affects seedlings that have not yet developed roots to reach underground depths (Pettit *et al.* 2001). The impact of other factors, such as fires, floods, pathogens, competition, light, water regime (de Oliveira *et al*. 2014; Tsheboeng *et al*. 2017), and seed predators (Mwavu *et al.* 2009), must also be considered.

CONCLUSIONS

A better understanding of anthropogenic factors affecting the density of seedlings, young individuals, shrubs, and trees is essential for achieving the regeneration of *A. glutinosa*. The slope and cover favor the seedling recruitment and young individuals' establishment. However, the altitude was not associated with the natural regeneration. Based on PCA analysis and LME analysis, our findings indicate that the natural regeneration of *A. glutinosa* is significantly influenced by agricultural practices and the cutting of trees. This leads to a reduction in the habitat of *A. glutinosa* in its rear-edge populations in Morocco. In addition, this human impact will be added to the loss of their genetic diversity of these isolated populations due to inbreeding and genetic drift, which subsequently leads to the accumulation of deleterious mutations. Protection and conservation of this habitat in the range of *A. glutinosa* in Morocco from fragmentation and disturbance caused by human activities should be in the purview of conservation programs. Further studies on seed germination and control of grazing, protection of seed trees may prove valuable in elucidating the status of this species and in formulating conservation strategies for its populations in Morocco.

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