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Influence of honey bees on fruit-set and production of shea trees (*Vitellaria paradoxa*) in the Sahelian parklands

Antoine Kalinganire, Brehima Kone, Patrice Savadogo,
Ademonla A D D Arinloye, Catherine Ky-Dembele

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Influence of honey bees on fruit-set and production of shea trees (*Vitellaria paradoxa*) in the Sahelian parklands

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LIST OF ABBREVIATIONS AND ACRONYMS

ACT	Australian Capital Territory
ANOVA	Analysis of variance
CSIRO	Commonwealth Scientific and Industrial Research Organization
DBH	Diameter at breast height
FAO	Food and Agriculture Organization of the United Nations
GPS	Global Positioning System
ICCO-Cooperation	Interchurch Organization for Development Cooperation
ICRAF	World Agroforestry
SmAT-Scaling	Scaling up Climate-Smart Agroforestry Technologies
US$	United States Dollar
USAID	United States Agency for International Development
WATH	West Africa Trade Hub
WCA	West and Central Africa

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EXECUTIVE SUMMARY

Shea (*Vitellaria paradoxa*) is an important fruit tree in the West African parklands; its successful pollination is a requirement for fruit production. A study was conducted to monitor the leafing, flowering and fruiting patterns of *Vitellaria paradoxa*. The aim was to understand whether or not the presence of beehives increased the frequency of visitation of honey bees to target trees, thereby enhancing fruit production in Mali.

Vitellaria trees shed most of their leaves in the dry season (January-April) when the atmospheric relative humidity is low and a combination of other climatic factors, higher average minimum temperatures) ensures dry conditions. Flowering occurs during this period (February-May) when the moisture stress is high, and trees are leafless. Fruit growth starts at the end of the dry season (May-September). Fruit harvesting mainly occurs from June to September, during the rainy season when the soil is well supplied with plant-available water. This study revealed that the presence of beehives in the parklands is likely to increase the visitation intensity to shea trees, thus improving cross-pollination fruiting. However, its implication on higher yields, particularly fruit weight or fruit quantity per tree, needs to be further investigated.

The study, which combined quantitative data collection with visual observation, revealed that the presence of honey bees (*Apis mellifera* L.) was important for pollination, and thus the production of fruit. Other visitors, including nectarivorous insects, such as stingless bees and birds, have also been observed in Mali.

Key words: Agroforestry parklands, honey bees, tree phenology, pollination, fruit-set, Shea tree

1. INTRODUCTION

Vitellaria paradoxa (Gaertn C. F.) subsp. *paradoxa* (Sapotaceae), a multipurpose tree, commonly known as Karité in French or Shea in English, produces an edible fruit that is the source of one of Africa's oldest food oils (Hall et al. 1996, Jasaw et al. 2015, Aleza et al. 2018). Shea butter, extracted by processing nuts of ripe fruits through roasting, crushing and boiling of the butter paste which is rinsed multiple times, is the main product of the shea tree and is sold in both local and international markets (Addaquay 2004, Boffa 2015), while the fruit pulp is eaten fresh. The butter is used in chocolate and confectionery industries as a substitute for cocoa butter. Its oil fraction is used in margarines and for baking in place of olive oil. Shea butter is growing in economic importance as a major export product, worth an estimated US$ 284 million annually in producer countries (Bockel et al. 2020). The vast majority of shea butter production, from collection of fruits to oil production, is carried out by women and girls, and is thus dubbed "women's gold" (Pouliot 2012, Naughton et al. 2015 and 2017, Bockel et al. 2020). The annual gross income per woman collector is estimated at US$ 75 (Bockel et al. 2020). Shea fruits are also eaten by bats, which play a key role in seed dispersal (Djossa et al. 2008).

Vitellaria paradoxa is indigenous to semi-arid and sub-humid savannas of sub-Saharan Africa, occurring on nearly 1 million km^2 in 21 countries (Boffa 2000, Bouvet et al, 2004, Breman and Kessler 2011, Boffa 2015, Naughton et al. 2015). Countries include Benin, Burkina Faso, Cameroon, Central Africa Republic, Cote d'Ivoire, Democratic Republic of Congo, Ethiopia, Gambia, Ghana, Guinea-Bissau, Guinea Conakry, Mali, Niger, Nigeria, Sierra Leone, Senegal, South Sudan, Sudan, Chad, Togo and Uganda; from the eastern part of Senegal and Gambia to the high plateau of East Africa into south-eastern Uganda forming an almost unbroken belt, 5000 km long and averaging 500 km wide. The species is represented by the sub-species *paradoxa* in the western part of its distribution area and the sub-species *nilotica* in the eastern part (Hall et al. 1996, Bouvet et al. 2004, Nikiema and Umali 2007). Both sub-species occur in a wide range of ecological conditions. According to Bouvet et al. (2004) sub-species *paradoxa* occurs at altitudes of 100-600 m above sea level with a mean annual rainfall of 600-1400 mm. Stands of the *nilotica* sub-species occur at higher altitudes of 650-1600 m with a mean annual rainfall of 500-1500 mm. The species is well adapted to poor shallow soils and land suitable for rainfed crops (Ruyssen 1957). It does not do well in flooded areas, highly sandy or clayish soils (Boffa 2015). Shea trees have been protected by farmers for many centuries both in the wild and in the agricultural landscape (Lovett and Haq 2000, Maranz 2009, Rousseau et al. 2015). Productive shea trees are retained when new fields are cleared, giving rise to the so-called *Vitellaria* parklands, in which more than 40% of the trees are *Vitellaria paradoxa* (Figure 1).

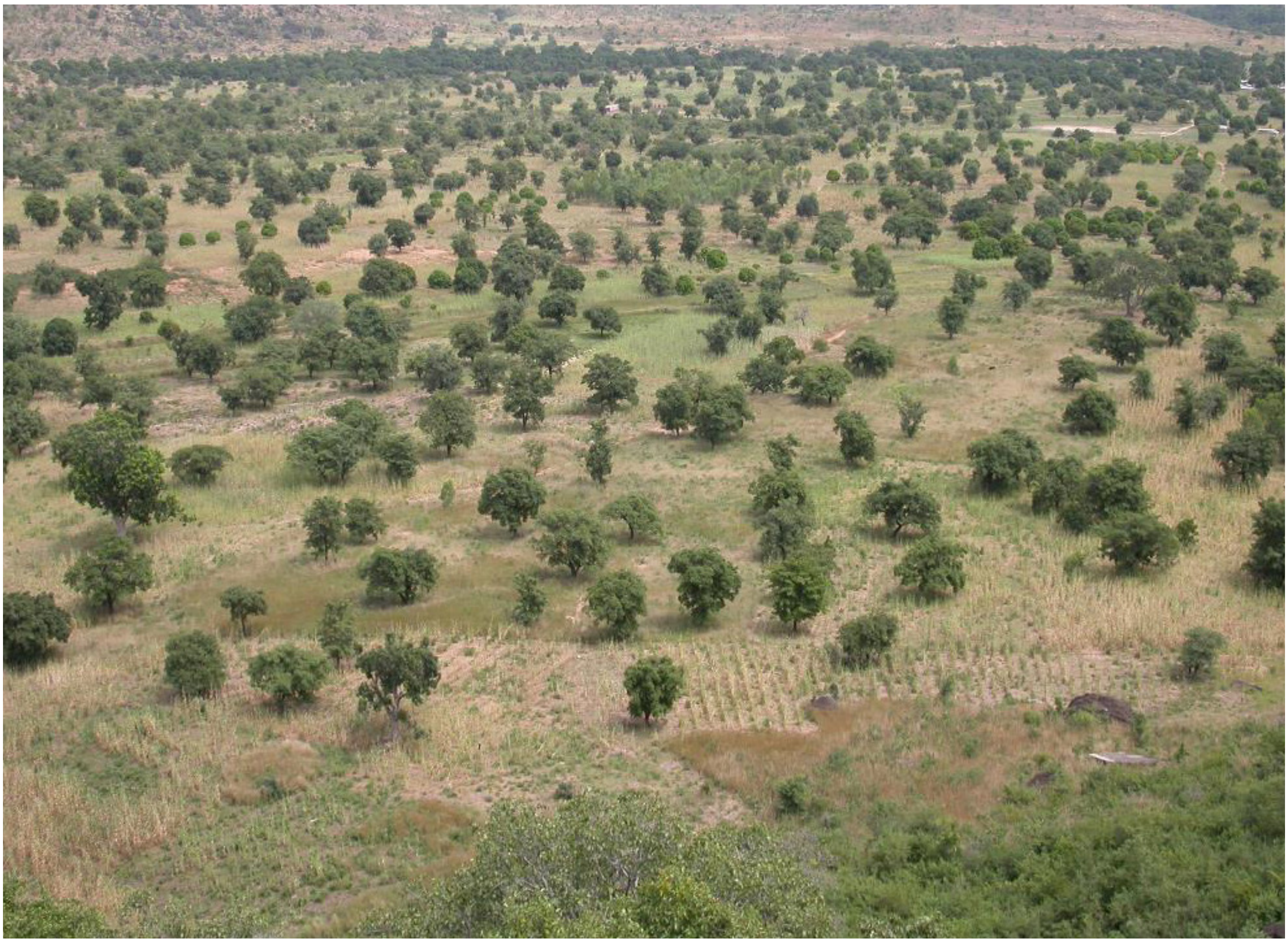


Figure 1. ***Vitellaria paradoxa* subsp. *paradoxa* parkland in Sikasso, Mali** (Photo by Patrice Savadogo)

Selection of particular shea nut trees for retention during land clearance is based on complex criteria that include spacing, health, fruit traits and yield characteristics of individual trees (Lovett and Haq 2000). Natural regeneration is favoured by fallow of at least five years. However, permanent cultivation and/or grazing or mechanized farming practices with reduced or non-existent fallow periods prevent naturally regenerating shea from attaining the preferred size at which farmers select seedlings for protection and recruitment into the parkland populations (Raebild et al. 2012, Boffa 2015). In addition, a lack of tree planting, increased intensification and mechanization of cropping, uncontrolled tree felling for fuel, and increased urbanization greatly reduce habitat diversity and contribute to degradation of shea parklands (Lovett and Haq 2000, Elias 2013, Boffa 2015). Moreover, several studies have highlighted declining tree densities in parklands in several agricultural areas of the Sahel (Kelly et al. 2018, 2019). The combination of drought and increasing population pressure (thereby resulting in shorter fallows) and threats by a plant parasite of the genus *Tapinanthus* are contributing to the decrease in shea populations (Boussim et al. 2003, Samake et al. 2011).

Shea is a slow-growing and long-lived fruit tree (up to 300 years), which can attain heights of up to 20 m and diameter at breast height of up to 50 cm (Hall et al. 1996, Nikiema and Umali 2007, Boffa 2015). Fruit production increases with tree age. Shea trees normally start fruiting when they are about 10-25 years old, while fruit production peaks at 45-100 years (Hall et al. 1996, Nikiema and Umali 2007, Elias 2013, Boffa 2015). However, shea plantations from grafted seedlings indicated a mean annual height growth of about 1 m (Antoine Kalinganire, personal observations), and an earlier fruiting period of 2-3 years after planting (refer to Figure 4). Nikiema and Umali (2007) reported that grafted seedlings started to bear fruit one year after grafting. A mature tree can bear, on average, 15-30 kg of fruits per year, and up to 50 kg during the very good harvest years (Boffa et al. 1996, Nikiema and Umali 2007). Shea productivity thus appears to depend both on the genetic make-up of the tree, as well as external factors (Ruyssen 1957, Boffa 2015). There is a five-fold difference between the best-producing trees and the population average, indicating potential for improvement. However, one of the barriers to shea selection and improvement is the lack of a planting culture of indigenous tree species in the region (Boffa 2015). The planting of thousands of grafted shea seedlings by communities in the Sahel indicate an end to that philosophy.

Shea populations remain largely wild and diverse in phenotype and genotype (Fontaine et al. 2004), and fruit production is known to fluctuate from year to year (Lovett and Haq 2000). The irregularity of production (rate not yet understood) and the strong variability of the fruit production from one tree to another is a hindrance to its industrial exploitation. Several studies suggest that variation in pollination success plays a significant role in explaining the annual variation of fruit production in shea trees (Millogo-Rasolodimby 1989, Soro et al. 2011, Lassen et al. 2018). The production potential of shea trees is influenced by the percentage of productive trees and percentage of trees collected. Lovett (2004) estimated that only 42% of the shea fruits available are collected due to accessibility, time, economic and transportation limitations experienced by the women. Shea production is cyclical – with one poor harvest following two good ones (Bockel et al. 2020).

Shea flowers are regular, hermaphroditic and protogynous (Lassen et al. 2018). They grow in bunches of 30-40, and produce strongly scented nectar, which entices the tree's several visitors and pollinators: nectarivorous insects, including bees (Figure 5). Shea trees are allogamous and predominantly outcrossing (Bouvet et al. 2004, Kelly et al. 2004 and 2007), and cross-pollination between trees can result in large phenotypic differences that are accentuated by environmental factors. Several pollination agents can affect fruit-set, and successful entomophilous pollination has been proven to play a significant role in the variability of the fruit production of shea trees (Millogo-Rasolodimby 1989, Lassen et al. 2018). In their study in southern Mali, Kelly et al. (2004) assumed that most self-pollination events were unsuccessful, in that they set no fruits.

Most authors recognize different species of bees as main pollinators (Lamien et al. 2004, Nikiema and Umali 2007, Lassen et al. 2018), but wind could also play a key role (Soro et al. 2011). Recent studies in a village in southern Burkina Faso suggested that *Apis mellifera* L. (honey bees) are the primary pollinating species, and confirmed increases in pollination success when *A. mellifera* hives were nearby (Lassen 2016). However, other potential pollinators, including other bee species, *Diptera, Lepidoptera* and Coleoptera, as well as several bird species also visit shea flowers. Land-use change and rapid habitat transformation in recent decades are considered important drivers of insect pollinator declines, thereby increasing the risk of future pollination deficits (Klein 2007) in areas of high and increasing pollination demands such as shea-based parklands.

Though it may be understood that visitation by wild insects and honey bees promotes fruit-set as it does for other fruit tree species, it is not clear whether or not pollination is limiting fruit-set and fruit weight, i.e., whether increased pollination could result in improved yields, particularly given the differences in yields recorded in different land-uses for *Vitellaria paradoxa* (Lamien et al. 2004). They reported that the proportion of fruiting trees in the population, as well as fruit size and weight, are higher in agroforestry parklands than in neighbouring forests. Pollinator limitation is common in many plant species, caused by either insufficient pollinator visitation resulting in sub-optimal pollen export and import, or inappropriate pollen deposition (Stein et al. 2017).

To address these knowledge gaps, this study tested the effect of introducing honey beehives on shea fruit yields, in terms of number of fruit-set and fruit weight. The researchers hypothesized that introduction of hives could increase the visitation frequencies of honey bees and produce more uniform fruit than those visited less often due to the absence of hives. Based on the findings, the potential positive relationship between beekeeping and fruit yield of shea trees are discussed.

Moreover, an analysis based on literature review on pollinators of shea trees was made, with special emphasis on entomophilous pollination. The review covers the natural distribution area of the species. Based on findings from the study in Mali and from the literature, the positive effects of bees on fruit production in a shea-tree-based parklands are discussed.

2. METHODOLOGY

The focus of the current analysis and study is on shea trees. It covers literature on its pollination and subsequent fruit production. Grey literature, peer-reviewed publications and research reports contain the geographic areas of the natural distribution of the species , with special reference to the Sahel. The study on shea pollination and fruit production was conducted in Mali (Figure 2) and implemented through the ‘Scaling-up Climate-Smart Agroforestry Technologies in Mali (SmAT-Scaling)’ program, a project funded by USAID Mali. Approaches for the pollination and fruit production study are herewith detailed.

Description of the study site

The focus of the current study is in a Malian shea tree-based parkland. The study was conducted in six different sites: Galo and Ngalamadibi (Koulikoro region); Beh and N’gorn (Koutiala region); and Sirakorobougou and Banankoro (Sikasso region), selected along the south-north climatic gradient in Mali (Figure 2).

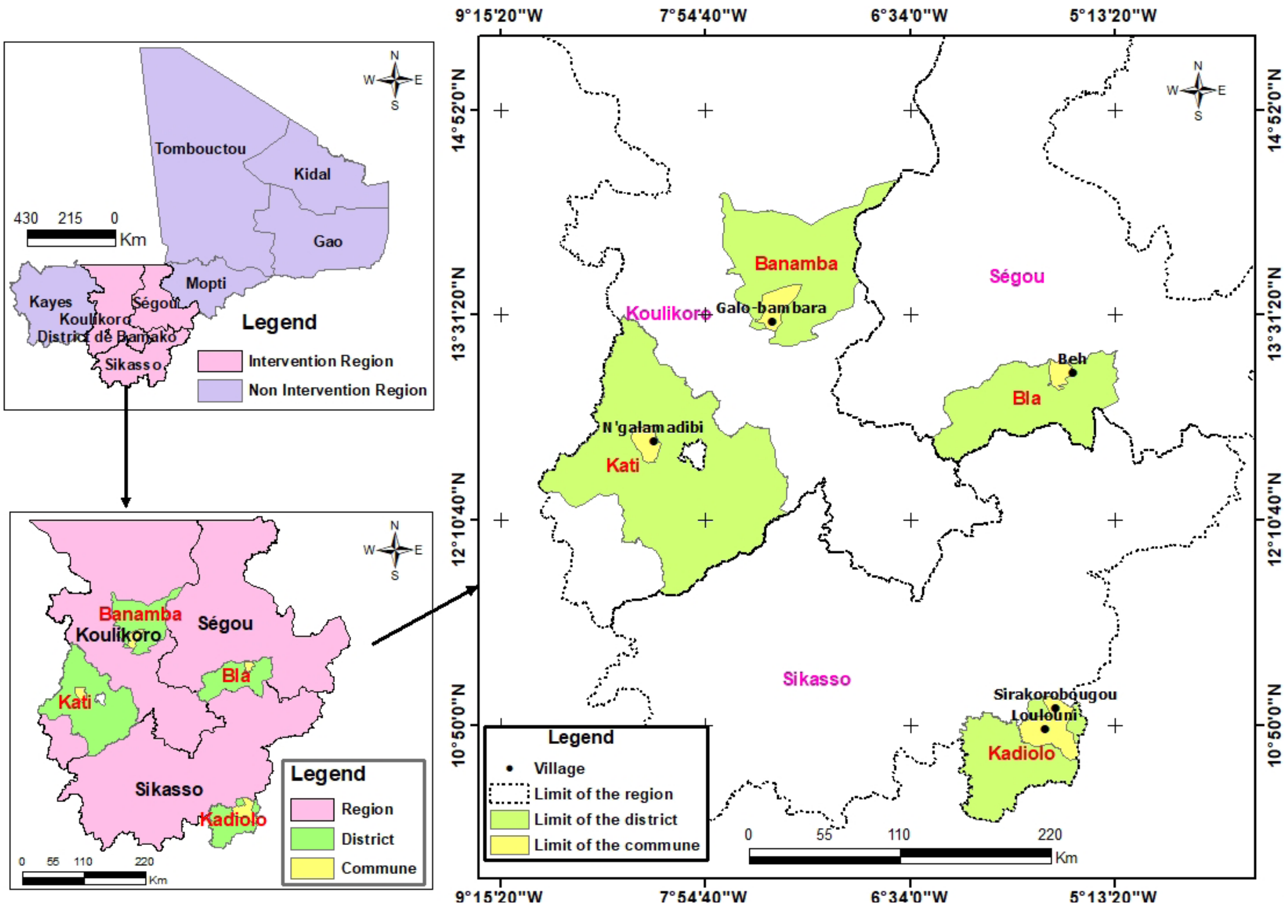


Figure 2. Map of Mali, indicating research sites (Kalinganire et al. 2021)

Sites were identified in partnership with local forest office technicians and local community authorities, based on the abundance of shea tree resources in village territories. The choice was also made to work in sites where ICCO-Cooperation (Interchurch Organization for Development Cooperation) was carrying out field work with women's associations on the shea value chain.

The local climate is dry tropical with a long dry season from October to May, and a rainy season from June to September. The selected sites follow a rainfall gradient from semi-arid (Koulikoro: 40°C, 700 mm/year, Ségou: 35°C, 800 mm/year) to sub-humid (Sikasso: 30°C, 1200 mm/year). The landscape is characterized by tree and shrub natural savanna forests. Dominant tree species include *Vitellaria paradoxa, Khaya senegalensis, Parkia biglobosa, Lannea microcarpa, Piliostigma thonningii, Detarium microcarpum, Mitragyna inermis* and *Sclerocarya birrea.*

Shea flowering characteristics

Flowers (Figure 4) are actinomorphic, approximately 15 mm in diameter, have 8-10 creamy-white petals, and are protogynous, with the style (occasionally two styles) and fertile stigmas protruding from the buds before petals open (Hall et al. 1996, Lassen et al. 2018).

After flowering, the ovary develops into a fruit containing one (occasionally two) seeds. Each inflorescence typically produces a small number of fruits (Figure 5, typically 2-3, rarely >10 (Antoine Kalinganire 2018, personal observation). Fruiting spans the rainy season months of May to mid-September, depending on the latitude. The ellipsoid fruits, which mature around July or August, grow in groups of six to eight. Each fruit generally carries one, or rarely two, nut(s) (Arbonnier 2004). The pulp, which is normally sweet, is an important source of nutrients for humans, other mammals, birds and bats.

Figure 3. Nine-year old grafted shea tree plantation at Kledou Farm, Tieman-Baguineda, Mali (Photo by Brehima Kone)

Figure 4. Flower cluster blossoming in successive groups (Photo by Brehima Kone)

Figure 5. Fruit cluster (Photo by Patrice Savadogo)

Data collection

At each of the six villages, 30 mature trees were selected (Table 1). Field observations were made on the flowering, pollination, phenology and fruiting behaviour, and fruit yield. Five modern beehives were fixed and installed in each of the three sites (Figures 7 and 8), namely: Galo, Beh and Banankoro. The other three villages were considered control sites with "no beehives" (i.e., Ngalamadibi, Ngoron and Sirakorobougou). No other human-controlled beehives were observed in and/or near these villages during the experiment.

Beehives were installed under the following conditions:

- Villages with beehives: 30 shea trees in fruiting age were selected in each of the three designated sites;
- "No-hive" villages: 30 shea trees in fruiting age were also selected in each of the three designated sites, i.e., Ngalamadibi, Ngoron and Sirakorobougou;
- The selected shea trees were located at least 100 m away from each other;
- Villages with beehives and "no-hive" villages were located 5 km away from each other, on average;
- In each of the villages, the trees were marked with paint (Figure 6) and geo-referenced using a Global Positioning System (GPS) receiver for mapping and reference purposes.

The size of each shea tree was measured and recorded. For each tree selected, diameter at breast height (DBH) or 1.3 m, and north-south and east-west crown diameters were recorded. The basal area of individual trees was calculated from the measurements of DBH.

Figure 6. Marking shea trees with paint (Photo by Brehima Kone)

Figure 7. Preparing to mount the hives on the trees (Photo by Brehima Kone)

Figure 8. Installation of a beehive (Photo by Brehima Kone)

Recording of phenological events

Observations were made on all 180 marked individuals picked for the fruit yield assessment. Four major branches approximately aligned to the four compass directions were selected, and on each branch four twigs (currently growing shoots of last-order branches) were marked with metal tags for visual observation of phenological events. Bi-weekly observations were carried out on each individual. Following Le Floc'h (1968) and Grouzis and Sicot (1980), the ensuing phenological events were derived in all conspecific trees from the monthly counts of leaves, flowers and fruits: leaf flush initiation; leaf flush completion; leaf fall initiation; leaf fall completion; leafless period; initiation of flowering; completion of flowering; time lag between start of vegetative (first-leaf flush) and reproductive (first-visible flower) phases; initiation of fruiting; completion of fruiting; fruit-fall initiation; and completion of fruit fall.

Table 1. The different phenological phases of development observed

(L) Leaf initiation, development and abscission	(F) Anthesis and flower senescence	(V) Fruit maturation
L1: no new leaf development	**F1**: no flowers	**P1**: no fruits (pods)
L2: first appearance of new leaves	**F2**: initial anthesis of inflorescence	**P2**: early development of pods
L3: approximately 50% of leaves fully expanded	**F3**: approximately 50% of inflorescence fully open	**P3**: green pods fully developed but still unripe
L4: beginning of leaf senescence	**F4**: beginning of flower senescence	**P4:** pods brown and seeds fully ripe
L5: virtually all leaves fallen from tree	**F5**: flowering finished or nearly so	**P5**: end of fruit maturation; some pods fallen from tree

Stages L2, F2 and P2 thus corresponded to the beginning of successive phenophases, stages “3” and “4” to intermediate development, and stage 5 to the culmination of a phenophase

To determine flower production (availability) for subsequent evaluation of fruit-set and hence pollination success, five trees were randomly selected in each of these six villages. Once sampling was done among the selected and marked trees, 10 inflorescences were chosen on each sampled tree. These identified inflorescences were the subject of an observation which consisted of counting the number of visible flower buttons, number of open flowers, number of visible fruits and the number of fruits attaining maturity.

Fruits of a shea tree do not develop synchronously; some mature before others. For the annual *shea* tree fruit yields assessment, the mature fruit was collected every day throughout the fruit ripening period. The technicians collected and weighed the fallen fruits from each tree. For any given tree, the collection started with the fall of the first ripe fruits and stopped when fruit drop ceased. For each tree, total production was calculated by summing up the daily collections of fallen fruits.

Data analysis

Dendrometric parameters (basal area and the average crown spread) from the six villages were compared using a one-way analysis of variance (ANOVA) followed by a Tukey’s test at $p = 0.05$ to test for significant differences between means value per village. The relationships between dendrometric parameters and shea fruit yield (mass) were examined. Categorical coding was used to examine the presence/absence variables in regression analysis. An alpha level of 0.05 was used for all statistical tests.

For the phenological observations, the synchrony index for flowering, fruiting and fruit-fall phenophases of each individual was calculated as the ratio between the individual’s mean duration of a phenological phase and the overall duration of the phase (Devineau 1999). The higher the ratio, the greater the coincidence between different individuals of a species (i.e., the ratio 1·0 denotes perfect synchrony amongst individuals and as the ratio decreases, asynchrony increases). The value of the synchrony index was subtracted from 1·0 to obtain the asynchrony index. Synchrony indices based on the duration of phenological phases represent the whole population and vary minimally with the number of individuals under observation; thus, it can be compared in terms of overall intra-site and inter-site synchrony.

3. EFFECT OF HONEY BEES ON FRUIT PRODUCTION IN SHEA-BASED PARKLANDS – INCLUDING SITES OF IMPLEMENTATION

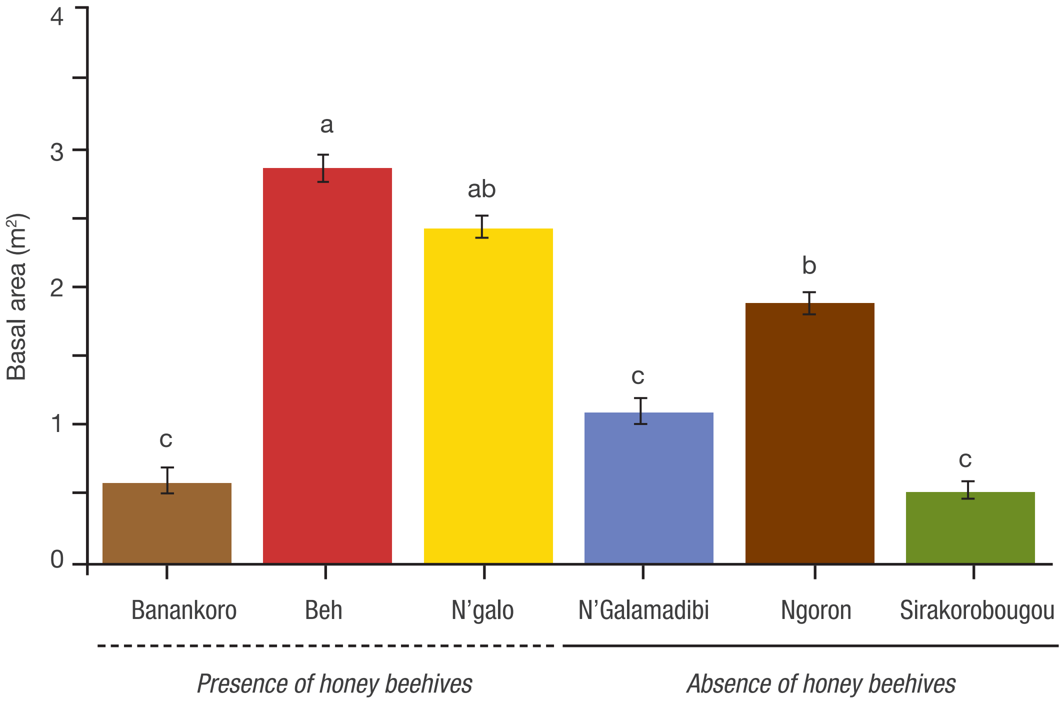
Diversity of flowering, fruiting phenology and leaves development of shea trees

The flowering process of *Vitellaria paradoxa* in the studied parkland from March to May 2016 was highly distributed over the period. Shea flowering is a cyclical process that occurs annually for most of the trees and every two years for a few of them. The flowering of shea in the study area extends from March to May. The opening of flowers occurred over a period of five days, but few flowers blossomed during the third and fourth days. So, considering the average numbers (trees) of the flowering cases monitored, 12.2% of flowers opened at the beginning and end of the flowering period, compared with 91.10% during the peak flowering period, i.e., the second day. During the same flowering period, 1,102 flowers (± 125 flowers) bloomed over a period of three days in the parklands under observation. During the peak flowering period, the average flower mass was 1,008 (± 220 flowers), representing an average of 9.60 flowers (± 2.95 flowers) per tree under observation and, more specifically, 9.40 (± 2.95 flowers) per tree in Beh, compared with 8.74 flowers (± 2.95 flowers) per tree in Galo.

Fruit and seed maturation in *Vitellaria* occurs during the rainy season (June-September). Fruit ripening coincides with the rainy season when the soil is well supplied with plant-available water. Socio-economically, this is the season when there is the highest probability of food shortage, making the fruits very useful – both pulp and kernel. As soon as the *Vitellaria* ripening season arrives, intensive collection from tree to tree by both children and women begins. The results indicate that *Vitellaria* sheds most of its leaves during the dry season when the atmospheric relative humidity and a combination of other climatic factors ensure dry conditions. The leaf flush starts in the dry season when the atmospheric relative humidity is just beginning to rise. Once the first new leaves of the season have expanded, production of leaf buds and young leaves is almost constant, without a clear distinction of transition from old to new foliage set. This type of leaf development is more closely connected to changing conditions in water availability than to flowering or fruit production (Okullo et al. 2004, Jasaw et al. 2015, Karambiri et al. 2017). As reported by Boffa (2015), there is a clear pattern regarding the effect of rainfall on shea productivity.

Shea tree dendrometric parameters

Overall, the basal area of the sample trees ranged from 0.55±0.05 to 3.05±0.29 m^2. Basal area differed significantly between villages ($p < 0.001$). Beh had the largest basal area, followed by N'galo, with Banankoro, N'Galamadibi and Sirakorobougou registering similar figures (Figure 9). The average crown spread, which is the average of the lengths of longest spread from edge to edge across the crown and the longest spread perpendicular to the first cross-section through the central mass of the crown, also varied significantly between villages ($p < 0.001$). Just like in the basal area, the highest value was recorded in Beh.



Means that do not share letters are significantly different

Figure 9. **Shea tree dendrometric parameters (basal area and average crown spread)**

Shea tree fruit yield dynamics

Shea flowers emit a strong scent of honey and attract many visitors, especially insects and birds (a few sunbirds) (Millogo-Rasolodimby 1989, Lassen et al. 2018). Honey bees mostly visited open flowers of shea trees (Brehima Kone, pers. obs.). Previous reports indicate a need for pollen vectors for fruit production in shea trees (Chevalier 1948, Abome Bilounga 2002).

In general, though our observation on fruit production was limited to 120 individual trees, it appears that around beehives, the number of observed trees bearing fruit was higher when compared to trees without fruit (82% versus 18%). In contrast, in the absence of beehives, up to 45% of the trees were without fruit. The presence of beehives in shea trees tends to have a positive impact on the visitation intensity of pollinators, hence increased fruit production. This information was confirmed by women's networks (Brehima Kone, unpublished survey data) and the technicians.

There was significant difference between villages in terms of average fruit weight per tree. These recorded differences in yields could be due to the different land uses which has been reported as a determining factor in shea tree productivity (Lamien et al. 2004, Aleza et al. 2018). Moreover, there was no significant influence of tree size (basal area and crown spreads) on fruit production both number of fruiting trees and fruit weight, per village. The finding confirms Boffa et al. (1996) and Kelly et al. (2007) who reported poor correlation between fruit yield and tree size in their studies in southern Burkina Faso and southern Mali, respectively. Farmland in Sirakorobougou registered the highest yield despite the absence of beehives, while Ngoron site registered the lowest. Sirakorobougou had better soil and favourable climate conditions when compared to the other sites. These trends on farmland lead to increased nutrients and water availability for the parkland trees, which may in turn increase the fruit yield of individual trees. Differences in shea nut weight can be linked to soil fertility and variations in climate, particularly rainfall (Lovett and Haq 2000, Maranz et al. 2004, Sanou et al. 2006, Kelly et al. 2007).

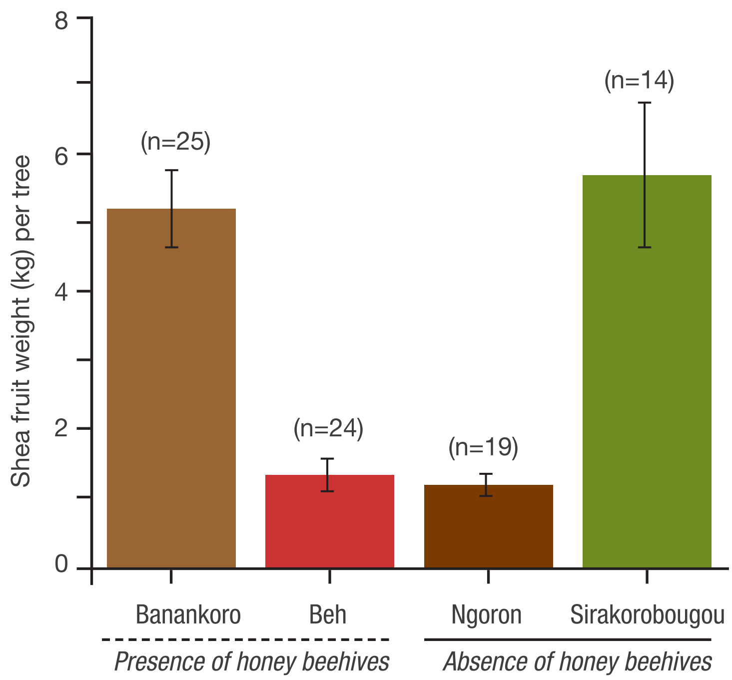


Figure 10. Average production of fruit per Shea (*n* indicates the number of fruiting trees)

Furthermore, the various traits examined have different patterns of variation (Sanou et al. 2006). Hence, farmland management appears to be an area of potential recommendation for shea parkland productivity. Kelly et al. (2019) revealed the importance of land management practices in fruit production of shea. They stated that the older the cultivated fields, the higher the impact on fruit production; the older fallows have a negative impact on fruit production. The proportion of fruiting trees in the population as well as fruit size and weight are higher in agroforestry parklands than in woodlands (Lamien et al. 2004).

Despite the introduction of beehives, fruit yield was relatively low at the site in Banankoro when compared to Sirakorobougou. The poor fruiting of *Vitellaria paradoxa* is not only linked to the number of visits by pollinators, but most probably to the pollinators' foraging behaviour and/or to the different sexual systems of the species. This could also be linked to self-incompatibility or poor performance of pollinators. The fruit-set and quality of a fruit may depend on the amount of compatible pollen received by the flower. This pollination is influenced by several factors, including weather conditions (rainfall, wind and temperature), the effectiveness and performance of pollinators, the floral mass (the number of flowers that open simultaneously), pollen quality and the genetic relatedness between shea trees. All these factors become critical and sometimes limiting, especially for shea which requires cross-pollination.

Table 2. **Summary output for regression of shea tree fruit yield as function** (basal area and average crown spread) at sites with beehives

SUMMARY OUTPUT FOR REGRESSION Fruit yeild=f(Basal area, average crown spread)								
Regression Statistics								
Multiple R	0.4500							
R Square	0.2025							
Adjusted R Square	0.1678							
Standard Error	2.7747							
Observations	49							
ANOVA								
	df	*SS*	*MS*	*F*	*Significance F*			
Regression	2	89.92	44.96	5.84	0.005			
Residual	46	354.15	7.70					
Total	48	444.07						
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	5.70	1.54	3.70	0.00	2.60	8.81	2.60	8.81
BA	-0.74	0.57	-1.30	0.20	-8.81	0.41	-1.88	0.41
Avg_crown_spread	-0.09	0.22	-0.40	0.69	-0.52	0.35	-0.52	0.35

Table 3. **Summary output for regression of shea tree fruit yield as function** (basal area and average crown spread) at sites without beehives

SUMMARY OUTPUT								
Regression Statistics								
Multiple R	0.46							
R Square	0.212							
Adjusted R Square	0.159							
Standard Error	3.294							
Observations	33							
ANOVA								
	df	*SS*	*MS*	*F*	*Significance F*			
Regression	2	87.359	43.679	4.026	0.028			
Residual	30	325.505	10.850					
Total	32	412.863						
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	5.871	2.089	2.810	0.009	1.604	10.137	1.604	10.137
BA	-1.524	0.975	-1.563	0.129	-3.515	0.468	-3.515	0.468
Avg_crown_spread	-0.060	0.297	-0.200	0.842	-0.666	0.547	-0.666	0.547

The shea fruit yield prediction model was established based on dendrometric parameters (basal area at breast height and the average crown spread). In the presence of beehives, the probability of the resulting model is significant ($p = 0.005$) at $R^2 = 0.20$, indicating that 20.2% of the observed variation in fruit yield is accounted for by the model (Table 2; Annex 1 - Supplementary material S1). Both the shea tree basal area and crown spread were not significantly associated with fruit yield. In the absence of beehives, the probability of the resulting model is significant ($p = 0.028$) at $R^2 = 0.21$, indicating that 21.2% of the observed variation in fruit yield is accounted for by the model (Table 3; Annex 2 - Supplementary material S2).

4. FUTURE DEVELOPMENTS OF SHEA FRUIT PRODUCTION

Vitellaria paradoxa parklands are some of the dominant features of the Sudan savannah. The species plays a very important role in the rural livelihoods of local communities and provides income as both the national and international markets for shea kernel and butter continue to grow. This attempt to evaluate the effect of the presence of beehives on fruiting is expected to contribute to the understanding of the erratic nature that characterizes fruit yields. Our findings emphasize that increased fruiting of *Vitellaria paradoxa* subsp. *paradoxa* is probably linked to the pollinators' visitation intensity. Therefore, it is important to ensure appropriate management of shea trees, including establishing appropriate conditions of access and visitation of honey bees to the trees during the flowering period.

Generally, honey bees are known as pollinators of many plants (Lassen et al. 2018, Ricketts et al. 2004, Salle et al. 1991, Roubik 1995, Free 1993). Various studies show that both wild (e.g., stingless bees) and managed bees are effective pollinators of many crops (Ricketts et al. 2004). Lassen et al. (2018) confirmed that honey bees are the most efficient pollinators, generating the highest yield of shea trees in Burkina Faso. Therefore, the presence of beehives in shea tree-based parklands could probably increase fruit production. It is clear that beekeeping (i.e., honey bee management), with beehives established in farmed shea tree-based parklands, could increase visitation intensity of the pollinators, thus enhancing fruit production. There is need to conduct further research on the foraging behaviour of pollinators and their effect on fruit weight. This study recommends the use of modern beehives which enhance honey and beeswax production. Parkland management practices associated with beekeeping techniques and indigenous local knowledge could contribute to increased fruit production.

Shea is mainly bee-pollinated (Lassen et al. 2018), outcrossing; and fruit set limited by pollination (Hall et al. 1996). The species is highly vulnerable to decline in pollination services (Potts et al. 2010). In shea and other tree crops, pollinator diversity and visitation rate have been found to decline with increasing isolation from patches of native habitats, but more importantly, with the use of pesticides in agricultural production (Roubik 1995). Therefore, it is important to sensitize communities on the effects of pesticides, including weed and pest control methods, and in the maintenance of wild and managed bees through conservation of their natural habitats within agricultural landscapes. A diverse community of pollinators may provide greater and more stable pollination services through foraging behaviour. Honey bees are strong flyers and can fly several kilometres (Millogo-Rasolodimby 1989, Lassen et al. 2018), about a mean radius of exploitation of one-kilometre in Burkina Faso (Guinko et al. 1992). It is clear that to ensure effective pollination and fruit production, one must establish an optimum number of beehives per hectare of parklands. However, further research on bee management [e.g., providing water for bees to avoid the natural migration during the dry season (Lassen et al. 2018)] and pollinators' foraging behaviour, need to be conducted.

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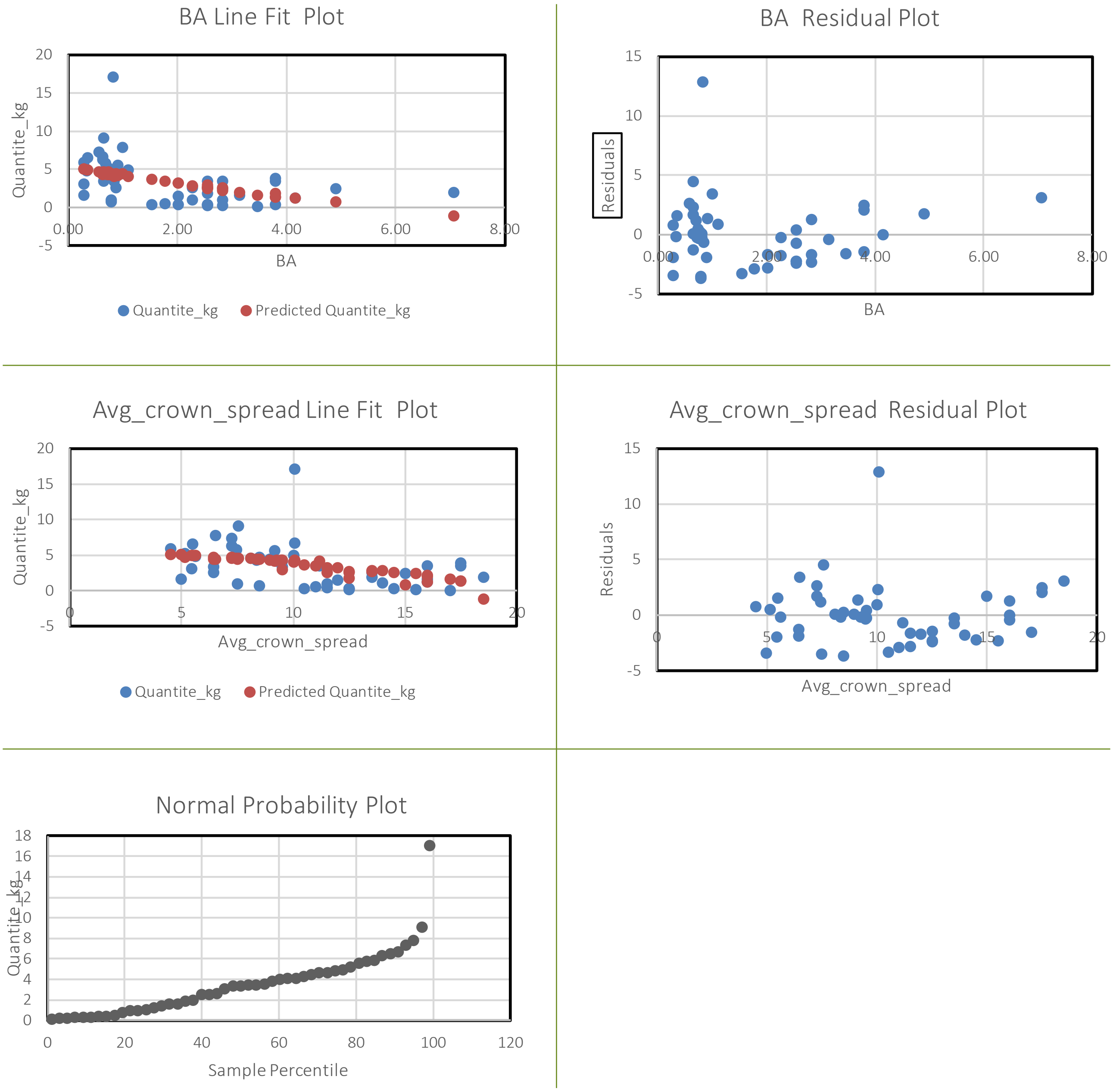
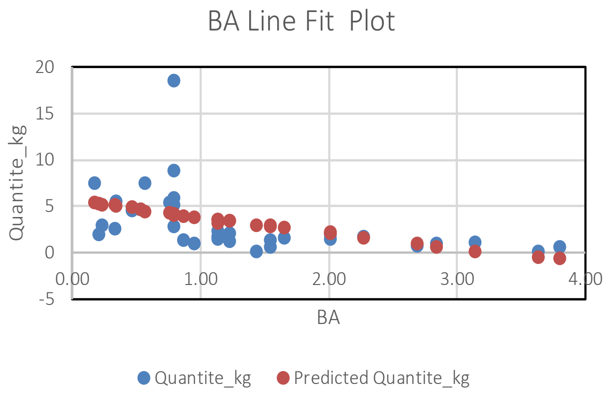
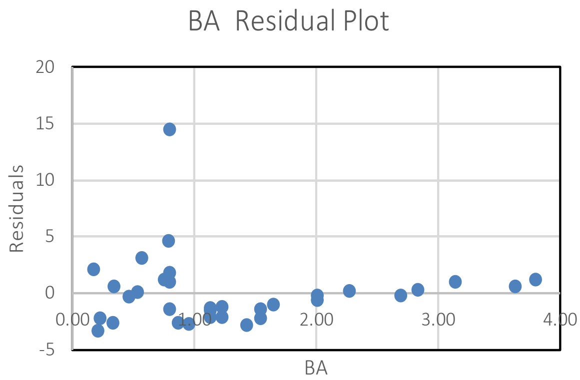
6. APPENDICES

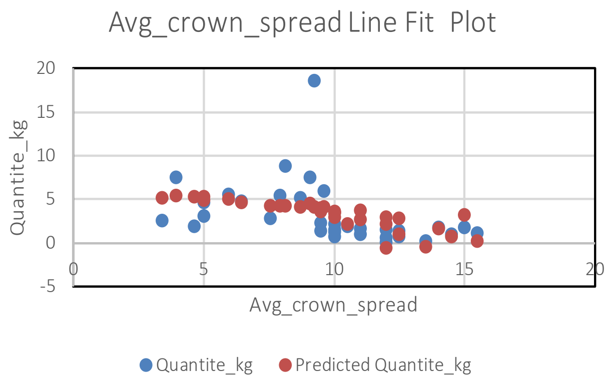
Appendix 1. Supplementary material S1. Regression diagnostic plot in the presence of beehives

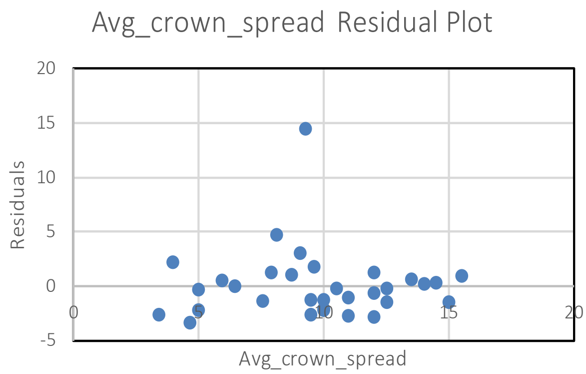


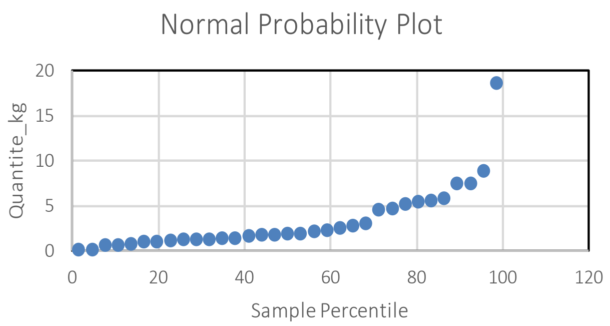
Appendix 2. Supplementary material S2. Regression diagnostic plot in the absence of beehives











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