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Should the silviculture of Aleppo pine (*Pinus halepensis* Mill.) stands in northern Africa be oriented towards wood or seed and cone production? Diagnosis and current potentiality

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The aim of this work is to review studies on the silviculture of Aleppo pine (*Pinus halepensis* Mill.) in North Africa and the Mediterranean basin over a period of 50 years. The study presents a synthesis of: (i) silviculture; (ii) wood productivity and growth; (iii) cone and seed production; and (vi) the socio-economic role of Aleppo pine. The results show that the production of the Aleppo pine is enhanced by the potential of the site, which is closely related to the bioclimatic stage and soil fertility. For instance, production increased from 0.4 to 4 m^3 ha^{-1} yr^{-1} in an Aleppo pine stand with a dominant height varying between 9.7 and 22.8 m. Previous studies confirmed that the average maximum volume in annual growth of Aleppo pine is 3.3 m^3 ha^{-1} yr^{-1} for 40-year old stands at good-fertility sites. The lowest values (<0.5 m^3 ha^{-1} yr^{-1}) were recorded for the fourth and last class of productivity in >100-year old stands. There is high demand for Aleppo pine seeds in North Africa, making their production profitable, and this represents an important sector for the sustainable development and improvement of living-standards of the local populations. There has been a steady increase in the demand for seeds across years, with seed production becoming a very promising niche. Silviculture oriented towards the commercial production of seeds is expected to enhance this species, as well as facilitate its preservation.

Keywords: Aleppo Pine, *Pinus halepensis* Mill., Silviculture, Wood Production, Seed Production, Socio-economic Role

Introduction

For centuries, Aleppo pine (*Pinus halepensis* Mill.) forests have been subject to heavy human pressure (clearing, illegal logging, fires, pastures), leading to the degradation of plant cover. In addition, successive and prolonged droughts cause the drying and withering of standing trees. As for production and growth, the Aleppo pine has been the subject of many studies in Mediterranean countries, particularly France (Bedel 1986, Couhert & Duplat 1993), Spain (Montero et al. 2001), Morocco (Belghazi et al. 2000), Italy (Ciancio 1986), Algeria (Bentouati 2006), and Tunisia (Souleres 1975, Souleres 1969, Chakroun 1986, Ammari et al. 2001, Sghaier & Garchi 2009, Sghaier & Ammari 2012). Because of its low requirements and high plasticity, Aleppo pine has been extensively used as a reforestation species to restore degraded areas. Indeed, Aleppo pine is one of the few species that easily grows on poor and dry soils. In semi-desert regions, particularly in Libya, this species is distinguished by its tolerance to drought, growing in areas with 250 mm annual rainfall. However, the species cannot withstand prolonged periods of frost and is vulnerable to heavy snowfall, as its branches are fragile and easily broken (Ricodeau 2013). In Tunisia, Aleppo pine forests (*Pinus halepensis* Mill.) have fundamental environmental, economic, and social roles. According to the last national forest inventory (DGF 2010), pure stands of Aleppo pine cover an area of 361,222 ha. The average increase in height and diameter of this species does not exceed 7 cm year^{-1} and 0.25 cm year^{-1}, respectively (Belghazi 1998). Many stands of Aleppo pine originate through reforestation activity. Since 1988, planting densities in Tunisia were reduced from 2500 to 1600 trees ha^{-1}. Consequently, because of the mechanization of soil preparation, particularly in the richest sites, the production of Aleppo pine stands has increased from 6 to 8 m^3 ha^{-1} yr^{-1} (Jalel 1996).

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Silviculture of Aleppo pine stands

Thinning

Thinning is a treatment used to improve the structure of growing forest stands. Thinning gives rise to woody samples or intermediate products that can be marketed. For a forest stand, thinning enhances the availability of water to trees (Breda et al. 1995, Ducrey & Huc 1999, Jiménez et al.

2008) and decreases the magnitude and duration of water stress (Aussenac 1987). According to Donner & Running (1986) and Misson et al. (2003), thinning improves the resistance of trees to drought, at least in short term (within about 5 years of thinning). In fact, there is no ideal thinning regime across all forest stands, because each stand occupies a site with unique characteristics. However, within the same forest compartment, several successive clearings are made before regeneration method (Alaoui et al. 2011). Belghazi (1998) concluded that the periodicity of thinning could be decided with a fixed rotation every 10 years. Boudy (1952) observed that thinning rotation ranges between 6 and 15 years, in general. Bentouati (2006) reported that, in Algeria, the Aleppo pine has a very high juvenile growth rate. This suggestion was confirmed by stem analyses, which showed a gain in height of 20 cm year^{-1} during the first 40 years, 15 cm year^{-1} between 40 and 80 years, and a gradual decline to 5 cm year^{-1} after 100 years. Montero et al. (2001) used a rotation from 10 years when constructing Aleppo pine production tables in Spain. Frantz & Forster (1979) adopted a rotation of five years in Beni-Imloul in Algeria. Couhert & Duplat (1993) chose a variable rotation strategy based on the fertility classes adopted in France. In Morocco, Alaoui et al. (2011) distinguished two distinct periods of rotation for thinning Aleppo pine stands: every five years in reforested Aleppo pine stands and every 10 years in natural stands. In Tunisia, 70% of Aleppo pine stands are less than 60 years old, with thinning practices reflecting this status (Sghaier & Ammari 2012). In Algeria, Bentouati (2006) suggested that thinning intervenes with the removal of dominant trees, benefitting future elite trees only. In France, Couhert & Duplat (1993) recommended the use of high intensity thinning to eliminate almost 43% of trees from first class of fertility that are 43-years old. In the Beni-Imloul massif in Algeria, Frantz & Forster (1979) practiced intensive thinning, which was justified mainly because of the advanced age of most forest stands and because of the health status of trees that had been attacked and infected/infested by insects and diseases.

Age of operability of Aleppo pine stands

The current annual increment (CAI) and mean annual increment (MAI) curves converge with age. The highest point of the MAI is the age used to determine the age of operability of Aleppo pine stands in management. It is possible to use this indicator (age of operability) to maximize wood production in forest stands (Clutter et al. 1983, Davis & Johnson 1987, Davis et al. 2001). According to Chakroun (1986), the age of operability of Aleppo pines in Tunisia corresponds to an average diameter of 30 cm. According to Bentouati (2006), this age is set between 70 and 90 years, depending on fertility classes. Sghaier & Ammari (2012) showed that, for Aleppo pine in Tunisia, the age of operability for the first productivity class is about 50 years, while it is 80 years for the second class and exceeds 100 years for the third class.

Silviculture of Aleppo pine stands after fire

Aleppo pine is very sensitive to fire, which causes the cones to burst, thus facilitating regeneration. Seed dispersal is favored by wind and animals. Germination begins after the first rains, towards the end of summer, and continues over the rest of the year (Vennetier 2003). Following fire, natural regeneration leads to the formation of a very dense thicket stage during earliest years. This excessive density leads to slow growth, caused by competition between young plants and a decline in stand vigor. In this case, it is necessary to intervene as soon as possible by implementing cleaning operations aimed to reduce the number of seedlings and regulate density. Intervention in regeneration is obligatory in the young forest compartment, and improvement operations must be gradual and repeated at short intervals (Bentouati 2006).

Management of Aleppo pine forests

Aleppo pine forests are managed as even-aged forest. This type of treatment makes thinning interventions economically feasible (Vennetier et al. 2010). A study by Bentouati (2006) showed that the structure of natural Aleppo pine forests is clumped in Aurès-Algeria. Therefore, regeneration was achieved by clear-cutting small areas in mature stands. These cut surfaces in stands grew as the seedling developed from 10 to 20 years.

Chakroun (1986) proved that the even-aged forest regime in Tunisia is the most appropriate for managing Aleppo pines, because it is simple to apply. Nevertheless, the spatial typology of stands, which is generally clumped, implies the differentiation of interventions according to stand typology. While the basic unit of technical management in forest stands is the compartment, compartments are grouped into regeneration, improvement, and/or reconstitution areas, according to use and typology. The management planning period is usually 20 years in Tunisia.

Natural regeneration of Aleppo pine forests

To regenerate Aleppo pine forests, seeds must be regularly spaced and removed from the influences of man and animals (Nsibi 1997). In a study of the natural regeneration of Aleppo pine forests in Oum Jeddour (central Tunisia), Langley (1976) showed that the natural dispersal of seeds was weak in Aleppo pine stands. Consequently, spreading branches containing cones during thinning or clearcutting could increase the quantity of seeds dispersed. Furthermore, tillage associated with high cover density facilitates the establishment of seeds.

Acherar et al. (1984) showed that the colonization of Aleppo pines is restricted to a limited distance from the parent tree, with just 3% of seeds falling more than 24 m from the parent tree. Seeds germinate quickly, with the germination rate being high during the wet season. However, despite the high mortality of young seedlings, especially in the first two years, the loss of regenerated plants is compensated for by the production of large numbers of seeds and the high germination rate (Acherar et al. 1984). Quezel & Médail (2003) reported that, even in dense Aleppo pine forests, regeneration is not a problem, as long as there is sufficient illumination. Bedel (1986) showed that Aleppo pines are easily regenerated, even on very degraded soils. Certain factors, like grazing and repeated fires, are likely to hinder the survival of young seedlings, weakening the success of natural regeneration. To obtain medium and sufficient regeneration in Aleppo pine forests, trees must be cut in the form of clumps, taking care to retain young trees that carry many vital seeds.

The selection of productive seed trees must be evenly distributed on the cutting area and preserved for 3 to 5 years until a total regeneration is achieved. A density of 50 pines per hectare is considered as the minimum threshold (D'hanens 1998). In rugged relief, cutting should be conducted in broad strips that are wide one to two times the height of trees. When there is invasive undergrowth of Aleppo pine, coppicing is necessary. Once regeneration is achieved, it is necessary to intervene starting from the 5th year by cleaning and eliminating poorly trained trees. This operation aims to distribute seedlings optimally in the space, enhancing the living space of each individual and reducing the effect of competition. This approach allows future seedlings that establish to develop naturally, possibly facilitated by tillage (Neveux et al. 1986).

Regeneration is practiced by the localized clearcutting of mature stands in small areas, which increase in size as seedlings develop, followed by a set of protection over 10 years (Nsibi 1997). El Hamrouni & Sarson (1975) showed that the density of seed trees does not limit the natural regeneration of Aleppo pines, rather the rate of undergrowth recovery. Thus, reducing cover causes the number of young pines to decrease, making regeneration difficult. Medium-density stands form canopies with a more or less continuous cover, which determines a microclimate favorable for seed germination and seedling development (Nsibi 1997). The authors also reported that seeding in dense stands produces a relatively high density of natural seedlings (*i.e.*, from 2611 to 2739 seedlings ha^{-1}, with a density of more than 500 trees ha^{-1}).

Stand density of Aleppo pines after regeneration

In the semi-arid conditions of Tunisia, Tschinkel (1976) demonstrated that the most suitable spacing for the reforestation of Aleppo pine was 1.5 × 5 m, corresponding to a planting density of 1300 plants ha^{-1}. Sghaier & Ammari (2012) reported that, by adopting average silviculture, stand density remained relatively high, exceeding 600 stems ha^{-1} for stands up to 80-90 years of age. This high density might reflect the fact that forests in Tunisia have always been protected, with silviculture being absent in most stands. Ciancio (1986) showed that a density of 2222 plants ha^{-1} with a rectangle layout (distance of 3 × 1.5 m) was the optimal density. Letreuch Belarouchi (1991) suggested that the optimal density would be 1100 plants per hectare, with a spacing of 3.5 × 2.5 m, reflecting that stated in the National Reforestation Plan. Bentouati (2006) suggested that the number of stems should be stabilized between 700 and 900 stems ha^{-1} for pines of 20 and 30 years old, depending on the forest site. This suggestion is justified by the fact that the Aleppo pine is a light demanding species, with high density stands generally being characterized by slow growth. For reforestation, planting density is usually 1100 stems ha^{-1} in the plains and 830 stems ha^{-1} in the mountains (Alaoui et al. 2011). An increase in density causes smaller spacing between trees, which leads to a decrease in growth (both diameters and height), due to inter-tree competition. Consequently, the volume and productivity of the entire stand decreases (Cherak 2010).

Productivity and growth of Aleppo pine forests

An important characteristic of forest stands for silviculturists to be precisely documented is wood production (Garbaye et al. 1970). Wood production corresponds to the volume of the tree, with and without branches, under bark. Wood volume is evaluated by scaling methods, using simple parameters, such as diameter (or circumference) and height measured on well-chosen trees distributed in the most representative way at a site. Dominant height at a reference age is used to classify stands in a fertility scale, and is closely linked to total production (Bentouati 2006). Many studies exist examining the productivity of stands across different countries in the Mediterranean (Pardé 1957, 1967, Decourt 1966, 1973, Souleres 1969, 1975, Garbaye et al. 1970, Yi 1976, Ottorini & Nys 1981, M'hirit 1982, Toth & Turrel 1983, Couhert & Duplat 1993, Ammari et al. 2001, Sghaier et al. 2001, Sghaier & Ammari 2012). Souleres (1969) showed that the production of Aleppo pine in Tunisia increased with the potential of the forest site, the bioclimatic stage, and soil fertility. For an average basal area of 7 m^2, the annual productivity increases from 0.67 m^3 ha^{-1} yr^{-1} in an arid bioclimate to 0.82 m^3 ha^{-1} yr^{-1} in a semi-arid bioclimate, and finally to 0.95 m^3 ha^{-1} yr^{-1} in a subhumid bioclimate. Sghaier & Ammari (2012) showed that the average annual maximum growth of Aleppo pine is 3.3 m^3 ha^{-1} yr^{-1} at 40 years old in good forest sites, declining to less than 0.5 m^3 ha^{-1} yr^{-1} for the fourth and last productivity class (*i.e.*, at an age exceeding 100 years). Boudy (1950) and Chakroun (1986) stated that natural forests of Aleppo pine have very low production capacity, ranging from 0.5 to 3-4 m^3 ha^{-1} yr^{-1} at good forest sites. In comparison, artificial stands produce 1.2 m^3 ha^{-1} yr^{-1} to 5.8 m^3 ha^{-1} year^{-1}. For Aleppo pine at the reference age of 45 years, Ammari et al. (2001) estimated the total growing stock to be 154.96 m^3 ha^{-1} in fertility class 1, 71.52 m^3 ha^{-1} in fertility class 2, 40.86 m^3 ha^{-1} in fertility class 3, and 15.25 m^3 ha^{-1} in fertility class 4. These classes were characterized by a reference dominant height of 4.5 and 13.5 m. In addition, the average annual increment in volume ranged from 0.67 to 5.1 m^3 ha^{-1} yr^{-1}, depending on the fertility of the forest site. Bentouati (2006) reported that the Aleppo pine in Algeria was optimal at 50 years old, with growth in height significantly slowing down by 80 years old. This finding is consistent with the observations of Souleres (1969), who reported that the growth in height of Aleppo pine in Tunisia slowed down between 50 and 70 years old, depending on site conditions. Ciancio (1986) reported that the annual average increment in Italy ranged from 1.9 m^3 ha^{-1} yr^{-1} at 25 years of age for the first fertility class to 12.2 m^3 ha^{-1} yr^{-1} at 50 years old. Pardé (1956) documented a production of 4 m^3 ha^{-1} yr^{-1} on soil of exceptional fertility at a forest site in France for stands aged 75 years. In the Ouled Yagoub and Beni-Oudjana ranges in Algeria, the average volume increase of sampled stands in pine forests ranged from 0.5 to 4.8 m^3 ha^{-1} yr^{-1} (Bentouati 2006).

The average maximum increase in volume for all classes combined peaks at 2.8 m^3 ha^{-1} yr^{-1} for the Ouled-Yagoub and Béni-Oudjana massifs in Algeria at the age of 80. In comparison, the same value was reached at an earlier age (<60 years) in stands in Spain. Furthermore, 2.6 m^3 ha^{-1} yr^{-1} was documented at a reference age of 50 years for stands in Provence, France (Bentouati 2006). In Morocco, the productivity of stands in Tamga for three classes of fertility reached an average value of 2.53 m^3 ha^{-1} yr^{-1} for stands aged around 75 years (Belghazi et al. 2000). Serre-Bachet (1992) and Vila et al. (2008) investigated the structure and growth of Aleppo pine in Jebel Mansour, Tunisia, showing that rainfall enhanced growth, which was also closely associated to altitude and continentality. Guit et al. (2015) showed that altitude and exposure have a highly significant effect ($P < 0.001$) on the dominant height and density of dendrometric parameters. Mérian & Lebourgeois (2011) showed that there is a strong positive correlation between rainfall and radial tree growth. The growth of Aleppo pine is optimal at sites between 100 and 300 m a.s.l. (Vennetier et al. 2010). In the French Mediterranean area and below 600 m a.s.l., the Aleppo pine exhibits major variation in growth related to its ecological requirements. It is generally well adapted to most types of forest sites, except for hydromorphic soils close to the surface. The main factors influencing the growth of Aleppo pine are related to the water balance of the forest site, while trophic balance only has a marginal effect (Vennetier et al. 2010). In Mediterranean forests, Aleppo pine has an average growth of 3 to 5 m^3 ha^{-1} yr^{-1} (Ricodeau 2013). Ciancio (1986) reported an average increase of 10 to 12 m^3 ha^{-1} yr^{-1} at a good forest site in Italy. Souleres (1969) concluded that, in Tunisia, artificial stands and stands resulting from fire regeneration had much higher productivity than natural forests, while productivity was lower in old stands. Tab. 1 presents the various studies on the growth of Aleppo pine that have been conducted in Tunisia and other countries, taking into account different classes of fertility and dominant tree height. Garchi (1991) showed that the fertility of Aleppo pine sites mainly depends on the depth of soil that can be exploited by the roots, humus thickness, soil texture, and the relief. Forest sites on little evolved soils with rich colluvial intake and a loam-clay texture have a fertility class 1, and correspond to a site index of 13.5 to 16.5 m tree height for 50-year-old trees. Sites on calcareous brown soil and rendzine correspond to fertility class 2, with a site index of 10.5 to 13.5 m for 50-year-old trees. Sghaier et al. (2001) identified four classes of fertility, with a reference height of 45 years in descending order: class 1, with a reference height of 13.5 m; class 2, with a reference height of 10.5 m; class 3, with a reference height of 7.5 m; and class 4, with a reference height of 4.5 m. The authors concluded that about 49% of Aleppo pine stands in Tunisia belong to fertility class 3. Akrimi (1984) and Garchi (1991) studied the production of Aleppo pine in northwestern Tunisia (Sakiet region), showing that the most important production was between 0.4 and 4 m^3 ha^{-1} yr^{-1} for a dominant height (9.7-22.8 m). The second most important production was defined by three classes of fertility, with the dominant height being between 5 and 15 m. Couhert & Duplat (1993) stated that, to obtain a high fertility class (Dominant height: H_{dom}= 16 m at 50 years old), the age of exploitation is 80 years, following three major thinnings at 30, 45, and 60 years. When considering total production and average annual increment, Aleppo pine stands belonging to the first productivity class in Tunisia are comparable to those belonging to the second productivity class in Spain and Algeria (Tab. 2). However, the average quadratic diameter of trees in Tunisia (38 cm), which seems to be directly related to density (Sghaier & Ammari 2012), is intermediate between that of Algeria (42.5 cm) and

Tab. 1 - Maximum average increases for Aleppo pine for different classes of fertility and dominant heights (Bentouati 2006). (MAG): Maximum average growth; (H_{dom}): dominant height; (H_{tot}): average total height.

Authors	Country (Region)	Parameter	Fertility class	Value (m)	MAG (m^3 ha^{-1} yr^{-1})
Couhert & Duplat (1993)	France (Provence)	H_{dom} at 50 yrs	1	16	6 at 80 yrs
			2	12	3 at 70 yrs
			3	8	1 at 60 yrs
Pardé (1957)	France	H_{tot} at 75 yrs	1	21	4
			2	18	3
			3	14	1.5
Brochiero et al. (1999)	France	H_{dom} at 70 yrs	1	23.4	5 at 70 yrs
			2	20.1	3 at 50 yrs
			3	16.7	2 at 30 yrs
			4	13.4	1 at 20 yrs
			5	10	-
			6	6.7	-
Montero et al. (2001)	Spain	H_{dom} at 60 yrs	1	20	4 at 50 yrs
			2	17	3.1 at 50 yrs
			3	14	2.4 at 60 yrs
			4	11	1.5 at 70 yrs
Belghazi et al. (2000)	Morocco	H_{dom} at 60 yrs	1	16.9	3.9
			2	13.9	1.9
			3	12.3	1.8
Frantz & Forster (1979)	Algeria (Béni-imloul)	H_{dom} at 100 yrs	1	19	2.8 at 110 yrs
			2	16	2.21 at 50 yrs
			3	13	1.6 at 120 yrs
			4	10	1.10 at 130 yrs
Ammari et al. (2001)	Tunisia	H_{dom} at 45 yrs	1	13.5	3.44 at 45 yrs
			2	10.5	1.59 at 45 yrs
			3	7.5	0.91 at 45 yrs
			4	4.5	0.34 at 45 yrs
Bentouati (2006)	Algeria (Oueld Yagoub, Béni Oudjana)	H_{dom} at 70 yrs	1	19	4.40 at 70 yrs
			2	16	3.3 at 80 yrs
			3	13	2.3 at 80 yrs
			4	10	1.4 at 90 yrs

Spain (30.7 cm). Finally, El Khorchani (2006) showed that the radial growth of Aleppo pine declined significantly from 1950 to 2001, when investigating how climate change affects the productivity of this species. This decrease in the productivity of natural stands was attributed to increased water stress caused by decreased precipitation and increased temperatures.

Production of cones and seeds

Ayari (2012) showed that fructification is better in subhumid stands compared to semi-arid stands, possibly because the scarcity of rainfall and water resources in semi-arid stands. The subhumid environment seems to offer higher yields in terms of the number and weight of cones and seeds produced. These results are of great practical interest, enabling foresters to make better decisions for future reforestation programs. For instance, plantations in subhumid areas should be oriented preferentially towards seed production, whereas plantations in more arid areas (semi-arid and arid bioclimates) should serve other purposes, such as the conservation of water and soil. Previous research on the reproductive characteristics of conifers (Goubitz et al. 2002), seed dispersal (Benkman 1995, Lanner 1998), and sap levels (Moya et al. 2008) showed that several factors influence forest structure, including fire, erosion, and climate change (Fady et al. 2003). In a study conducted in a natural Aleppo pine forest at Jbel Mansour in Tunisia, Garchi & Ben Mansoura (1999) showed that the forest stand consisted of a small proportion (4.8%) of stems with an estimated diameter at breast height (DBH) greater than 30 cm. Ayari et al. (2011a) showed that, in natural Aleppo pine forests in Tunisia, only 1.3% of trees had DBH > 30 cm. Mencuccini et al. (1995) and Castagneri et al. (2008) showed that the structure of the forest in Italy mainly depended on the geographical variability of the forest site and/or its density. Similarly, Ayari et al. (2011a) showed that optimum seed production was achieved when trees are 8 m tall (height) with 8 m crown diameter, with any increase in height or crown diameter having a positive effect on the production of cones and seeds.

Trees with large crowns might have better light reception, improving the rate of photosynthesis (Smith et al. 1988, Greene et al. 2002, Sutton & Staniforth 2002). Ayari (2012), Ayari & Khouja (2014), Esis et al. (1965), and Greene et al. (2002) confirmed that the production of cones and seeds is enhanced by a larger basal area. Thus, the morphological parameters of trees influence on their reproductive capacity (Ordonez et al. 2005, Turner et al. 2007). Ayari & Khouja (2014) showed that a subhumid bioclimate enhances cone production over semi-arid climate. For instance, 117,036 cones ha^{-1} and 119.2 kg ha^{-1} of seeds were produced in a semi-humid stand, while 8,960-54,376 cones ha^{-1} and 88.1-110.7 kg ha^{-1} were produced in a semi-arid stand. One hectare of Aleppo pine forest in the Kef region, Tunisia, was estimated to produce 400 kg of cones every three years, corresponding to 10 kg seeds (cone to seed yield is 2.5% – MARHPT 2015). Ayari et al. (2011b) showed that the weight of seeds per cones was 1.72 g in a sub-humid area, while it was 1.12-1.53 g in a semi-arid area. In comparison, seed production was 261.5 g $tree^{-1}$ in a subhumid area, while it was 118.4-166.2 g $tree^{-1}$ in a semi-arid area. Cone weight per tree was 3.96 kg in a sub-humid

Tab. 2 - Comparison of Aleppo pine production in Tunisia, Spain and Algeria (comparison at age 80 years) – Sghaier & Ammari (2012). (Dg): mean quadratic diameter; (N): number of stems ha^{-1}; (Hd): dominant height; (Vt): total volume (m^3 ha^{-1}); (AAM): mean annual increment (m^3 ha^{-1} yr^{-1}).

Param	Tunisia (class)			Spain (class)				Algeria (class)			
	1	2	3	1	2	3	4	1	2	3	4
Dg	38.0	35.0	32.0	39.4	30.7	23.1	18.0	50.9	42.5	34.0	25.5
N	248.0	201.0	149.0	246.0	408.0	684.0	862.0	169.0	197.0	237.0	300.0
Hd	15.9	12.8	9.6	20.0	17.0	14.0	11.0	20.7	17.5	14.2	10.9
Vt	250.9	142.8	66.3	285.1	230.1	185.7	113.8	350.1	264.1	184.3	107.5
AAM	3.1	1.8	0.8	3.6	2.9	2.3	1.41	4.4	3.3	2.3	1.3

area, while it was 1.6-2.4 kg in a semi-arid area. Finally, there were 160 cones per tree in a sub-humid area, while there were 70-119 cones per tree in a semi-arid area. Ayari et al. (2016) showed that there was an average of 8-97 cones $tree^{-1}$, with an average cone weight of 15-20.6 g, the average cone weight per tree weight was 137.7-2018.6 g, and an average seed weight per tree of 7.3-82. 9 g. Ayari (2012) showed that tree density has a significant negative effect on the number and weight of cones and/or the number and weight of seeds/cone. For instance, production is almost halved when the density of Aleppo pines in forests rises from 250 to 1000 trees ha^{-1}. To enhance the harvest of cones and seeds, Ayari (2012) suggested an optimal density of 250 trees ha^{-1}. Ayari (2012) confirmed that the production yield of cones and seed was less important for stands with low densities and high basal areas. Furthermore, any increase in diameter at breast height enhanced profitability. Similarly, Smith et al. (1988), Arista & Talavera (1996), and Karlsson & Orlander (2002) concluded that the rate of fruiting in conifers is reduced in stands with high density. The decrease in cone and seed production was explained by a reduction in leaf photosynthesis activity (McDowell et al. 2000, Delzon et al. 2005).

Thus, reducing the density of Aleppo pine trees would enhance processes associated with regeneration and fruiting (Moya et al. 2009, Ayari et al. 2010). Ayari (2012) showed that the effect of tree age on cone and seed production is secondary to that of the dendrometric variables of the tree. Moreover, Ayari et al. (2011a, 2011b) showed that altitude has a significant effect on the number of seeds per cone and the number of seeds per hectare. Thus, any increase in ground elevation should lead to heavier cones, with a weight gain of up to 6.8 g between 250 m and 1185 m a.s.l. (Ayari 2012). Regarding the effect of site exposure on fructification in conifers, Ferrio et al. (2003) showed that slopes facing NE, SE, S, and NW in a typical Mediterranean climate (characterized by optimal temperatures, sufficient light and moderate humidity) enhanced tree growth. Ayari (2012) obtained similar results, showing that slopes facing NE, NW, S, and SE enhanced seed production in the Aleppo pine forests of Tunisia. Thus, slopes with these exposures should be selected in future reforestation efforts of Aleppo pine, to maximize seed production. In Tunisia, the areas proposed for harvesting Aleppo pine cones and seeds by the forest services range from 60 to 100,000 ha in size. Overall, the national production of Aleppo pine seeds (or *zgougou*) is in the order of 300 to 320 tons per year. The Kasserine Governorate is the main region producing Aleppo pines, with an average production of 100 to 120 tons of seeds per year. The Siliana Governorate also has a center of production, conservation, and marketing, with an annual production of 40 to 50 tons of seeds.

The Kef Governorate produces just 10 tons per year, despite its importance in terms of Aleppo pine coverage. At present, national consumption is estimated at 1.5 kg seeds or 500 g of *zgougou* ground per family per year, with an upward trend. Over the next two years, an increase up to 2 kg of ground *zgougou* per family per year is expected (MARHPT 2015). The consumption of Aleppo pine seeds is a typical Tunisian tradition, and is constantly increasing across years. The seeds are marketed throughout the country on the festival of *Mouled* (a religious feast), and used to prepare the *zgougou* cream, also known as *Assida* in Tunisia. Such cream is marketed in some pastries and, even, some restaurants, while ground seeds are marketed throughout the year in grocery stores and supermarkets.

Socio-economic role of the Aleppo pine in Tunisia

In addition to its ecological role, Aleppo pine in Tunisia has a significant productive potential that should not be neglected, given the size of the areas occupied by this species. At the socio-economic and cultural level, few studies have been conducted on Aleppo pine, despite its multiple and diverse uses, including the production of seeds for human consumption. The decision to consume Aleppo pine seeds is justified by the specific taste of their aroma and by their high nutritional value (Way 2006). In 2012, the national consumption of seeds of the Aleppo pine was in the order of 300 to 320 tons, with a family consuming 1.5 kg of seeds or 500 g of ground *zgougou* per year, with a predicted upward trend (GIZ 2014).

The Aleppo pine is a very important forest species that forms an important component of the national economy and human being in Tunisia. Aleppo pine seeds are the product most sought after by consumers and farmers. The seeds represent the main non-wood forest product at the socio-economic level by regional and local forestry services. In addition to their direct consumption as a pastry cream, several products available on the market are based on the Aleppo pine seeds, including yoghurt, aromatic ice creams and vegetable oil. Aleppo pine seeds are a true national wealth and source of income for many families. In total, 2334 farmers harvest of this product, employing 3000 seasonal workers and generating about 625,000 € $year^{-1}$ of revenue (MARHPT 2015). The collection of cones for sale is a dangerous, though this activity generate an additional income for workers. At the micro-enterprise stage, *zgougou* businesses are profitable. The exploitation of the Aleppo pine meets strict criteria, including the obligation of specifications, the conclusion of operating contracts, and technical monitoring. Seed extraction in an area of one ha is estimated to return 32 €. Based on a selling price of 5 € per kg of seeds, the total revenue per hectare is estimated at 50 €. The profit margin generated by one ha in one year out of three is of the order of 16 € ha^{-1} (MARHPT 2015). In Tunisia, the cream prepared from the flour extracted from Aleppo pine seeds, commonly called *Assida zgougou*, has an authentic flavor and confirmed nutritional value based on its calorific, lipid, and carbohydrate content. According to the National Institute of Consumption in Tunisia (INC), 100 grams of *Assida*, covered with a layer of cream and dried fruit, provides nearly 595 calories, or 25% of the daily energy needed by an adult. Without ornamental substances, the nutritional value of this same quantity is estimated at 275 calories.

Suggestions to enhance seed production

El Guemri (2018) showed that the reforestation density of Aleppo pine should be 1111 trees ha^{-1}, because under these condition, four times more Aleppo pine seeds are harvested per hectare in the Northeast of Tunisia compared to the Northwest of Tunisia. Thus, the reforestation of Aleppo pine trees should be directed towards seed production in the Northeast of Tunisia and oriented towards wood production in the Northwest of Tunisia. Several factors had a combined effect on Aleppo pine seed/cone production in natural forests growing in Tunisia. Ayari et al. (2011a) suggested that bioclimatic areas with higher moisture conditions have a positive effect on fructification, producing greater cone crops and seed yields. The sub-humid zone produces greater quantities of cones and seeds (with higher mean yields) compared to other bioclimatic areas in Tunisia. Geographical variability of the bioclimatic areas is associated with the latitude, longitude, elevation, and land aspect (Ayari 2012).

Overall, longitudinal gradients represent the strongest geographical determinant causing a marked increase in cone dimensions and seed content, mainly in the semiarid zone. High consistency was found regarding the effect of elevation and longitude on cone dimensions and average individual seed mass (Ayari et al. 2011b). The effect of the geographical distribution on fructification is greater under drought conditions (Schiller & Atzmon 2009). Furthermore, NE, NW, S, and SE facing slopes are the optimal aspects to enhance the cone harvests of Aleppo pine stands, and should be considered in future reforestation efforts (Ayari et al. 2011a). These suggestions on optimal site characteristics is expected to help Mediterranean foresters enhance cone and seed production by choosing appropriate locations for future Aleppo pine plantations. This research offers easy-to-use suggestions for owners/managers to recognize the best reproductive sites for Aleppo pine forests and to increase the profitability of stands. This information might also help to satisfy the growing demand for Aleppo pine seed consumption, especially in Tunisia.

Conclusions and future perspectives

The sustainability of forest ecosystems depend on their management. Regeneration method represents a key phase in the life of a stand, as it determines its composition and structure in the long term. Indeed, achieving the most abundant regeneration possible is often a stated goal. It is necessary to maintain the sustainability of ecosystems and their ecosystem services within the context of silvicultural plans, allowing foresters to select individual trees that reflect the overall management objectives and ensure the production to serve human households. Low economic value and poor technological characteristics of Aleppo pine products have not favored more ambitious silviculture in the past. Several authors (Sghaier & Ammari 2012, Garchi et al. 2001) placed more emphasis on the importance of Aleppo pines in protecting the environment over production in Tunisia. However, today, seed production represents a very promising niche, especially for human consumption (pastry, ice creams, flour, etc.). Aleppo pine seeds also have many other medicinal and cosmetic uses, and high added value. Sylviculture oriented towards the commercial production of Aleppo pine seeds could only enhance the importance of this species in Northern Africa.

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