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Full Length Research Paper

Gum arabic yield in different varieties of *Acacia senegal* (L.) Willd in Kenya

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A comparative study was conducted at four locations namely Ngare Ndare, Daaba, Kulamawe and Ntumburi to assess gum arabic yield per tree per picking for different varieties of natural stands *Acacia senegal* (var. *kerensis*; var. *senegal* and var. *leiorhachis*) in Kenyan drylands for a period of five months. Sample plots measuring 1 hectare were established, one at each study site. Trees in each sample plot were measured for basal diameter and classified into three diameter classes (3.0 - 6.0, 6.1 - 9.0 and 9.0 cm). 10 trees from each diameter class were tapped while another 10 trees left untapped. Data collected was analyzed using Genstat version 10.0. Results showed that there was a significant difference in gum arabic yield ($p<0.001$) between tapped and non-tapped *A. senegal* trees as well as between tree stems and branches. Tapping increased gum arabic yield by 77.42%. Yield was highly affected by soil moisture and soil temperature, correlating negatively and positively respectively. Trees with basal diameter of 3.0 - 6.0 cm produced high quantities of gum arabic than big trees of basal diameter >6.0 cm for *A. senegal* varieties *senegal* and *leiorhachis* ($p<0.001$). These findings in the present study can be used for predicting yield in relation to the variety and site.

Key words: Natural stands, gum arabic, yield, *Acacia senegal* varieties, tree tapping, basal diameter.

INTRODUCTION

Acacia senegal is native to the Sahelian regions of Africa and the Middle East (NAS, 1979). It is one of the most common trees in Africa's arid and semi-arid savannas and occurs throughout the Sahel and Sudanese wood lands, in the Great Rift Valley and into Southern Africa (White, 1983). It is widely distributed in the drier parts of tropical Africa, from Senegal and Mauritania in the west to Eritrea and Ethiopia in the North-East and to South Africa in the south. Of the four recognized varieties *A. senegal* var. *senegal* is the most widespread and is found throughout the area of distribution of *A. senegal* except along the west coast of central and southern Africa (Brenan, 1983). Outside Africa, it occurs in Oman, Pakistan, India, Australia, Puerto Rico and the Virgin Islands. This variety is the major source of gum arabic. *A. senegal* var. *kerensis* occurs in Ethiopia, Somalia, Uganda, Kenya and Tanzania; *A. senegal* var. *leiorhachis* throughout eastern Africa from Ethiopia to South Africa; *A. senegal* var. *rostrata* occurs in the same area as *A. senegal* var. *leiorhachis* and in Namibia, Angola and in Oman (Brenan, 1983).

A. senegal is a xerophytic plant and grows in dry habitats. The plant tolerates water deficit and therefore able to endure conditions of prolonged drought associated with the arid region of Kenya. It belongs to the family Mimosacea and genus Acacia. This tree is a leguminous, nitrogen-fixing tree that is a pioneer species that thrives well on sandy soils. *A. senegal* thrives well on dry rocky hills, in low-lying dry savannas, and areas where annual rainfall is 250 - 360 mm (Bekele-Tesemma et al., 1993). This hardy species survives many adverse conditions, and seems to be favored by low rainfall and absence of frost. *A. senegal* is reported to tolerate annual precipitation of 380 - 228 mm, annual mean temperature of 16.2 - 27.8°C, and soil pH of 5.0 - 7.7, but Cheema and Qadir (1973) report a pH of 7.4 - 8.2. The tree ranges from

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from 100 - 1700 m elevation in the Sudan to 1950 m around Nakuru in Kenya (Maundu et al., 1999).

A. senegal is a woody species varying in habit from a shrub about 2 m to a tree about 15 m high. It is generally recognized by its three-hooked prickle, central one curved downwards and the two laterals more or less curved upwards, or singly, the laterals being absent and with the flowers in spikes. These characters are however shared by a number of other *Acacia* species and *A. senegal* forms part of this complex group of spicate-flowered acacias with prickles in threes or singly. *A. senegal* exhibits three different growth forms in Kenya, recognized as three varieties (Gachathi, 2002). Varietal differences in *A. senegal* are based on variation in natural distribution as well as differences in morphological characteristics such as presence or absence of hair on the axis of the flower spike, colour of the axis, shape of pod tips, number of pinnae pairs, occurrence of a distinct trunk, and shape of the crown. Three different varieties of *A. senegal* recognized in Kenya are var. *senegal*, var. *kerensis*, and var. *leiorhachis*.

Typical, *A. senegal* var. *senegal* is recognized as a tree with a flat or rounded crown and rough non-papery and non-peeling bark commonly growing on sandy alluvial loamy soils in plains or at the foot of hills in semi-humid to semi-arid areas. *A. senegal* var. *kerensis* grows as a single or several-stemmed shrub with lateral branches form near the base and with smooth yellowish-brown peeling bark on the stem. It is common on rocky hills and ridges or sandy plains in arid to the very arid areas (Gachathi, 2002).

A. senegal var. *leiorhachis* exhibits two growth forms; either as a struggling slender tree starting with a very branched bushy base then thinning out to 1-4 slender whippy erect tall stems with peeling bark or a well grown tree with open rounded spreading crown and yellowish papery and peeling bark on the main trunk. The whippy form occurs in clusters of small populations on extremely rocky gneiss-derived sandy soils in semi-arid to arid areas in plains while the tree form occurs on red deep sandy soils along drainage lines and areas with high water table (Gachathi, 2002).

Gum arabic is a dried exudate obtained from the stems and branches of *A. senegal* (L) Willd or *Acacia seyal* (FAO, 1999). The gum is found immediately under the bark, where it is sometimes collected in regular cavities. It is formed within the plant by metamorphosis of the cells of the inner bark. The tissues involved are chiefly those of the sieve and the cambiform cells (Anderson, 1995). While to some extent it is a natural change, yet it is usually looked upon as being in part a pathological production, as gummosis develops more largely upon the wounding of the trees. The attack of the *A. senegal* trees by various parasites/insects is held by some researchers to account for the enormous production of gums in these trees.

High gum arabic production requires severe physiological stress from water depletion and heat (Anderson, 1995). Gum arabic formation has been re-garded as a natural response of trees under dehydration stress to store a strongly hydrophilic form of reserve carbohydrate (Anderson, 1995). Gum arabic is known to be formed at the time of leaf-fall and translocated to roots even before the tree has been tapped. Gum arabic exudes from the cracks on bark of wild trees in the dry season, with little or none in the rainy season when flowers are out.

Year-to-year fluctuation and instability in gum arabic production have been observed in Kenyan ASAL areas. Many authors (ITC, 1972; FAO, 1978; NAS, 1979; Duke, 1981; Muthana, 1988; Badi et al., 1989; Ballal et al., 2005; Dagnew, 2006; Chiveu et al., 2009) have presented varying estimates of gum arabic yields. These estimates contain little information on the different va-rieties of *A. senegal*. Yields of gum arabic from individual trees are very variable and hardly any reliable data is available. A tree, on an average, may yield 250 g of gum arabic per annum (two seasons), although production may range from a few grams to as high as 10 kg (NAS, 1979; Dagnew, 2006) or 0.2 to 6.7 kg (Duke, 1981). Chemulanga et al. (2009) has reported that the yield of gum arabic range between 0.66 and 0.81g/tree/season for *A. senegal* var. *kerensis* in Kenya. The highest yields are observed on individuals aged from 7 to 12 years. Yield per ha per year ranges between 30 to 40 kg in case of open stands and as much as 100 kg in case of dense stands (ITC, 1983). Yields from cultivated trees are said to increase up to the age of 15 years, when they level off and then begin to decline after 20 years (ITC, 1983; Abdel Rahman, 2001).

Presently, the major problem facing gum arabic industry in Kenya is lack of reliable information on gum arabic yield and yields trends that can be used as a basis for monitoring gum arabic production. Consequently, there is need to evaluate quantitatively gum arabic yield by three different varieties growing in Kenyan dryland areas and in sites with different biophysical charac-teristics. Besides, information on how tree size and/or age affect the quantity of gum arabic produced by *A. senegal* growing naturally in ASALs of Kenya is lacking.

The aim of the present study was to determine and analyze the gum arabic yield and its picking variations in relation to different varieties of *A. senegal* and site conditions, including the size of the tree, so as to facilitate gum yield improvement in order to provide information needed for gum arabic yield improvement and to offer new management guidelines for the benefit of local communities living in the drylands of Kenya.

MATERIALS AND METHODS

This research was undertaken in Isiolo District, Kenya. The study Site was selected because it has high natural population of *A. senegal* trees. Moreover, Isiolo is one of the Districts in the ASALs with high gum arabic production potential. Four sites in the District;

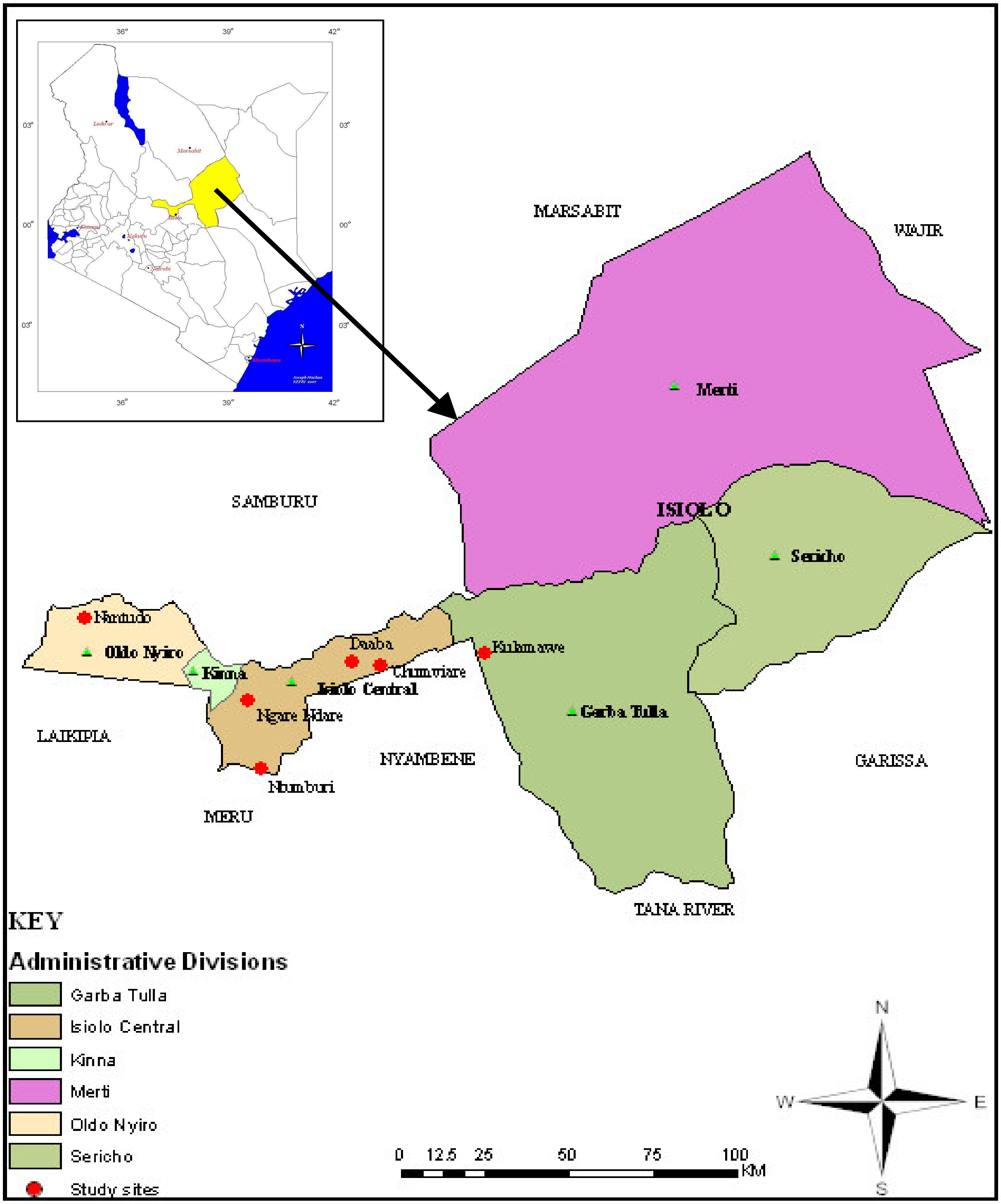

Figure 1. Map of Kenya showing the position of Isiolo District and the study sites

Ngare Ndare, Kulamawe, Ntumburi and Daaba, which exhibit different biophysical characteristics hence made it possible to compare the effects of these conditions on gum arabic yield, were selected for the study. Isiolo District is located between longitude 36°60' East and 39°50 'East and latitudes 0°5 North and 2° North. The District covers an approximate area of 25,605 km^2 (Figure 1).

Most of the District is a flat, low lying plain. The plain rises gradually from an altitude of about 200 m above sea level (m.a.s.l) at Lorian Swamp in the northern part to about 947 m and 300 m above sea level at Daaba and Merti Plateau respectively. The altitude is highest to the south where Ntumburi site is located, about 1748 m.a.s.l. To the west towards Laikipia District where there are volcanic hills, the altitude is 987 m.a.s.l and to the east towards Garba-Tulla, the altitude is 1020 m.a.s.l at Kulamawe plot. The District is hot and dry for most of the year. It has two rainfall seasons; the short rains, coming in October and November, and the

Table 1. ANOVA table for sites physical characteristics.

Characteristic	Daaba	Ngare Ndare	Kulamawe	Ntumburi	S.E	% CV
Atmospheric temperature (ºC)**	29.9a	28.3b	31.8c	25.7d	2.857	9.9
Soil temperature (ºC)***	32.3a	31.3a	33.4a	29.9a	5.49	17.3
Soil moisture (%)**	5.3a	3.6b	5.6a	12.9c	1.435	20.7

*Any means in the same column having a common letter are not significantly different.**Significant at p<0.01. ***Significant at p<0.05

long rains, which fall between March and May. The rainfall received in the District is scarce and unreliable. The District is arid with an average annual rainfall of 580.2 mm. The wettest months are November during the short rains with an average of 143 mm and April with an average of 149 mm during long rains. High temperatures are recorded in the District throughout the year, but there are slight variations in some places due to differences in altitude. The mean annual temperature for Isiolo station, at an altitude of 1,104 m above sea level is 26.6℃ while in Merti, which is 300 m above sea level, it is 27℃. The soils are poor over most places and are characterized by lithic soils mainly sandy clay to gravel clay, well drained, shallow, stony and rocky, and hold no water but support vegetation that remains green for long after the rain. The soils vary in colour ranging from reddish-brown in Ngare Ndare to greyish in Daaba and Ntumburi and brownish in Kulamawe.

The field experiments on tapping were conducted in the natural stands of *A. senegal*. Four sites namely Ngare Ndare, Kulamawe, Ntumburi and Daaba were selected and four sample plots measuring 100m by 100m (1 ha) established, one in each site. Within each sample plot, all individual *A. senegal* trees in the sample plots were identified, counted and basal diameter (BD) measured. They were classified into three different diameter classes as follows: 3.0-6.0 cm, 6.1-9.0 cm and >9.0 cm. From each diameter class, ten trees were randomly selected by casting the dice and then tapped for gum arabic production. Further randomization was performed to select an additional ten trees from each diameter class that were left untapped as a control to replicate natural conditions under which local communities collect their gum arabic exudates.

Tapping of the trees was done by making one incision on one selected branch and one incision on the main stem using the sonkey. The incision had a length of 10-15 cm and a width of 3 cm. Gum arabic was collected after 25-30 days from the date of tapping from both the tapped and untapped trees and thereafter at a regular interval of three weeks until the end of dry season. Gum exudates were collected from 30 tapped trees and 30 untapped trees *A. senegal* trees at each site and the quantity obtained from the stem and the branch of each tree was weighed and recorded to estimate the gum arabic production potential. Thus, 240 trees were sampled for gum arabic collection. In total, three collections (pickings) were made. Soil moisture, soil temperature and atmospheric temperature in the sites were recorded at tapping time and during each gum arabic picking date.

Data analysis was done using Genstat version 10.0. Kruskal-Wallis one-way ANOVA was performed to determine the significant difference in yield between sites, diameter class and pickings, followed by Least Significance Difference test ($p < 0.05$, $p < 0.001$ and $p < 0.01$) where the F-test demonstrated significance. Mann-Whitney U (Wilcoxon rank-sum) test was used to determine the differences in gum arabic yield for tapped and untapped trees and between the branches and the stems ($p < 0.001$). Regression analysis was carried out to determine the effect of soil moisture on gum arabic yield in the sites. Kendall's rank correlation was performed to determine relationship between soil moisture and soil temperature, soil temperature and atmospheric temperature and soil temperature and gum arabic yield. Ms Excel was used for graphing.

RESULTS, DISCUSSION AND RECOMMENDATIONS

Physical characteristics of the study sites

The following physical characteristics were studied, atmospheric temperature, soil temperature and soil moisture. These physical characteristics were studied because they have a significant effect on the physiology and growth rates of trees. Gum arabic production by *A. senegal* trees is a physiological process and as such these physical factors affect its production specifically, the yield and quality.

The mean variation of physical characteristics of the study sites is presented in Table 1. The mean atmospheric and soil temperatures were highest at Kulamawe, followed by Daaba, Ngare Ndare and then Ntumburi. Ntumburi had the highest mean soil moisture followed by Kulamawe, Daaba and then Ngare Ndare.

A significant difference ($p<0.01$) in atmospheric temperature between sites existed with Kulamawe being the hottest followed by Daaba and Ngare Ndare respectively while Ntumburi had the lowest recorded atmospheric temperature (Table 1). Daaba experienced highest atmospheric temperature at tapping time than the rest of the sites, which decreased from tapping to first picking and then remained steady in subsequent pickings. In Kulamawe, atmospheric temperature increased steadily from tapping time to third picking. The atmospheric temperature at Ngare Ndare and Ntumburi decreased slightly from tapping time to first and second pickings before going up slightly at third picking (Figure 2b). The variation in atmospheric temperatures in the sites is due to differences in elevations. Kulamawe, Daaba and Ngare Ndare, which have low elevations (altitude), have high atmospheric temperatures compared to Ntumburi, a site with high altitude.

There was no significant difference ($p<0.05$) in soil temperature between the sites ($p>0.532$). Soil temperature was high during the tapping dates and at third picking in all the sites but low during the second picking (Figure 2a). Daaba had the highest soil temperature at tapping time compared to the other sites whereas Kulamawe exhibited this condition of high soil temperature at third picking.

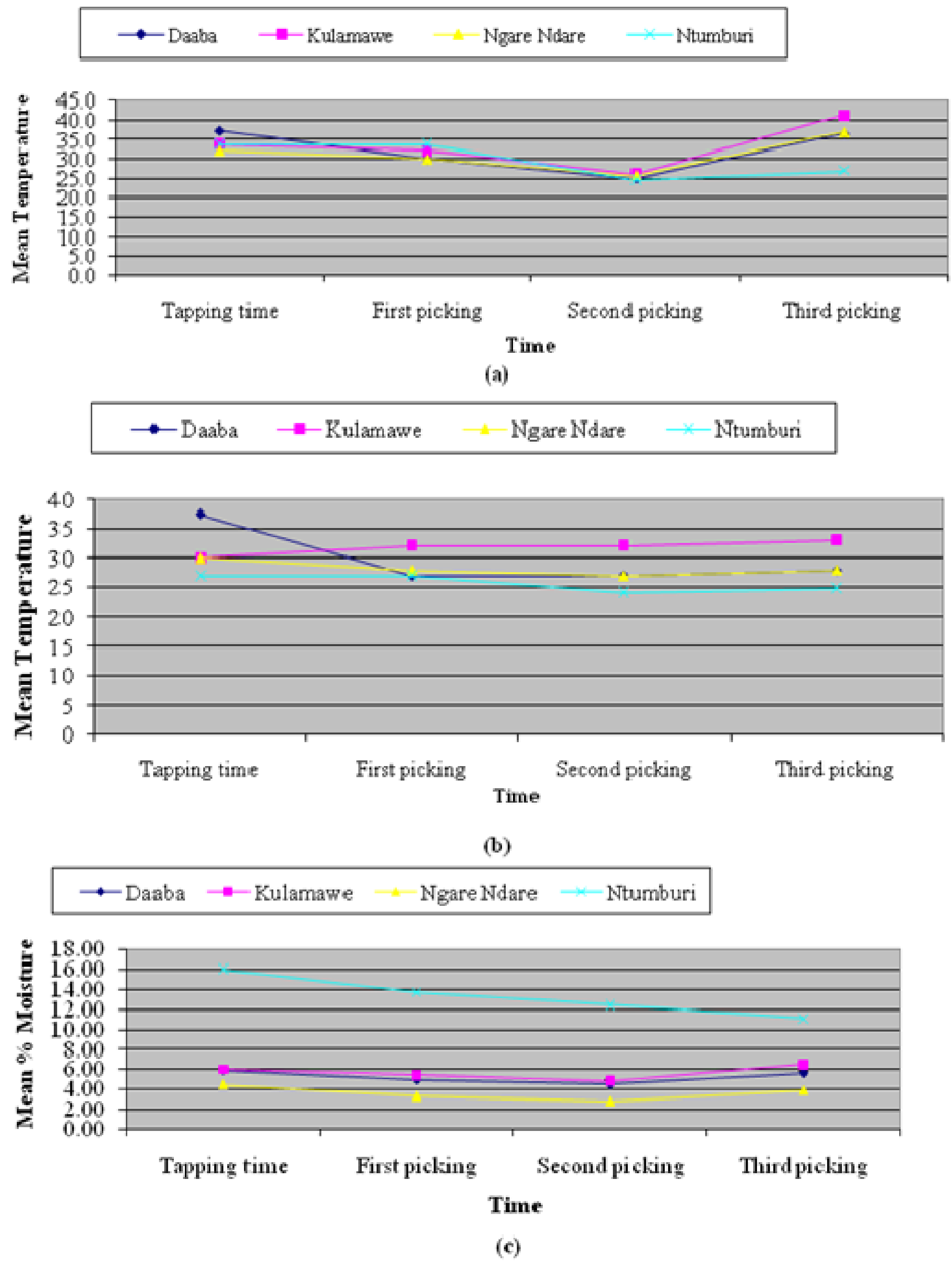

Figure 2. Trend in sites physical characteristics (a) Soil temperature (b) Atmospheric temperature (c) Soil moisture.

General analysis of variance revealed a highly significant difference ($p<0.01$) in soil moisture content between sites (Table 1). Ntumburi had the highest soil moisture content while Ngare Ndare had the lowest throughout the study period. When individual sites are compared for soil moisture content, there was no significant difference in soil moisture content between Kulamawe and Daaba ($p<0.05$). However, soil moisture content differed significantly ($p<0.05$) between Ngare Ndare, Daaba and Kulamawe and Ntumburi. Soil moisture content at Ntumburi decreased from tapping date to third picking and was lowest during the third picking of gum arabic (Figure 2c). The trend was different for the rest of the three sites where soil moisture content decreased slightly from tapping date to first picking but remained steady at first and second pickings before slightly increasing at the third picking.

The different soil types explain the variations in soil moisture levels observed in the study sites. Ngare Ndare is dominated by sandy soils, which loses moisture fast due

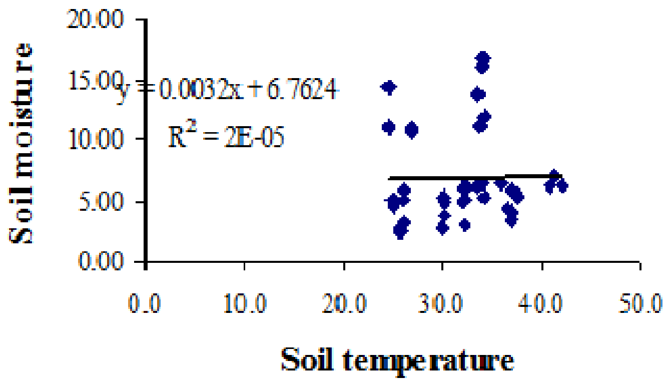

Figure 3. Relationship between soil moisture (%) and soil temperature (°C) Effect of atmospheric temperature on soil temperature.

Figure 4. Relationship between soil and atmospheric temperatures (°C): Effect of soil temperature on gum arabic yield.

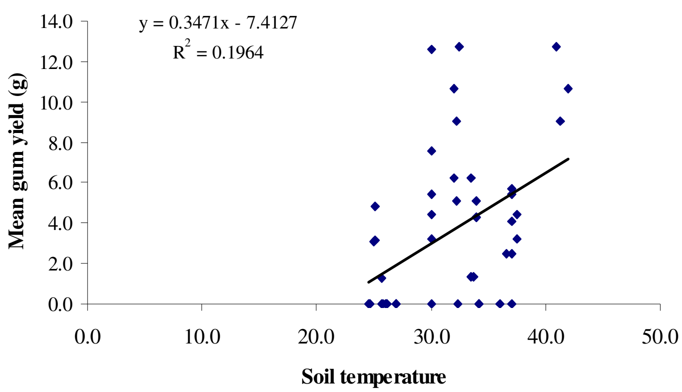

Figure 5. Relationship between soil temperature (°C) and gum arabic yield (g): Effect of soil moisture on gum arabic yield

due to their coarse texture. Ntumburi has clay-loam soils with good water retention ability and hence hold moisture for a long period. Soils at Kulamawe and Daaba are rocky-sand and sandy-loam respectively hence not able to hold and retain moisture for long. The results in the present study are in line with what was previously reported by Raddad and Luukkanen (2005) that the finer the soil particles, the larger the soil water capacity implying that clay, silt and loam soils have a high water holding capacity than sand soil. Thus, *A. senegal* growing in sites with sandy soils experience rigorous water stress and therefore produce high quantities of gum arabic than their counterparts in sites exhibiting clay, silt or loam soil.

Effect of soil temperature on soil moisture content

Correlation analysis (Kendall's rank correlation) pointed out that there was no significant ($p<0.05$) positive correlation ($r=0.1339$, $p=0.0869$) between soil moisture and soil temperature (Figure 3). These data therefore suggests that soil temperature does not influence the level of soil moisture. Thus, other factors such as the amount of precipitation and soil type influenced soil moisture levels in the sites. According to Raddad and Luukkanen (2005) soil texture, largely govern the amount of water that infiltrates or can be held in a soil body and this seems to be the main factor influencing soil moisture in the study sites and not soil temperature.

Results obtained in the present study shows that there was a significant positive correlation ($r= 0.5439$, $p < 0.01$) between the atmospheric temperature and soil temperature (Figure 4). This was expected because the prevailing atmospheric temperature influences the soil heat at a given period and therefore, the atmospheric temperature can be used to predict the soil temperature which is a critical factor that influences gum arabic production and hence the yield.

There was a highly significant positive correlation ($p < 0.05$) between soil temperature and gum arabic yield ($r = 0.4431$, $p= 0.0037$) as shown below (Figure 5). Consequently, gum arabic yield is positively influenced by soil temperature. This obviously reflects the sensitivity of *A. senegal* trees to high soil temperature when adjusting to physiological stress and comply with earlier reports by (Jackson, 1968; Duke, 1981) that the higher the average soil and atmospheric temperatures, the higher the yield of gum arabic.

Regression analysis ($p<0.01$) indicates that gum arabic yield by *A. senegal* is a function of the amount of water retained or available in the soil. Thus, as the moisture content in the soil increased, there was a decline in the yield of gum arabic ($r=-0.8670$, $p=0.002$) as shown below (Figure 6). According to Jackson (1968) and Gaafar et al. (2006), soil moisture has an effect on the yield of gum arabic with low soil moisture favoring increased gum arabic production.

A combined analysis of the yield data revealed a highly significant ($p<0.001$) interactive effects between site conditions, treatment and tree part on gum arabic yield

Figure 6. Relationship between soil moisture (%) and gum arabic yield (g): Gum arabic yield assessment.

for each of the three pickings of gum arabic.

Effect of site physical characteristics on gum arabic yield

There was significant difference (χ^2=30.69, p<0.01) in gum arabic yield between the sites with Ngare Ndare with a mean rank (768.06) having the highest yield followed by Kulamawe, which is inhabited by *A. senegal* var. *leiorhachis* with a mean rank (739.41).

Comparatively, Ngare Ndare had significantly higher yield than Daaba although the two sites are occupied with *A. senegal* var. *kerensis*. Ntumburi, the study site for *A. senegal* var. *senegal* had the lowest production of gum arabic. Generally, different varieties of *A. senegal* yield different quantities of gum arabic with *A. senegal* var. *kerensis* being the main producer. The present findings therefore confirm that *A. senegal* var. *kerensis* is the main species that produces commercial gum arabic in Kenya and confirms the results of earlier studies by Chikamai and Banks (1993).

This study has assertively established that site physical characteristics influences gum arabic yield because though Daaba and Ngare Ndare have the similar variety; Ngare Ndare produced high quantity of gum arabic than Daaba. The yield differs in these two sites due to differences in soil physical properties, altitude and both atmospheric and soil temperatures. Ngare Ndare has sand soil that loses moisture faster and the site exhibited low soil moisture throughout the study period than Daaba, which has sandy-loam soil, and therefore retains moisture longer. Since low soil moisture favors high gum arabic production due to the gum producing trees being subjected to high physiological stress, *A. senegal* trees at Ngare Ndare yield more gum arabic than those at Daaba where the stress level of the trees resulting from water deficit is not very high. Other related studies by Raddad and Luukkanen (2005) have shown that soil texture; largely influences the yield of gum arabic with *A. senegal* growing in sandy soils producing high quantities than their counterparts in clay soils and this is mostly because of the amount of soil moisture a soil type can hold for a period of time.

Personal observation by the author found that phenological behavior of *A. senegal* var. *kerensis* in Daaba and Ngare Ndare differed sharply with trees in Daaba having an extended leafing period than those in Ngare Ndare. Since gum arabic begins to ooze out when trees start shedding leaves, there is a delay in its production at Daaba compared to Ngare Ndare and this explains why trees in Ngare Ndare yield more gum arabic than Daaba. The differences in genetic composition of the two populations of *A. senegal* var. *kerensis* at Ngare Ndare and Daaba also account for the differences in gum arabic yield because neighbor-joining topology grouped the two populations of *A. senegal* var. *kerensis* in two different main groups (Omondi, 2009).

Effect of tapping and tapping position on gum arabic yield

The experiments clearly show that tapping increases gum arabic production and consequently the yield in all the three varieties of *A. senegal*. There was a significant difference (p<0.01), (U=206683, Z=10.24), in gum arabic yield between tapped and untapped trees whereby tapped trees had higher average yield (3.1 g) per tree per season than untapped trees (0.7g) per tree per season (Figure 7). Besides, the average gum arabic yield per picking per tree resulting from tapping *A. senegal* trees

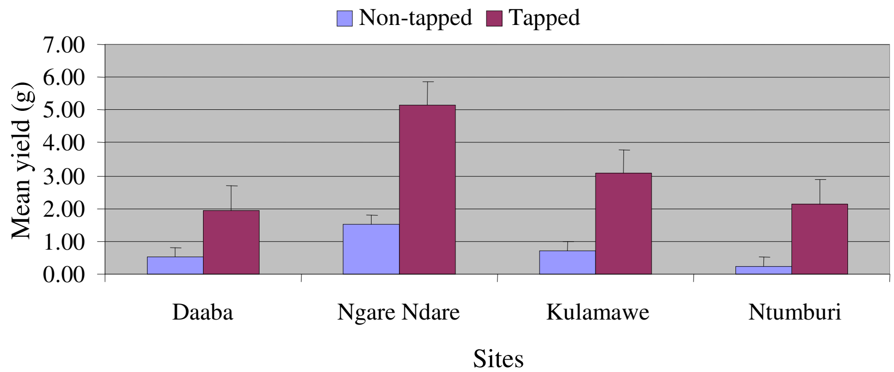

Figure 7. The overall mean gum arabic yield for non-tapped and tapped A. senega in sites. Bars indicate S.E (± 0.5).

Table 2. Mean gum arabic yield of tapped tree stems and branches.

Tree part	Mean yield/tree/season (g)
Tree stem	2.6
Tree branch	1.1

Table 3. Overall average gum arabic yield/tree/season for tapped *A. senegal*.

	Mean yield/tree/season for diameter classes (g)			Mean yield (g)
Site	3.0 - 6.0 cm	6.1 - 9.0 cm	>9.0 cm	
Daaba	1.45	1.6	2.8	1.95
Ngare Ndare	3.2	6.4	5.85	5.15
Kulamawe	3.9	3.4	1.85	3.05
Ntumburi	2.0	4.35	0.1	2.15

was higher than the average gum arabic yield per picking per tree for non-tapped trees in all the three diameter classes.

Analysis of variance using Mann-Whitney U (Wilcoxon rank-sum) test showed a significant difference in yield ($Z=7.24$, $p<0.01$) between stems and branches whereby the stems produced higher gum arabic yield than the branches (Table 2). The stem tapping caused the highest mean gum arabic exudation/yield per individual tree per season (2.6 g) irrespective of the diameter classes whereas tapping the branches gave the lowest gum arabic yield per tree per season (1.1 g).

These results of this study demonstrates that in order to enhance gum arabic production, tapping has to be done which is consistent with common yield enhancement practices in other gum arabic producing countries like Sudan, Nigeria and Senegal where *A. senegal* trees are tapped to increase gum arabic production. Agriculture Research Corporation (ARC) of Sudan reported that tapping increases yield of gum arabic by 47-60% and this report deviate from the results of present study, which have established that tapping of *A. senegal* trees increases gum arabic yield by more than 77.42%.

Gum arabic yield per tree in relation to tapping

The overall average gum arabic yield for tapped trees (1.95 g/tree/season) at Daaba (*A. senegal* var. *kerensis*) constituted 37.86% of that (5.15 g/tree/season) at Ngare Ndare (*A. senegal* var. *kerensis*) and was 36 and 9.5% less than 3.05 and 2.15 g/tree/season at Kulamawe and Ntumburi respectively (Table 3). The overall average gum arabic yield/tree/season (3.05 g) for *A. senegal* var. *leiorhachis* at Kulamawe was 29.5% more than (2.15 g/tree/season) obtained in natural stand of *A. senegal* var. *senegal* at Ntumburi and 40.8% less than 5.15 g/tree/season at Ngare Ndare (*A. senegal* var. *kerensis*). Accordingly, the overall average gum arabic yield for tapped trees (2.15 and 1.95 g/tree/season) for Ntumburi and Daaba respectively was not significantly different ($p<0.05$) although the sites were inhabited with different varieties of *A. senegal*.

In the view of present study, gum arabic yield for natural stands of *A. senegal* var. *senegal* in Kenya was not similar to that found in natural stands of *A. senegal* var. *senegal* in Sudan and generally was lower. Ballal et al. (2005) reported an overall average gum arabic yield of 99.2 g/tree for *A. senegal* var. *senegal* growing in natural stands in the Sudan's gum belt region for an assessment period of eight years which is equivalent to 16 gum arabic production seasons because each calendar year has two seasons. Taking the overall average gum arabic yield of 99.2 g per individual tree and dividing it by 16 seasons, the overall average yield/tree/season is 6.2 g. Therefore, the outcome of present study is lower than what Ballal et al. (2005) reported. In fact, the overall average gum arabic yield of *A. senegal* var. *senegal* per tree per season (2.15 g) in Kenya represents only 34.7% of what is harvested from an individual tapped tree of *A. senegal* var. *senegal* in natural stands in the Sudan in a single season.

Conversely, overall average yield of gum arabic for tapped *A. senegal* var. *senegal* in scientifically well managed plantations of the Sudan according to the earlier results of Ballal et al. (2005) was 10.88 g/tree/season which is five times more than 2.15 g/tree/season for natural stand of *A. senegal* var. *senegal* in Kenya. Consequently, *A. senegal* var. *senegal* trees in well managed plantations yield high quantities of gum arabic than those growing in natural and disturbed stands.

Further, present study findings on gum arabic yield of *A. senegal* var. *senegal* contradict previous reports by several authors such as NAS (1979), Duke (1981) and Dagnew (2006) who reported that *A. senegal* var. *senegal* gum arabic yield range from 200-6700 g per tree per year a figure that translate to about 100-3350 g per tree per season. Additionally, the present findings on gum arabic yield of *A. senegal* var. *kerensis* which range between 1.95 and 5.15 g/tree/season are in sharp contrast to the report of Chemulanga et al. (2009) that the yield ranges from 0.66-0.81 g/tree/season. No previous studies have been done to quantify gum arabic yield of *A. senegal* var. *leiorhachis* in Kenya; nevertheless, the results of present findings with authority assert that this variety yield 3.05 g/tree/season.

The overall average gum arabic yield for *A. senegal* var. *kerensis* (5.15g/tree/season) at Ngare Ndare compares well with the figure (6.2 g/tree/season) reported for *A. senegal* var. *senegal* found in natural stands in Sudan (Ballal et al., 2005) although the two varieties are different. This emphasizes the fact that *A. senegal* var. *kerensis* is the main species for commercial gum arabic production in Kenyan ASALs as earlier reported by Chikamai and Banks (1993) and its yield can therefore be compared to the yield of *A. senegal* var. *senegal* in Sudan which is the main species producing commercial gum arabic. It's essential to note that *A. senegal* var. *leiorhachis*' overall average gum arabic yield (3.05 g/tree/season) gives a strong signal that this variety has a great potential for gum arabic production to supplement *A. senegal* var. *kerensis*.

Gum arabic yield per tree in relation to non-tapping

The overall average gum arabic yield for non-tapped trees (0.52 g/tree/season) at Daaba (*A. senegal* var. *kerensis*) was 34.07% less than (1.52 g/tree/season) at Ngare Ndare for *A. senegal* var. *kerensis* and 30.7% less than 0.75 g/tree/season at Kulamawe for *A. senegal* var. *leiorhachis* (Table 4). The overall average gum arabic yield (0.23 g/tree/season) obtained in natural stand of *A. senegal* var. *senegal* at Ntumburi was 55.8% less than 0.52 g/tree/season collected from non-tapped *A. senegal* var. *kerensis* at Daaba.

A survey carried on traditional ecological knowledge (TEK) relating to gum arabic production indicated that though locals collect natural exudates of gum arabic, there are no records on individual tree yield per season because collectors do not keep such records, as the collection is randomly carried out (C. Wekesa, Egerton University, Kenya, personal communication). However, field experiments in this study suggests that gum arabic yield resulting from natural exudation is very low ranging from 0.23-1.52 g/tree/season depending on the variety of *A. senegal* and site physical characteristics such as soil type which has come out strongly in this study as a significant factor influencing gum arabic yield especially when similar variety is considered. As it was the case for tapped trees, Ngare Ndare yielded high quantity of gum arabic, followed by Kulamawe, Daaba and Ntumburi in that order.

Effect of tree size on gum arabic yield

Kruskal-Wallis one-way analysis of variance showed no significant difference ($p<0.05$) in gum arabic yield between different diameter classes in sites ($\chi^2=4.951$, $p=0.084$) implying that the diameters classes' assessment had no effect on the quantity of gum arabic in the study sites. However, gum arabic yield per basal diameter class within Kulamawe and Ntumburi sites varied significantly ($p<0.001$) with small sized trees in diameter class (3.0-6.0 cm) producing higher yields than the other two classes (6.1-9.0 cm and >9.0 cm). Big trees with a basal diameter of >9.0 cm for *A. senegal* varieties *leiorhachis* and *senegal* did not produce substantial amounts of gum arabic at all whether tapped or not tapped.

The gum yields for *A. senegal* var. *kerensis* at Daaba and Ngare Ndare showed no significant difference ($p<0.001$) among the three different basal diameter classes although Ngare Ndare had higher overall gum arabic yield than Daaba in all the diameter classes. This probably because of the similar variety, that occupies the two sites.

The interpretation of these results regarding prediction of gum arabic yield for *A. senegal* var. *senegal* and *A. senegal* var. *leiorhachis* in view of basal diameter classes largely validates the idea that gum arabic yield is related

Table 4. Overall average gum arabic yield for non-tapped *A. senegal*.

Site	Mean yield/tree/season for diameter classes (g)			Mean yield (g)
	3.0 - 6.0 cm	6.1 - 9.0 cm	>9.0 cm	
Daaba	0.5	0.7	0.35	0.52
Ngare Ndare	0.6	1.15	2.8	1.52
Kulamawe	0.6	1.25	0.4	0.75
Ntumburi	0.7	0	0	0.23

related to the size and/or age of the trees. In this connection, a series of linkages between factors affecting tree growth or gum arabic production and age of the tree might have caused trees of different sizes to yield different quantities of gum arabic. Other studies (ITC, 1983; Abdel Rahman, 2001) in contrast, have found that gum yield is low in trees 5 to 10 years of age, increases to reach its peak at 15 years of age, and then decreases at the age of 20 years.

Traditional ecological knowledge (TEK) based on experience of gum arabic collectors pointed out that small trees produce more gum arabic than big trees and comply with result of field experiments for the case of *A. senegal* var. *senegal* and *A. senegal* var. *leiorhachis* which reveal that trees in diameter class 3.0-6.0 cm yield more gum than those in diameter classes 6.1-9.0 and >9.0 cm (C. Wekesa, Egerton University, Kenya, personal communication). But for *A. senegal* var. *kerensis*, the diameter class did not affect the average gum arabic yield per individual tree and thus deviates from traditional ecological knowledge (TEK) report which indicated that small sized *A. senegal* trees produced large amount of gum arabic than big sized trees.

The higher yield observed in small sized trees than big trees at Kulamawe (*A. senegal* var. *leiorhachis*) and Ntumburi (*A. senegal* var. *senegal*) can be attributed to the roots architecture of the trees. The number of fine root intersects in the surface soil layer depend on tree age and increases with tree age. Thus, tree root density of small sized trees decreases sharply with increasing soil depth, with most fine roots being found in the surface layers where they mainly utilize accumulated soil water content in the upper soil layer and hence not deep enough to reach deep water table as compared to big sized trees, which are deep rooted. As a result, small sized trees experience high water stress levels during the dry spell than big trees. Secondly, variation in gum arabic production in different diameter classes can be due to the differences in the rate of metabolic activities of the trees. Small sized trees are young and hence are still in active growth phase and are very sensitive to physiological changes especially due to change in soil water status.

Effect of pickings on gum arabic yield

A combined analysis for tapped and non-tapped trees shows that there was significant difference ($p<0.05$) in yield between different picking times in *A. senegal* varieties in the study sites ($\chi^2=7.119$, $p=0.028$). Generally, the mean gum arabic yield per tree irrespective of the treatment (tapping or non-tapping) and the tree part (stem or branch) at Daaba decreased from first picking to third picking whereas at Ngare Ndare, the yield decreased from first picking to second picking before slightly increasing in the third picking. Further, at Kulamawe, the yield decreased slightly from first picking to second picking and then increased sharply at third picking to reach the peak. The mean gum arabic yield at Ntumburi increased from first picking to second picking before remaining steady in the third picking (Figure 8).

The mean gum arabic yield trend per tree in the study sites was dependent on soil moisture. As the amount of moisture in the soil increased as observed in Figure 2c of this study, the yield of gum arabic declined in all the study sites (Figure 8). The yield of gum arabic was also reliant on soil temperature whereby high soil temperature enhanced gum arabic yield. This directly proportional relationship between soil temperature and gum arabic yield is clearly revealed by soil temperature and gum arabic yield trends in Figures 2a and 8 of this study respectively. However, the atmospheric tempe-rature remained constant throughout the three pickings in all the study sites and therefore did have an impact on the yield of gum arabic at different pickings (Figure 2b of this study).

Trends in gum arabic yield for tapped *A. senegal*

The trends on average gum arabic yield per tree for tapped trees collected from the stems and the branches of tapped trees and relating to the diameter class for the different varieties in the sites is presented below (Table 5). The general yield trend of type of *A. senegal* variety or site for different basal diameter classes on trees' stems and branches at different pickings was quite different.

The findings in this study demonstrates that at Daaba (*A. senegal* var. *kerensis*), the average gum arabic yield/tree collected from tapped tree stems decreased from first picking to third picking for all the diameter classes. For diameter class (3.0-6.0 cm), the yield was 3.0, 1.6 and 1.3 g for first, second and third pickings respectively while classes 6.1-9.0 cm and >9.0 cm gave values of 4.3, 2.9 and

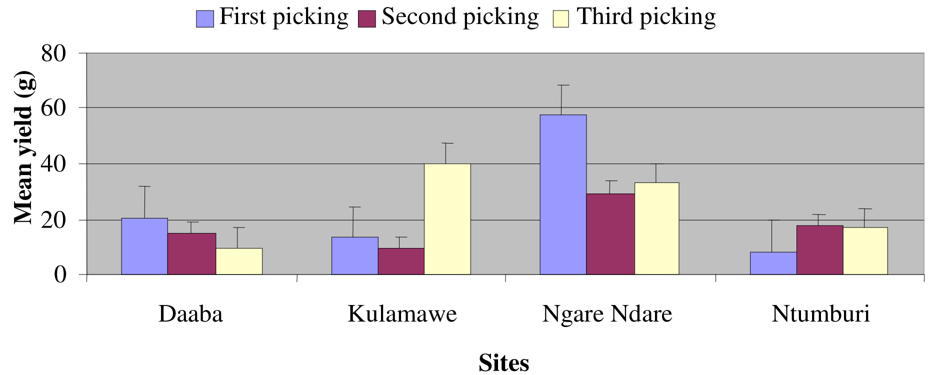

Figure 8. Mean gum arabic yield per tree at different pickings. Bars indicate S.E (± 0.5).

Table 5. Trends of gum arabic yield for tapped *A. senegal*

		Mean gum yield/tree/season (g)								
		Basal Diameter (BD) Classes (cm)								
		3.0 - 6.0 cm			6.1 - 9.0 cm			>9.0 cm		
Site	**Tree part**	1^{st} picking	2^{nd} picking	3^{rd} picking	1^{st} picking	2^{nd} picking	3^{rd} picking	1^{st} picking	2^{nd} picking	3^{rd} picking
Daaba	Stems	3	1.6	1.3	4.3	2.9	0	4.8	3.8	1.5
	Branches	0.2	2	0.9	0.2	0.7	1.7	4.2	1	1.7
Ngare Ndare	Stems	2.3	4.8	5.4	9	7	6.9	10.5	2.8	5
	Branches	1.5	3.3	1.8	12.9	0.6	1.9	11.2	2.9	2.7
Kulamawe	Stems	4.6	3.9	7.2	3.2	2.1	7.5	0.9	0.7	7.9
	Branches	2.7	1.2	4.1	1.4	1.2	5	0	0	1.4

4.3, 2.9 and 0 and 4.8, 3.8 and 1.5 g for first, second and third pickings respectively.

The branches, on the other hand showed a different trend for different diameter classes. In diameter class 3.0-6.0 cm, the second picking (2.0 g) had the highest average yield followed by third picking (0.9 g) while first picking (0.2 g) produced the least yield while for diameter class 6.1-9.0 cm, the average yield per tree increased with subsequent pickings with values of 0.2, 0.7 and 1.7 g for first, second and third pickings respec-tively. The average gum arabic yield from tapped branches of trees in class >9.0 cm at Daaba was highest in the first picking (4.2 g), followed by third picking (1.7 g) and then second picking (1.0 g).

The average gum arabic yield at Ngare Ndare (*A. senegal* var. *kerensis*) from stems of tapped trees in diameter class 3.0-6.0 cm showed an increasing trend from first picking to third picking with values of 2.3, 4.8 and 5.4 g for first, second and third pickings respectively being recorded. However, a decreasing average yield per tree from first picking to third picking (9.0, 7.0 and 6.9 g respectively for first, second and third pickings) was observed on stems of tapped trees falling within 6.1 - 9.0 cm diameter class. The trend in diameter class >9.0 cm showed that first picking yielded more gum (10.5 g) followed by third picking (5.0 g), whereas second picking generated the least amount (2.8 g) of gum arabic on tapped tree stems. In contrast, results of average gum arabic yield by the branches of tapped trees in diameter class 3.0-6.0 cm indicated that second picking (3.3 g) yielded more gum than first (1.5 g) and second (1.8 g) pickings. In the case of trees in diameter class 6.1 - 9.0 cm, the average branches' yield per tree was 12.9, 0.6 and 1.9 bg for first, second and third pickings respectively. Gum arabic average yield on tree branches (diameter class >9.0 cm) decreased from first picking to third picking (11.2, 2.9 and 2.7 g) for first, second and third pickings respectively.

The average yield of gum arabic showed consistent trend in Kulamawe (*A. senegal* var. *leiorhachis*) for the tree stems in all the diameter classes. The average yield trend on tapped tree stems for diameter classes 3.0-6.0 cm, 6.1-9.0 cm and >9.0 cm decreased from the first picking (4.6, 3.2 and 0.9 g) to 3.9, 2.1 and 0.7 g in the second picking before it reached its peak in the third picking (7.2, 7.5 and 7.9 g) respectively. However, branches' average gum arabic yield showed inconsistent trend for different diameter classes. The branches' average gum arabic yield for diameter classes 3.0-6.0 and 6.1-9.0 cm decreased from the first pick (2.7 and 1.4 g) to 1.2 and 1.2 g in the second picking before it reached its peak in the third picking (4.1 and 5.0 g) respectively. Tapped branches of trees in diameter class >9.0 cm did not produce any gum during first and second pickings but at third picking, an average yield of 1.4 g/tree was collected from the tree branches.

The average yield of gum arabic showed incoherent trend at Ntumburi (*A. senegal* var. *senegal*) for both tapped tree stems and branches in the entire diameter classes. The average yield trend in tapped tree stems for diameter class 3.0-6.0 cm decreased from the first picking (3.5 g) to 2.1 g in the second picking before slightly decreasing again in the third picking (3.3 g). The trend was however, different for diameter class 6.1-9.0 cm whereby the average gum arabic yield per tree on tree stems increased from 2.4 g in the first picking to 12.5 g in the second picking before slightly falling to 9.0 g at third picking. The tapped stems for trees in diameter class >9.0 cm yielded no gum in first and second pickings before producing an average amount of 0.7 g at third picking. The branches' average yield showed different trends for different diameter classes. The branches' average gum arabic yields for diameter class 3.0-6.0 cm increased from 0.0 g in first picking to 2.0 g during the second picking before falling to 1.1 g in the third picking. On the other hand, trees in diameter class 6.1-9.0 cm, showed that the yield increased from the first picking (0.0 g) to 0.8 g in the second picking before it reached its peak in the third picking (1.4 g). Tapped branches of *A. senegal* var. *senegal* trees in diameter class >9.0 cm did not produce any gum during first, second third pickings.

Trends in gum arabic yield for non-tapped *A. senegal*

The trends on average gum arabic yield per tree for non-tapped trees collected from the stems and the branches of untapped trees and relating to the diameter class for the different varieties of *A. senegal* in the study sites are presented in Table 6. The general yield trend of type of *A. senegal* variety or site for different basal diameter classes on the trees' stems and branches at different pickings was to a certain extent different.

The findings in this study shows that at Daaba (*A. senegal* var. *kerensis*), the average gum arabic yield/tree collected from untapped stems of trees in diameter class (3.0-6.0 cm) was 0.8, 0.9 and 1.4 g for first, second and third pickings respectively while diameter classes 6.1-9.0 cm and >9.0 cm gave values of 2.1, 1.0 and 1.2 g and 0.9, 1.0 and 0.0 g for first, second and third pickings respectively. The branches, on the other hand yielded no gum arabic in all the diameter classes for the three pickings.

The average gum arabic yield at Ngare Ndare (*A. senegal* var. *kerensis*) from stems of untapped trees in diameter classes 3.0-6.0 and 6.1-9.0 cm showed a decreasing trend from first picking (1.6 and 3.6 g) to second picking (0.0 and 0.6 g) before slightly increasing to 1.2 and 1.3 g in the third picking respectively. The trend was different in diameter class >9.0 cm where the yield increased from first picking (2.2 g) to 7.1 g in second picking before slightly decreasing to 4.3 g at third picking. On the other hand, the branches of untapped trees in diameter class 3.0 - 6.0 cm yielded no gum arabic in the first and second pickings but third picking yielded little gum (0.8 g). In diameter classes (6.1-9.0 and >9.0 cm), the average branches' yield showed an increasing trend of 0.0, 0.5 and 1.1 g and 0.0, 0.4 and 1.1 g for first, second and third pickings respectively.

The average yield of gum arabic showed inconsistent trend in Kulamawe (*A. senegal* var. *leiorhachis*) for stems of untapped trees for the different diameter classes. The average yield trend on stems for diameter class 3.0 - 6.0 cm increased from first picking to third picking as represented by 0.0, 0.3 and 2.7 g for first, second and third pickings respectively. Untapped stems of trees in diameter class 6.1-9.0 cm did not yield gum arabic at all while the stems of untapped trees in class >9.0 cm produced gum arabic during third picking (2.5 g). The tree branches' average gum arabic yield also showed inconsistent trend for the three diameter classes. The branches' average gum arabic yield for diameter class 3.0 - 6.0 cm decreased from the first pick (0.4 g) to 0.3 g in the second picking before it reached 0.0 g mark at third picking whereas class 6.1-9.0 cm had an increasing yield trend of 0.0, 0.7 and 2.5 g for first, second and third pickings respectively. Untapped branches of trees in diameter class >9.0 cm did not produce third pickings gum

Table 6. Trends of gum arabic yield for non-tapped *A. senegal*

		Mean gum yield/tree/season (g)								
		Basal diameter (BD) classes (cm)								
		3.0 - 6.0 cm			6.1 - 9.0 cm			>9.0 cm		
Site	**Tree part**	**1st picking**	**2nd picking**	**3rd picking**	**1st picking**	**2nd picking**	**3rd picking**	**1st picking**	**2nd picking**	**3rd picking**
Daaba	Stems	0.8	0.9	1.4	2.1	1	1.2	0.9	1	0
	Branches	0	0	0	0	0	0	0	0	0
Ngare Ndare	Stems	1.6	0	1.2	3.6	0.6	1.3	2.2	7.1	4.3
	Branches	0	0	0.8	0	0.5	1.1	2.9	0	0.4
Kulamawe	Stems	0	0.3	2.7	0	0	0	0	0	2.5
	Branches	0.4	0.3	0	0	2.2	0.7	0	0	0
Ntumburi	Stems	2.7	0	1.4	0	0	0	0	0	0
	Branches	0	0	0	0	0	0	0	0	0

third pickings gum arabic in the entire three pickings.

The average yield of gum arabic at Ntumburi (*A. senegal* var. *senegal*) for untapped tree stems in diameter class 3.0-6.0 cm was highest in the first picking (2.7 g) with third picking in this diameter class producing 1.4 g which is almost half of the amount in the first picking. There were no gum arabic exudates in the second picking on tree stems in this particular diameter class. Untapped stems of trees in diameter classes (6.0-9.0 cm and >9.0 cm) failed to produce any gum arabic at all. In the case of untapped tree branches, there was no gum arabic that was produced in this site in all the three diameter classes.

Conclusion

These results reveal that different varieties of *A. senegal* yield varying amount of gum arabic. Further, there is a difference in the quantities of gum arabic produced by trees of a similar variety occupying different geographical locations. Generally, *A. senegal* var. *kerensis* ranked higher compared to the *A. senegal* var. *senegal* and *A. senegal* var. *leiorhachis* in average gum arabic yield per tree per season. As a result *A. senegal* var. *kerensis* remains the main source of commercial gum arabic in Kenya.

A key result in the present study was that tapping of *A. senegal* varieties stimulated gum arabic production and increased yield by over 77.42% when compared with untapped trees. When tapped, *A. senegal* tree stems produce more gum than the tree branches in all the three varieties.

The gum production process in *A. senegal* seems to be highly affected by soil temperature and the moisture content in the soil. A positive relationship existed between soil temperature and gum arabic yield with high soil temperatures stimulating high gum arabic yield. A decrease in soil moisture causes the gum trees to produce more gum whereas high soil moisture levels reduces gum arabic yield drastically. The size and age of *A. senegal* trees influenced gum arabic yield per individual tree per season for *A. senegal* var. *senegal* and *A. senegal* var. *leiorhachis* with trees in basal diameter class 3.0-6.0 cm producing more gum than their counterparts in diameter classes 6.0-9.0 cm and >9.0 cm. On the other hand, *A. senegal* var. *kerensis* produced almost the same average gum arabic yield/tree/season irrespective of the diameter class.

The data obtained in the present study conclude that the first gum picking appears to be an important factor in gum arabic production and could be used as an indicator for the prediction of the total gum yield for *A. senegal* var. *kerensis* at Ngare Ndare and Daaba because first picking yielded more gum than the second and third pickings for *A. senegal* var. *kerensis*. On the other hand, in the case of *A. senegal* var. *leiorhachis*, third picking yielded more gum than first and second pickings and can be used in providing a good hint of gum arabic yield for this particular variety. The quantity of gum arabic collected from *A. senegal* var. *senegal* during the three pickings was highest in the second picking.

The findings of the present study, with respect to yield levels and trends, could be used to estimate gum arabic yields per picking, per tree, per season and per unit area in natural stands for the three different varieties of *A. senegal*. This could help in overcoming the instability and decline in gum arabic production that have been described as the main problems facing the gum arabic industry in Kenya. In addition, the present results bridges the gap on information related to the effects of soil moisture and temperature on gum arabic yield and yield trends.

Recommendations

a) Further research should be done to assess the effect of tapping intensity on gum arabic yield *A. senegal* found growing in natural stands. The yield assessment should be carried out for several seasons to ascertain the effect of seasonal factors such as variation in rainfall on gum arabic yield.

b) The influence of different tapping dates/time on gum arabic yield should be looked into to determine the best tapping time/dates.

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