Agroforest Syst
DOI 10.1007/s10457-012-9564-y

Ethephon: a tool to boost gum arabic production from *Acacia senegal* and to enhance gummosis processes

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Received: 18 June 2012 / Accepted: 28 August 2012

Abstract Gum arabic production from *Acacia senegal* is lower in sub-humid areas than arid areas. Water stress is thought to be the reason for higher yields in arid areas. The application of ethephon is thought to mimic the effect of water stress in other plants. The objective of this study was to determine if the application of ethephon would increase the gum yields of *Acacia senegal* under sub-humid conditions in Cameroon. Trees receiving 40 or 120 mg ethephon were compared to controls in field experiments at a semi-arid and a sub-humid location in Northern Cameroon, over two seasons. Two provenances from drier areas (Sudan) were compared to the local one. In the first season, gum yield of the local provenance treated with ethephon was increased by 400–600 % compared to the untreated trees. Gum yield at the semi-arid location was 77, 313 and 214 g/tree with 0, 40 and 120 mg ethephon/tree, respectively, while at the sub-humid location, it was 30, 186 and 114 g/tree with 0, 40 and 120 mg ethephon/tree. However, in the second season, the effect of ethephon was not significant in the semi-arid area, whereas it was evident in the sub-humid area (up to 478 g/tree). Moreover, ethephon did not affect gum yield of provenances from drier areas (Sudan). This showed that the water-stress hypothesis has to be refined. The development of ethephon-based tapping systems is promising, but requires further studies with a wider range of environmental conditions and *A. senegal* provenances.

Keywords Ethylene · Gum yield · Northern Cameroon · Tree provenance · Water stress

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Introduction

Acacia senegal (L.) Willd. is a multi-purpose tree of the Sahel arid areas of Africa. It is the main species producing the internationally traded gum arabic. Gum arabic is a natural polysaccharide exuding from the trees either spontaneously or following manual tapping (Verbeken et al. 2003). Odourless, tasteless and translucent, it is an excellent natural emulsifier widely used in the food, pharmaceutical and cosmetic industries (Williams and Phillips 2000). Moreover, as *A. senegal* grows in dry conditions, it can represent a

Published online: 12 September 2012

significant source of monetary income for local communities of these areas. In Sudan for example, the revenue from gum arabic represents about 4 % of total national revenue (Elmqvist et al. 2005). In this country, *A. senegal* is cultivated in agroforestry systems (Elmqvist et al. 2005), whereas in other producing countries such as Nigeria, Chad and Senegal, most the gum originates from natural stands (NGARA 2004). However, natural and maintained stands face huge human pressure, which has reduced the tree populations, either for the use of wood or through a shortening of fallow periods (Elmqvist et al. 2005). Therefore, despite a consistent demand, gum arabic production has decreased from 1960 to 1996 (NGARA, 2004). This has triggered attempts to revitalize *A. senegal* based systems and the production has increased again since 1997 (NGARA 2004). The species has been used in many reforestation and development projects in areas such as Northern Cameroon, especially to restore soil fertility depleted by continuous cropping of cereals and cotton (Peltier et al. 2009). However, in Northern Cameroon most plantations remain unexploited and the gum production of the country is still very low. This is partly due to land-tenure and marketing issues (Madi et al. 2010) but also to the low productivity of the trees when they are tapped which is probably related to environmental factors (Harmand et al. 2012).

Gummosis, the gum synthesis process, and gum exudation occur only in dry conditions, i.e. in arid climates and during the dry season (Vassal 1991; Dione and Vassal 1998; Ballal et al. 2005b). Traditionally, *A. senegal* trees are tapped when they have lost half of their foliage which is believed to indicate a necessary threshold of water stress (Dione and Vassal 1998). Hence, the low gum production in the sub-humid zone (1,100 mm of annual rainfall) of Northern Cameroon may be due to the insufficient water stress encountered in this area, which is not as productive as semi-arid zones (650–800 mm of annual rainfall) of Northern Cameroon and Burkina Faso and arid zones (350–500 mm of annual rainfall) of Sudan and Senegal (Harmand et al. 2012). This may also explain why *A. senegal* trees introduced from drier areas of Sudan produce less gum than the local ones (Harmand et al. 2012), as *A. senegal* trees adapt their water use traits to their place of origin (Raddad and Luukkanen 2006).

However, the environmental and physiological factors controlling gum yield are not well understood. When trees are tapped too late in the dry season, after the 50 % of defoliation stage, gum yield also decreases (Ballal et al. 2005b; Harmand et al. 2012). This is not consistent with a simple necessary water threshold. Tapping may have to be done during a limited period of time related to defoliation patterns. The uncertain gum yield in the sub-humid zone may be related to sporadic late rainfall inducing erratic re-foliation in this area. The question is still open, as few studies have assessed this issue (Dione and Vassal 1998; Ballal et al. 2005b; Gaafar et al. 2006), and the choice of the tapping time remains uneasy, particularly when *A. senegal* is introduced in new areas. A two-week delay can reduce the yield by 50 % in Northern Cameroon (Harmand et al. 2012).

One way to alleviate such constraints could be the use of compounds which induce gummosis and gum exudation, such as plant hormones. Setia and Shah (1977) increased gum production by *Sterculia urens* after application of Indole-acetic acid (IAA). However, the most promising compound seems to be ethephon (2-chloroethylphosphonic acid), which releases ethylene inside plant tissues. As ethylene is often synthesized when plants encounter stress and then triggers stress reactions (Apelbaum and Yang 1981; Beltrano et al. 1999), its use could mimic the water stress believed to trigger gummosis. This use would be particularly relevant in the wetter areas of Northern Cameroon or with plant material introduced from drier areas. Moreover, ethephon is commonly used to improve latex yield in rubber plantations (*Hevea brasiliensis*). It increases both latex metabolism and latex flow and is a well-known tool in rubber tapping systems (D'Auzac et al. 1997; Lacote et al. 2010). Ethephon has been successfully tested in several gum or resin producing species (Greenwood and Morey 1979; Nair et al. 1995; Miyamoto et al. 2010). However, there so far has been only one study with *A. senegal*. The results of Bhatt and Ram (1990) in India were positive, although the trees were not properly tapped, as only holes and 'bruises' were performed. The authors found an increasing gum production (up to 800 g per tree) with increasing ethephon concentration. However, to our knowledge, this preliminary study (9 treated trees) has not been followed up.

Therefore, the purpose of the present field study was to test whether application of ethephon can increase gum production by *A. senegal*, particularly in two cases:

– In sub-humid areas of Northern Cameroon, which are wetter than the usual exploitation areas of *A. senegal*.
– In plant material (provenances) introduced from drier areas.

In addition, we also tested if the use of ethephon can provide flexibility in the tapping time.

Materials and methods

Study sites

The study area is in northern Cameroon at two locations with contrasting climate namely: Makalingay and Ngong. Makalingay (semi-arid) is the northern location, located in the region of Maroua (14°15′E, 10°48′N, 430 m above sea level) on dune sandy ferruginous soils. The climate is semi-arid, with 800 mm of annual rainfall and a dry season lasting usually from November to end of April. Annual average temperature is 27.5 °C. During the study period, the rainfall was unusually high (984 and 1002 mm in 2009 and 2010, respectively, Table 1), although the dry season was of normal duration. The natural vegetation is a dry savannah (Donfack et al. 1997). Ngong (sub-humid) is the southern area, located in the Garoua region (10°58′E, 3°45′N, 418 m above sea level). The climate is more humid, with an annual rainfall of 1100 mm despite a significant dry season from mid November to mid April. Annual average temperature is 28.1 °C. During the study period, the rainfall was similar to the long-term average (1,028 and 1,112 mm in 2009 and 2010, respectively, Table 1). The soil, derived from sandstone, is classified as ferruginous (Alfisol) and the natural vegetation is a woody savannah (Harmand et al. 2003).

Plant material

The trees were planted with a spacing of 4 m * 4 m (density of 625 trees/ha). In Makalingay, Cameroon Laf, a local provenance of *A. senegal* variety *senegal* originating from natural stands of the study site (Maroua region) was compared to two provenances from Sudan—Sudan Blue Nile and Sudan North Kordofan. These provenances, also from variety *senegal,* originate from drier areas than the study site (Table 2). The trial was set up in randomized complete block designs with four blocks. Plots were 28 m * 28 m large with 49 trees per plot. The other trial (Ngong) was a mono-provenance plot with the

Table 1 Rainfall in mm per month at the semi-arid (Makalingay) and the sub-humid (Ngong) location, northern Cameroon, from 2009 to 2011 and 10-year average of rainfall and of mean temperature per month at the closest meteorological station (Maroua and Garoua, source: Sodécoton, Garoua, Cameroon)

Month	Makalingay					Ngong				
	2009	2010	2011	1999–2008 (Maroua)		2009	2010	2011	1999–2008 (Garoua)	
	Rainfall (mm)				T (°C)	Rainfal (mm)				T (°C)
January	0	0	0	0	26.5	0	0	0	0	24.3
February	0	0	0	0	28.8	0	0	0	0	26.7
March	0	0	0	0	32.0	0	0	0	0	30.5
April	0	5	4	17	32.4	10	16	15	38	32.2
May	24	105	120	51	30.4	62	53	77	99	31.2
June	146	124	110	105	27.5	75	70	74	162	28.1
July	200	251	195	220	26.2	305	230	301	181	26.3
August	337	258	277	233	26.0	401	426	466	282	25.6
September	157	155	160	142	26.1	110	196	105	215	26.0
October	121	105	30	42	27.6	63	122	73	72	27.7
November	0	0	0	0	27.4	0	0	0	0	26.7
December	0	0	0	0	26.3	0	0	0	0	25.1
Total	984	1002	895	820		1023	1113	1110	1050	

same local provenance, without experimental design. Trees were 24 years old at the semi-arid location (Makalingay) and 15 years old at the sub-humid one (Ngong) when the experiment started in 2009.

Tapping and ethephon treatments

The experiment took place over two tapping periods, corresponding to the dry seasons, October 2009 to May 2010 (2009–2010) and October 2010 to May 2011 (2010–2011). Treatments are summarized in Table 3.

Tapping

Tree tapping, an essential treatment to induce gum exudation, was practiced following the standard method used in Senegal. It consisted in withdrawing with a specific tool a strip of bark, about 4 cm wide and 60 cm to 1 m long, to expose the sapwood. Tapping was performed on three branches of each tree. Selected branches had a diameter greater than 5 cm and a smooth bark. Trees were tapped once a year, basing the timing of this on the defoliation stage of the local provenance (Cameroon Laf). Defoliation percentage was estimated visually, referring to a template

Table 2 Environmental conditions at the site of origin of the *Acacia senegal* provenances planted at the study locations, Makalingay and Ngong

Study site	Provenances	Origin	Longitude	Latitude	Alt (m)	Rain (mm)	T_{max} (°C)
Makalingay	Blue Nile	Sudan	34°40′E	11°16′N	470	<600	45
	North Kordofan	Sudan	30°29′E	13°16′N	560	365	45
	Laf	Cameroon	14°15′E	10°48′N	430	800	45
Ngong	Laf	Cameroon	14°15′E	10°48′N	430	800	45

Rain and T_{max} indicate the mean annual rainfall and maximum temperature at the area of origin

Table 3 Summary of tapping and ethephon treatments for *Acacia senegal* tests conducted at two locations (Ngong and Makalingay) in Cameroon from 2009 to 2011

Season	Location	Provenances	Tapping timing (% of defoliation of the local provenance, date)	Ethephon mg/tree
2009–2010	Ngong (sub-humid)	Cameroon Laf	Late (75 %, 15/12)	0 40 120
	Makalingay (semi-arid)	Cameroon Laf	Late (75 %, 26/11)	0 40 120
2010–2011	Ngong(sub-humid)	Cameroon Laf	Early (35 %, 29/10) Standard (50 %, 26/11)	0 40
	Makalingay(semi-arid)	Cameroon Laf	Standard (50 %, 25/10) Late (75 %, 26/11)	
		Sudan North Kordofan	Standard (25 %, 25/10)[a] Late (65 %, 26/11)	
		Sudan Blue Nile	Standard (25 %, 25/10)[a] Late (65 %, 26/11)	

[a] Tapping dates were set according to defoliation status of the local provenance (Cameroon Laf). As provenances from Sudan defoliated later, their defoliation percentage was only 25 % at standard tapping (50 % in the local provenance) and 65 % at late tapping (75 % in the local provenance)

with 5 % graduation. Two tapping dates were tested at both locations. Standard tapping, when Cameroon Laf trees had lost about 50 % of their leaves and late tapping, 2–5weeks later, when they had lost about 75 %. Sudan provenances defoliated later but they were tapped at the same time. Their defoliation stages and tapping dates are specified in Table 3. During the second season, tapping was done earlier at the sub-humid area (Ngong). The first tapping was done at 35 % defoliation (early tapping) and the second one was standard tapping (50 %). After tapping, gum started to exude and formed nodules which were harvested and weighed every 2 weeks. The yield of the three branches in each tree was accumulated over the harvesting period, starting at the beginning of the dry season in October or November and ending in April.

Ethephon treatments

A stock solution of Ethrel® containing 100 g l^{-1} of ethephon (2-chloroethylphosphonic acid) was diluted with water to 10 g l^{-1} of ethephon and applied just after tapping, with a brush directly on the notches where bark has been removed. Cotton oil was then applied, to prevent evaporation. In the first season (2009–2010), ethephon was tested only on the local provenance and at the late tapping date, corresponding to 75 % of leaf fall. Two ethephon dose rates were compared: 40 and 120 mg of active matter per tree and compared to untreated trees tapped without ethephon (0). The two ethephon doses were chosen to be in the same range as the standard annual doses used in rubber trees (Gohet et al. 1996). There were 6–8 trees per treatment. In the second season (2010–2011), the study was extended to the provenances from Sudan (Blue Nile and North Kordofan) and two tapping dates were applied. However, only the low ethephon dose (40 mg/tree) was tested, following the results of the first season. The number of sampled trees was increased. At Makalingay, 12 trees received 40 mg ethephon and 20 trees were tapped without ethephon in each provenance and at the two tapping dates. At Ngong, there were 20 untreated and 20 trees treated with ethephon at both tapping dates (Table 3). To avoid carryover of treatment effects, the trees tapped in 2010–2011 were different from those tapped in 2009–2010.

Data analysis

Analyses of variance (ANOVA) were carried out to study the effects of ethephon treatments and tapping dates on the gum yield per tapping season. When a tree produced no gum despite tapping, it was included in the mean. The interactions between season, location and ethephon treatment could be tested only in the local provenance, at the second tapping date and with 0 and 40 mg ethephon per tree. For the 2009–2010 data, a one-way ANOVA was carried out to study the tapping treatment factor, separately for each location. As ethephon treatment was tested only at the late tapping date, 4 treatments were considered (Standard-0, Late-0, Late-40 and Late-120) without analyzing the effects of tapping date and ethephon factors independently. In 2010–2011, as there were 2 tapping dates and 2 ethephon treatments, either a one-way ANOVA with 4 treatments (Standard-0, Standard-40, Late-0 and Late-40 in Makalingay and Early-0, Early-40, Standard-0 and Standard-40 in Ngong) or two-way ANOVA, with tapping date and ethephon treatment as factors, were carried out. Each location and each provenance was analyzed separately. In the case of a significant F-test, treatment means were compared using a Tukey test.

Results

Ethephon effect on gum yield, in the local provenance Cameroon Laf

The intra-treatment variability was high (CV = 43–103 %), but significant effects of ethephon were found at both sites. Location had also a significant effect on gum yield of the local provenance (Table 4). The interactions between location and season and between location and ethephon were also significant.

Semi-arid location (Makalingay)

Ethephon significantly increased gum yield during the first season (2009–2010, Fig. 1). With 40 mg of ethephon per tree (Late-40), gum yield was quadrupled (313 g/tree, $P = 0.001$) compared to Late-0 (77 g/tree). A higher ethephon dose (Late-120) gave a lower gum yield (214 g/tree), although this was still significantly higher than the yield of Late-0. During

Table 4 Analysis of variance (ANOVA, Type I) of gum yield per tree of the local provenance (Cameroon Laf)

Source	DDL	SS	MS	F value	Pr > F
Location	1	441392.3	441392.3	26.84	<0.0001
Season	1	14647.1	14647.1	0.89	0.348
Ethephon	1	1193131.6	1193131.6	72.55	<0.0001
Location*Season	1	360582.1	360582.1	21.93	<0.0001
Location*Ethephon	1	268673.0	268673.0	16.34	0.0001
Season*Ethephon	1	1810.1	1810.1	0.11	0.741

Effects of location (Semi-arid and sub-humid), season (2009–2010 and 2010–2011), ethephon (0 and 40 mg per tree) and their interactions

this first season, ethephon was tested only with late tapping (75 % defoliation) which gave lower yield in untreated trees than standard tapping, 77 g/tree and 140 g/tree in Late-0 and Standard-0 respectively. However, Late-40 had significantly higher gum yield (313 g/tree, $P = 0.004$) than Standard-0.

During the second season (2010–2011, Fig. 1), only the lower dose (40 mg) was tested but with the two tapping dates. The effect of ethephon was much less than the previous season. It was significant ($P = 0.02$) only in late tapping (75 % defoliation), but the gum yield of Late-40 was only 113 g/tree in this season. The yield of the untreated trees was also lower than the previous season: 82 g/tree for Standard-0 and 57 g/tree for Late-0. Ethephon application resulted in the same yield following both tapping dates (Standard-40 and Late-40).

During these two seasons, the proportion of non-producing trees (less than 5 g/tree/season) was low in untreated trees (5–15 %) and only one case occurred in trees receiving ethephon.

Sub-humid location (Ngong)

Ethephon significantly increased gum yield in this sub-humid area, where the yield of Late-0 was very low (30 g/tree). During the first season (2009–2010, Fig. 2), gum yield was increased by 600 % for Late-40 (185 g/tree, $P = 0.01$). With a higher ethephon dose (Late-120), the gum yield was lower (114 g/tree) and not significantly different from that of Late-0.

Unlike the semi-arid area, the gum yield of ethephon treated trees was even higher during the second season (2010–2011, Fig. 2), 310 and 467 g/tree for Early-40 and Standard-40 respectively. The proportion of increase was not higher (450–500 %), as the untreated trees also gave a higher yield than the previous season (68 and 92 g/tree in Early-0 and Standard-0, respectively), but the differences were highly significant at both tapping dates ($P < 0.0001$). There were non-producing trees (20 %) only in one case (Standard-0, 2009–2010).

Ethephon effect of on gum yield, in Sudanese provenances

Ethephon had no effect on gum yield of provenances originating from areas of Sudan (North Kordofan and Blue Nile) which are drier than Northern Cameroon (Fig. 3). Gum yield remained very low in the two Sudanese provenances, at both tapping dates. It varied from 21 to 60 g/tree and from 2 to 25 g/tree in North Kordofan and Blue Nile, respectively. Following standard tapping date, the effect of ethephon was even negative for both provenances, although differences were not significant.

The proportion of non-producing trees (<5 g/tree/season) was high (50–70 %) in both provenances at both tapping dates. With ethephon, it was higher (83 %) in Blue Nile and was unchanged in North Kordofan.

Dynamics of gum production

Figure 4 shows examples of the gum yield per harvest of the local provenance, at the two locations. As harvests were performed every 2 weeks, this provided the dynamics of gum production from the tapping date to the end of the season.

In both cases, ethephon treated trees had a substantial gum yield from the first harvest, 2 weeks after tapping. Conversely, in untreated trees, gum yield at the first harvest was low and a significant amount was harvested only about 58 days after tapping at the

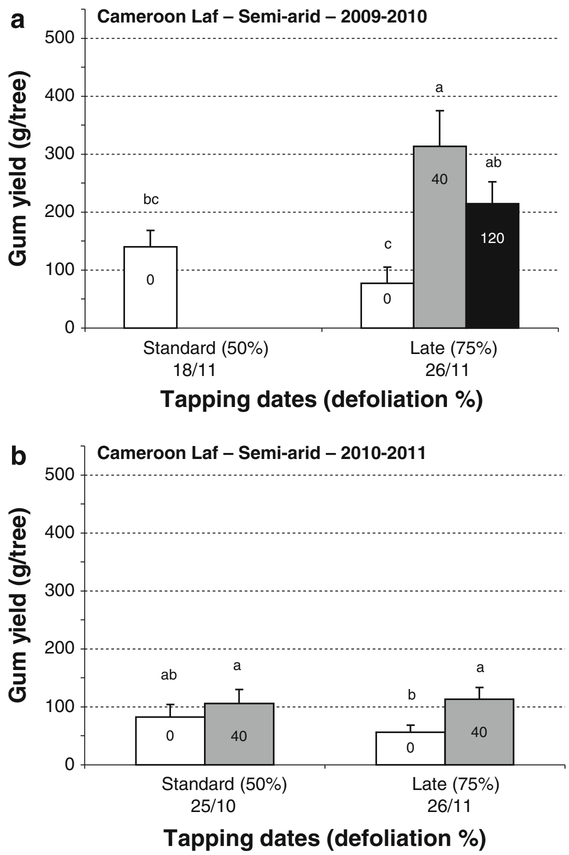

Fig. 1 Accumulated gum yield of the local provenance (Cameroon Laf) at the semi-arid location (Makalingay, 800 mm annual rainfall). Trees were tapped for gum production when they had lost 50 % (standard) and 75 % (late) of their foliage and the yield was accumulated over the harvesting period. In 2009–2010 (**a**), two doses of ethephon (40 and 120 mg/tree) were compared to untreated trees (0) at the late tapping date. In 2010–2011 (**b**), ethephon (40 mg/tree) was compared to untreated trees (0) at the standard (50 % defoliation) and late tapping date (75 % defoliation). *Bars* show the standard error of the mean. 2009–2010, $n = 20$ in Standard-0, $n = 8$ in Late-0, $n = 6$ in Late-40 and Late-120; 2010–2011, $n = 20$ in untreated trees (0), $n = 12$ in ethephon (40). Different letters indicate significant difference between treatments at $P < 0.05$ (Tukey test)

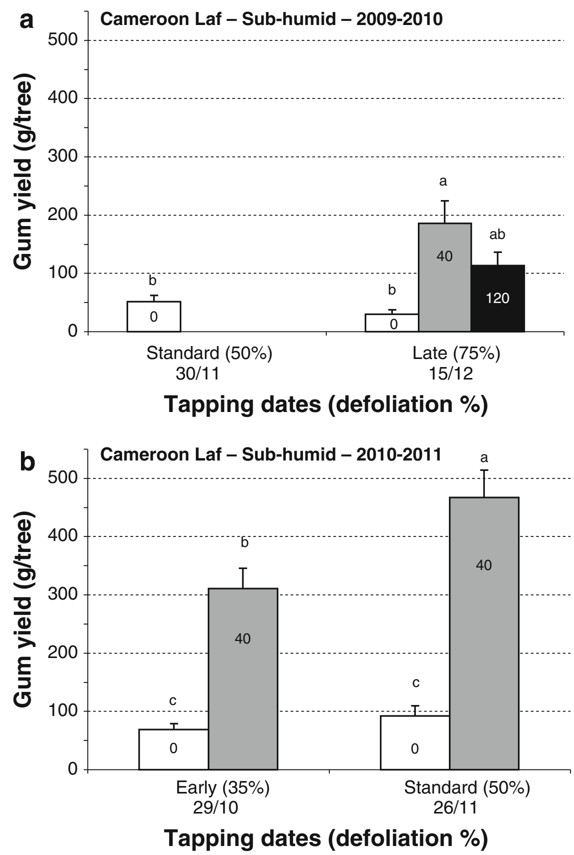

Fig. 2 Accumulated gum yield of the local provenance (Cameroon Laf) at the sub-humid location (Ngong, 1100 mm annual rainfall). In 2009–2010 (**a**), two doses of ethephon (40 and 120 mg/tree) were compared to untreated trees (0) at the late tapping date. In 2010–2011 (**b**), ethephon (40 mg/tree) was compared to untreated trees (0) at early (25 % defoliation) and standard (50 % defoliation) tapping date. Yield was accumulated over the harvesting period. *Bars* show the standard error of the mean. 2009–2010, $n = 20$ in Standard-0, $n = 6$ in Late-0, $n = 7$ in Late-40 and Late-120; 2010–2011, $n = 20$ in all treatments. Different letters indicate significant difference between treatments at $P < 0.05$ (Tukey test)

semi-arid location and 28 days after tapping at the sub-humid one. At the semi-arid location, this high initial gum production with ethephon was sustained (Late-40) or decreased (Late-120) before reaching a peak at the same time as the untreated trees (04/02/10). Thereafter, yield decreased more or less rapidly for all treatments and gum production stopped around the end of April 2010. At the sub-humid location, during the 2010–2011 season, the shape of the yield curves were similar in ethephon and in the untreated trees, but with much higher yield at all dates with ethephon. Early tapping resulted in an early peak (25/12/10) of 75 g/tree/harvest in Early-40 and 19 g/tree/harvest in Early-0, followed by a gradual decrease until mid April. Standard tapping resulted in a flatter curve for both treatments. For Standard-40, the trees produced substantial gum yield from the first harvest, with a plateau about 35 g/tree/harvest from the end of December to mid-February. Gum production was not prolonged by ethephon and, like that of the untreated trees, it stopped with commencement of the rain.

Discussion

Application of ethephon to the tapping cut substantially increased the gum arabic production of *A. senegal* trees in field conditions of Northern Cameroon, especially in the sub-humid area. This confirmed on a larger scale and with the conventional tapping system the preliminary results of Bhatt and Ram in India (1990).

In the local provenance and despite the huge intra-treatment variability, which is common to gum production trials in *A. senegal* (Dione and Vassal 1998; Gaafar et al. 2006), the increase was significant, as the gum yield was increased by 600 % as compared to the untreated trees. The highest concentration of ethephon (120 mg/tree) gave lower gum yield than the lower (40 mg/tree). This is contrary to the results of Bhatt and Ram (1990) who showed an increase in gum yield with higher ethephon doses. However, their study included few trees by treatment. Our results are similar to that obtained in rubber trees, showing that when the ethephon concentration or the stimulation frequency is too high, the yield also decreases (Gohet et al. 1996). Moreover, the tapped area in Bhatt and Ram study was much smaller than in our study (2.5 cm wide holes instead of 60 cm to 1 m long strips). Such little tapping cuts may require more ethephon to obtain high yield, as in rubber trees (Gohet et al. 1996). To obtain a proper dose response, it would be relevant to test more ethephon doses in *A. senegal* with the standard tapping cuts. The gum yield obtained with ethephon at the semi-arid location (800 mm year^{-1} rainfall) as well as at the sub-humid location (1100 mm year^{-1} rainfall) was in the same range as the best yield obtained in the more favourable areas of Sudan or Senegal (Dione and Vassal 1998; Gaafar

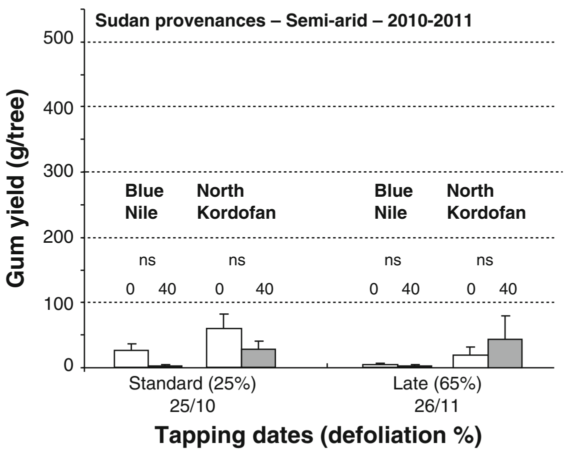

Fig. 3 Accumulated gum yield of two provenances from Sudan (Blue Nile and North Kordofan) at the semi-arid location (Makalingay, 800 mm annual rainfall) in 2010–2011. Ethephon (40 mg/tree) was compared to untreated trees (0) at the standard (25 % defoliation corresponding to 50 % in local provenance) and late tapping date (65 % defoliation). Yield was accumulated over the harvesting period. *Bars* show the standard error of the mean. $n = 20$ in untreated trees (0), $n = 12$ in ethephon (40). Gum yield with 40 mg ethephon was low and not significantly different from that of untreated trees in both provenances at $P < 0.05$ (Tukey test)

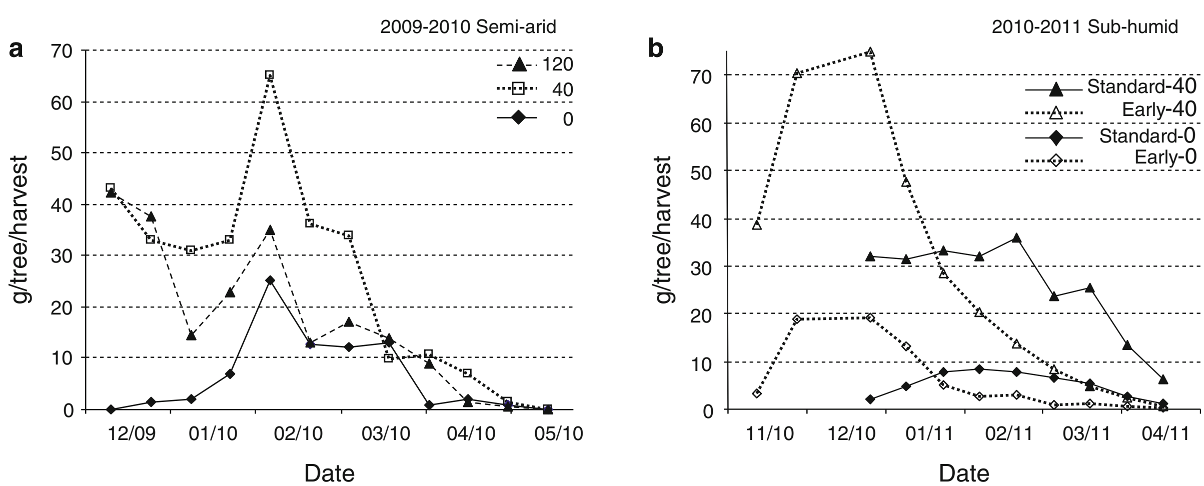

Fig. 4 Gum yield per harvest of the local provenance according to ethephon treatment. Gum was harvested every 2 weeks. **a** 2009–2010 at the semi-arid location (Makalingay, 800 mm of annual rainfall), following late tapping. **b** 2010–2011 at the sub-humid location (Ngong, 1100 mm of annual rainfall) following early and standard tapping

et al. 2006). The possible applications for gum production in Northern Cameroon are very promising, as ethephon is available in this country as a ready-to-use paste at affordable cost. Regarding the small necessary quantity (40 mg/tree/season) and the little manpower required applying the treatment, the huge proportion of gum increase may completely change the profitability of gum exploitation and provide the triggering factor to initiate adequate marketing channels (Madi et al. 2010). This may reveal a decisive incentive in favour of fallows planted with *A. senegal* to restore soil fertility in the large areas of degraded lands encountered in Northern Cameroon (Peltier et al. 2009).

The positive effect of ethephon was even more consistent in the wetter area (Ngong) where the gum production is uncertain (Harmand et al. 2012). This supports the hypothesis that the low production of untreated trees in such conditions is due to insufficient water stress and that ethephon application could mimic the effects of such a stress. However, the annual variability, with a much lower effect of ethephon in the second season (2009–2010) in semi-arid conditions, shows that this hypothesis needs to be tested further and that other unidentified factors were important. This lower effect could not be due to a fatigue of the trees after a second season of treatment, since different trees were treated in the second season. Moreover, the untreated trees also had a lower yield this season. This could be related to the unusually high rains in 2010, but in such conditions we would expect the same kind of response as at the sub-humid location. The lack of responsiveness could also be related to the age of the trees (24 years at this location). In Sudan, *A. senegal* trees are usually cleared when they are 15–20 year old (Ballal et al. 2005a) and the maximum gum yield is obtained from trees about 15 year of age (Gaafar 2005). Future studies on the use of ethephon in *A. senegal* should therefore focus on younger trees.

The Sudanese provenances originated from drier areas than Northern Cameroon (Sudan Blue Nile and Sudan North Kordofan). They are probably adapted to such conditions in terms of water use traits (Raddad and Luukkanen 2006). Therefore, our hypothesis was that their low gum production in Northern Cameroon was due to an insufficient water stress and that they would respond strongly to ethephon. However, the effect of ethephon was less than in the local provenance and was even negative in trees from Sudan Blue Nile. This showed that the possible effect of ethephon on gum yield may be more complex than just alleviating a water stress threshold. These provenances may also have a limited gum potential or may be radically unsuitable to Northern Cameroon conditions. This explanation is consistent with the fact that the provenance responding negatively to ethephon was the same one with a very low gum yield in the untreated trees (Sudan Blue Nile), confirming the previous results of Harmand et al. (2012). The age of the trees (24 years) may also have limited their potential response to ethephon, although they were at the same age as the local provenance which was responsive.

At both locations, our results confirmed the importance of tapping date in untreated trees (Ballal et al. 2005b; Harmand et al. 2012). A two week-delay after the 50 % defoliation stage could result in a 40 % loss of gum yield (semi-arid location, season 1). Although not significant, this decrease in gum yield with increasing water stress along the season was consistent with the occurrence of a physiological period for gum production, instead of a water stress threshold (Dione and Vassal 1998; Ballal et al. 2005b). The variations in air humidity (Harmand et al. 2012) and air temperature (Ballal et al. 2005b) may be determining. Our experiment was not specifically designed to address this question which would require more tapping dates and a closer survey of leafing phenology and climate to conclude. On the other hand, with ethephon, high yields could be obtained over a large range of tapping dates, corresponding to 25–75 % of defoliation. Particularly, we did not notice a decrease of gum yield in late tapping when ethephon was used, contrary to the untreated trees. From an applied point of view, this may prove very practical in non-traditional areas such as Northern Cameroon, where farmers lack the expertise to choose the right tapping time (Madi et al. 2010). Moreover, this could allow flexibility to adapt to manpower availability or to the gum market, as the gum price is often higher in early and late season (Madi et al. 2010). From a more scientific point of view, these results, together with the dynamics of gum production, indicate a direct and transient effect of ethephon on gum production processes. Actually, the effect of ethephon was to promote a high gum yield immediately after tapping, but the shape of the curves were thereafter similar between treatments, despite a wider range in ethephon. It was also clear that a single ethephon application at tapping time did not prolong the gum production period. Such a transient effect of ethephon has also been observed in rubber trees (Coupé and Chrestin 1989). It could be relevant to fraction the application of ethephon in *A. senegal*, as it is done in rubber trees. Applications outside the dry season would also help unravelling the effects of leafing phenology and water stress on gum yield.

The way ethephon acts on gum yield is not yet known. In rubber, ethephon increases both the metabolic pathways of rubber biosynthesis and water flow towards the laticifer cells, hence prolonging latex flow through a dilution process that delays coagulation (Coupé and Chrestin 1989; Tungngoen et al. 2011). Both processes are also possible in gum production by *A. senegal*. However, gum metabolism is more difficult to study than latex metabolism as little is known about gummosis processes and regulation (Vassal 1991; Vassal and Mouret 1993). The possible effects of ethephon on metabolism and water flow are not without danger for the tree. If increased resources are diverted towards gum yield, this may have detrimental effects on tree growth and tree resistance to adverse conditions (Silpi et al. 2006). The indiscriminate use of ethephon following the discovery of its effect on yield has induced many physiological disorders in rubber trees, from the reversible "Tapping panel dryness" due to fatigue to the irreversible "Bark necrosis" symptoms (D'Auzac et al. 1997). The detrimental effects of ethephon are also related to the non-specific action of ethylene in trees and its mobility (Apelbaum and Yang, 1981). Therefore, application of ethephon stimulation of gum production in *A. senegal* requires many precautions and careful research, as has been done to adapt the intensity of ethephon stimulation to each rubber tree clone (Jacob et al. 1995). One obstacle is that the plant material in *A. senegal* is very heterogeneous as compared to rubber clone, as provenances are only defined by a common geographic origin. They may have heterogeneous genetic material and this could explain the huge intra-treatment variability (Omondi et al. 2010). Besides the sustainability of gum production over years, one important parameter to monitor is the ability of the trees to regenerate the scrapped bark (healing process), to avoid branch dieback or pest attacks. Moreover, ethephon should be used according to the safety precautions stated by the Material safety data sheet (MSDS) of the product.

Conclusion

This field study shows the potential of ethephon to increase gum yield by *Acacia senegal* in Northern Cameroon, in semi-arid and especially in sub-humid conditions, where gum production is uncertain because of lack of water stress. As ethephon is available, affordable and easy to use, the potential application for improving gum yield is huge in Northern Cameroon and in other gum producing countries in Africa. However, it is too early to recommend the use of ethephon for farmers. Additional studies are required on a larger number of provenances and in different environmental conditions to understand factors affecting consistency of response. Moreover, the experience learned from extensive studies of ethephon to stimulate latex yield in the rubber tree (*Hevea brasiliensis*) showed that its use has to be adapted to each provenance to prevent physiological disorders.

These experiments with ethephon provided information on the regulation processes of gum production. The variable responses among provenances and among seasons showed that the original hypothesis—that gum yield was limited by insufficient water stress and ethylene could mimic such a stress—has to be refined. Particularly, ethephon had no effect on gum yield in provenances introduced from drier areas, contrary to the initial hypothesis.

Studies of application of ethephon could be combined with variation in other factors (leafing phenology, climate including air humidity and temperature, tapping methodology) to study further the regulation processes of gummosis and gum exudation. Hence, ethephon appears a very promising tool, not only to increase gum yield, but for experimental studies to better understand the physiological basis of gum production.

Acknowledgments This work was supported by ACACI AGUM project (EC FP6 Contract 032233, http://inco-acaciagum.cirad.fr/). The PRASAC regional platform (Ndjaména, Chad) provided logistic support. The staff of IRAD Forêt in Maroua are acknowledged for their field work. Thanks to Mr André Bonda, for welcoming the experiment at his plantation in Ngong.

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