Crop Protection 192 (2025) 107160

Contents lists available at ScienceDirect

Crop Protection

journal homepage: www.elsevier.com/locate/cropro

Drivers of cotton yield response to topping in farmers' fields in Mali

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ARTICLE INFO

Keywords:
Agroecology
Plant training
Integrated pest management
Cotton pests
Africa

ABSTRACT

Manual topping of cotton plants, which involves cutting off the terminal bud at the top of the main stem, has agronomic benefits, such as reducing vegetative exuberance, ensuring earlier production, or increasing yield by producing more bolls per plant. This technique also offers a promising alternative to chemical control by depriving certain pests of resources and triggering the plant's natural defenses. In Mali, though on-station experiments showed that topping did not substantially increase seed cotton yield, many growers have already adopted this technique mainly due to increased production.

In the present study, a survey of a network of 200 pairs (topped vs. non-topped) of farmers' cotton plots was performed to verify this statement and to identify the local (cultivation practices and environment) and ecological factors (rainfall, landscape context) that modulate the response of cotton yield to topping. In farmers' plots, cotton topping contributed to a 25% increase in the seed cotton yield. The yield response to topping increased with the earliness of planting, the cumulative rainfall received after topping, regardless of the planting date, the supply of manure, and the pressure of piercing-sucking insects, which topping significantly reduced. The integration of topping into cotton-growing systems should be associated with other levers to reduce the dependence on chemical inputs, and sociotechnical obstacles should be considered to stimulate the participatory design of new sustainable cotton production strategies.

1. Introduction

The induction of natural plant defenses has been described as a promising means of reducing insecticide use in insect pest management programs for cotton crops (Llandres et al., 2018). In West Africa, cotton topping was recommended in the early 20th century to improve yields and reduce pests, particularly bollworms and aphids (Vayssieres and Mimeur, 1926). This practice has gradually disappeared, particularly with the development of chemical control programs (Renou et al., 2011). Topping is the removal of the top of cotton plants. As a plant with indeterminate growth, cotton can continue to produce fruiting branches as long as environmental conditions allow. By suppressing apical dominance and vegetative growth, topping encourages the plant to redirect nutrients to the existing fruiting bodies (Yang et al., 2008). This operation, carried out manually, has several agronomic benefits, such as reducing vegetative exuberance and the risk of lodging, ensuring earlier production or increasing yield by producing a greater number of bolls per plant and, in some cases, increasing boll weight (Obasi and Msaakpa, 2005; Chaudhari et al., 2021; Nie et al., 2021; Dai et al., 2022; Zhu et al., 2022; Wu et al., 2023). A few publications, often unsubstantiated, point to a depressive effect of topping on the incidence of certain insect pests, such as bollworms in Egypt (Naguib and Esa, 1978; Nasr and Azab, 1969) or India (Sundaramurthy, 2002), or aphids at the end of the cycle in Central Africa (Deguine et al., 2000). In greenhouse experiments, Llandres et al. (2023) observed that cotton topping reduced aphid performance on both topped and neighboring cotton plants.

In Mali, experiments conducted from 2002 to 2008 showed (in 7 out of 12 tests) a significant reduction in the density of bollworms on topped cotton plants (*Helicoverpa armigera*, *Diparopsis watersi* and *Earias* spp.), but no effect on seed cotton yield (Renou et al., 2011). In addition to other indicators, the number of fruiting branches or the date of first flowering can be used to decide on the optimum time for topping as the

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https://doi.org/10.1016/j.cropro.2025.107160
Received 4 December 2024; Accepted 5 February 2025
Available online 6 February 2025
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best compromise between vegetative growth and production (Bynum and Cothren, 2008). Renou et al. (2011) recommend topping cotton plants 10 days after the appearance of the first flower. Earlier topping may result in a loss of cotton production, while later topping leaves the plant to form new fruiting bodies that will not contribute to production (abscission) and reduces the expected phytosanitary benefits. The recommended date for topping cotton plants generally corresponds to the appearance of the 15th fruiting branch (Renou et al., 2011). Two major hypotheses have been put forward to explain the reduced incidence of bollworm caterpillars on topped cotton plants (Renou et al., 2011): (i) a reduction in moth egg-laying linked to the suppression of suitable sites (terminal bunch leaves) or to the emission of repellent volatile compounds (in response to wounding or changes in plant physiology) and (ii) increased mortality of eggs or neonate larvae linked to a change in resources (quality, availability) or to the recruitment of natural enemies via the emission of specific volatile compounds. As most of the trials considered in this study received insecticide applications, we can also hypothesize that cotton topping facilitates insecticide penetration into the plant canopy, thus increasing the efficacy of end-of-cycle applications.

More recently, experiments carried out on experimental stations by Maiga et al. (2024) in Mali and Senegal showed that topping conferred five times less protection against bollworms than insecticide treatments, with a reduction of only 11% in the proportion of damaged fruiting bodies, compared with untreated topped plots. On the other hand, topping was moderately effective in reducing the incidence of piercing-sucking pests (−20 to −48% of infested plants), equivalent to insecticide treatments. Although topping in the absence of insecticide protection significantly reduced the proportion of damaged bolls at harvest (−31%, versus −55% for insecticide protection), it did not substantially increase seed cotton yield (+4%), unlike insecticide protection (+52%). This observation raises the question of the results of the survey on the perception of cotton topping carried out in Mali by Diarra et al. (2020), who reported that the main advantages of topping mentioned by farmers were the increase in income linked to higher yields and the effectiveness of insecticide treatments against pests. In Mali, many growers have already adopted this technique, sometimes even without technical support from extension services. By 2023, over 80% of cotton-growing areas had been topped (CMDT, 2023). Three non-exclusive hypotheses can be put forward to explain why topping would increase seed cotton yields on farmers' plots, in contrast to on-station trials: (H1) generally earlier planting, (H2) generally lower planting densities than recommended, and (H3) generally less effective insecticide protection due to fewer insecticide treatments than recommended or poorly carried out. Furthermore, it is expected that the yield response to cotton topping relative to non-topped cotton increases when environmental conditions do not provide sufficient resources, particularly water (rainfall) or nutrients (fertilization), or decreases when the technique is not implemented according to recommendations, in particular the timing of the operation in relation to the development stage of the cotton plants.

The present study aimed to verify these hypotheses by monitoring a network of 200 pairs (topped vs. non-topped) of farmers' cotton plots to identify the local factors (cultivation practices and state of the environment) and ecological factors (rainfall, landscape context) that modulate the response of cotton yield to topping. The results are discussed from an applied perspective of the integration of topping into cotton cropping systems in Africa.

2. Material and methods

2.1. Study sites

A total of 200 farmers' plots were set up in the eight (8) intervention sites (Fig. 1) of the AgrECo project (Beguene, Ziguena, Bouala and Diolo-Kagoua in 2021, Faragouaran, Bondala, Katele and Fignana in 2022), in the production zone of the Compagnie Malienne pour le Développement des Textiles (CMDT) and the Office de la Haute Vallée du Niger (OHVN).

Katélé, Ziguena and Faragouaran villages are located in CMDT's southern branch of Sikasso-Bougouni. The climate is Sudanian, with an average annual rainfall of around 900 mm. The villages of Beguene and Diolo-Kagoua are located in the North-West branch of the CMDT zone. The climate is Sudano-Sahelian, with an average annual rainfall of 800 mm. The village of Fignana is situated in the central branch of the CMDT zone. The climate is Sahelian, with an average yearly rainfall of 600 mm. The village of Bouala is located in the Office de la Haute Vallée du Niger (OHVN) zone. The average rainfall is around 800 mm. These villages experience a rainy season from June to September or October, a cool, dry season from October to January swept by the Harmattan winds (a north-easterly wind, very hot during the day, colder at night, very dry and most often dust-laden), and a hot, dry season from February to May, during which temperatures can reach 40 °C. Soils are clay, loam, and sandy clay. The biome is that of a herbaceous savannah with more or less trees (shea tree, baobab, African locust bean, African fan palm, tamarind, etc.) and uncultivated areas (usually used as grazing land for livestock), into which is integrated a mosaic of crops made up of cereals (maize, sorghum, millet), legumes (groundnuts, cowpeas) and cotton, and more rarely market gardening and arboriculture (mango and cashew trees).

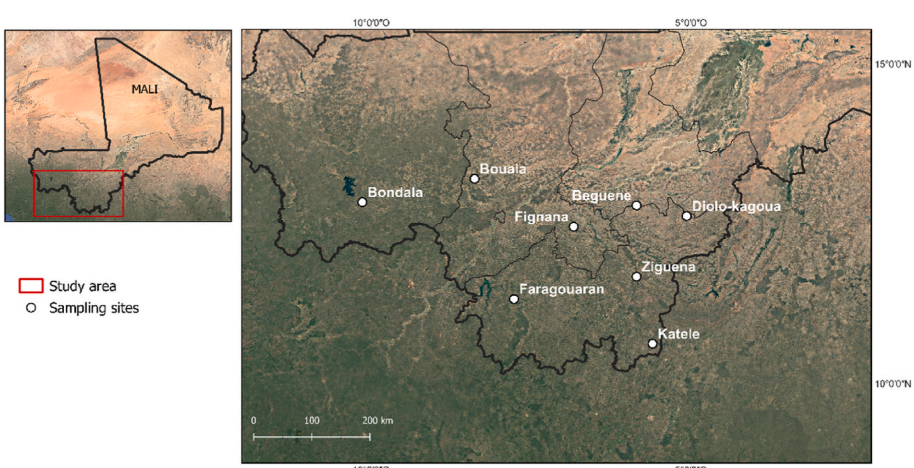

Fig. 1. Location of the eight study sites in Mali (2021, 2022).

2.2. Experimental design

A total of 25 cotton plots were selected three to four weeks after planting from volunteer growers in the eight (8) AgrECo project intervention sites, giving a total of 200 plots. In each plot, two 0.25 ha subplots were delimited, one not topped (control), the other topped (treatment). Both subplots underwent identical cultivation operations (soil preparation, planting date, variety, weeding, insecticide treatments, etc.), regularly recorded up to harvest. The growers carried out the topping of the cotton plants on one of the sub-plots, and the date and method of the operation were determined according to their criteria. Pest incidence was measured every 14 days, from the date of topping until the first bolls opened (at least 50% of plants with an open boll), at six five-plant sampling points along a diagonal of each sub-plot (a total of 30 plants per sub-plot). The occurrence of sucking pests (jassids, whiteflies, and aphids) was assessed on five leaves from the upper part of each plant observed, located below the level of the topping point. The incidence of bollworms was evaluated indirectly by counting plants showing at least one fruiting organ (squares, flowers, and bolls) with attack symptoms. Plants on which natural enemies (ladybugs, spiders, hoverflies, predatory bugs, mantids, ants, etc.) were observed were also counted. Yield was estimated by counting the number of plants, the number of harvestable bolls, the weight of seed cotton on plants in five 20-m rows in each sub-plot, and the length of the row spacing. Finally, a survey was conducted with the 200 growers to assess their knowledge of the topping technique and their perception of the associated benefits. All data were recorded by the monitoring manager at each site using the KoboCollect application.

2.3. Landscape characterization

Landscape composition around the cotton focal plots was characterized by radii of 250, 500, 750, and 1000 m. Cover types (trees, rangeland, lowlands, open forest, market gardening perimeters, and orchards) were digitized from a Google Satellite image (CNES Airbus Images, 2015–2020) available in QGIS (version 3.34.4). The different cover types were determined in the field using over 200 control points. We used the R *landscapemetrics* package (Hesselbarth et al., 2019) to calculate the respective area of each cover type in each buffer of each landscape, the area of semi-natural elements (trees + rangeland + lowlands + open forest), as well as Shannon's compositional diversity index (Shannon, 1948).

2.4. Data analyses

Our analysis focused primarily on the effect of topping on the level and variability of cotton yield and pest incidence. The effect of topping was assessed using Wilcoxon tests for paired samples. Data were then transformed using the logarithm of the response ratio (LRR):

$$LRR = \ln(Xt/Xc)$$

Where *Xt* is the mean observed for a given variable (crop yield, yield components, and pest incidence) in the "topped" treatment, *Xc* is the mean of variables observed in the "non-topped" treatment. The logarithmic transformation makes the ratio symmetrical around zero. It provides a direct measure of proportional variation by compressing the ratio scale, making it easier to interpret ratios as percentages of increase or decrease. To calculate the response (LRR) and 95% confidence interval (CI), we used the R package *SingleCaseES* (Swan and Pustejovsky, 2018). For ease of interpretation, all results were reported as "percent change or response" using the following formula:

$$Response = 100 * (\exp(LRR) - 1) \text{ or } 100 * (Xt-Xc)/Xc$$

Partial Least Squares Regression (PLS-R) was used to identify local variables (plot characteristics, cultivation operations, and environmental conditions) or ecological variables (rainfall, landscape context) affecting yield response to cotton topping, using the R package pls (Mevik and Wehrens, 2007). PLS regression is an alternative to multiple linear regression and principal component regression (Wold et al., 2001), particularly suitable when the explanatory variables are collinear (Carrascal et al., 2009). PLS regression calculates latent variables defined as a linear combination of explanatory variables that maximize the variance explained in the response variables. Explanatory and response variables were centered and reduced to give all variables equal weight and to simplify the expected variance partitions for each predictor (Quinn and Keough, 2002). The validity of the PLS regression model was assessed using the following indices: (R^2Y) the proportion of variance in the dependent variable explained by the model, and (Q^2) the proportion of variance in the response predicted by the model obtained by a cross-validation procedure. The strength of the relationship between each predictor and the dependent variable was illustrated by the importance of the variable in the projection (VIP) described by Chong and Jun (2005). The VIP was calculated as the sum of the influence of the predictor variable on all dimensions of the model divided by the total variation explained by the model. Variables with a VIP >0.8 were considered the most relevant and significant for predicting the dependent variable (Tenenhaus, 1998). The effect of the selected variables was then analyzed using a generalized linear mixed effects model with the R package *nlme4* (Bates et al., 2015), with "site" considered a random effect variable. In addition, a Moran spatial autocorrelation test was performed to ensure that there was no autocorrelation between the yield response to topping (LRR) in space for each of the sites, using the *ape* package (Paradis and Schliep, 2019). Data were analyzed with R software version 4.3.0 (R Core Team, 2023), and graphs were made with the R package *ggplot2* (Wickham, 2016).

3. Results

3.1. Knowledge and practice of cotton topping

Most surveyed growers confirmed that insect pests are a big issue for cotton production (Table 1). Bollworms were the most frequently cited cotton pests, followed by piercing-sucking insects such as whiteflies, aphids, and jassids. The most commonly cited damage was boll damage, followed by leaf and flower square damage. Just over half the growers

Table 1
Survey of growers' knowledge of pests and topping practices.

Variables	Responses	% citations
Insect pests as issue for cotton production	Yes	98.5
Most damaging insect pests	Caterpillars	93.0
	Whiteflies	38.5
	Aphids	36.5
	Jassids	29.5
	Bugs	25.0
Types of damage	Damage to bolls	85.5
	Damage to leaves	61.0
	Damage to squares	50.0
Experience with topping [*Experience_ecim*]	Yes	56.5
Main advantage of topping[a]	Length of fruiting branches	33.8
	Seed cotton yield	21.1
	Reduced incidence of pests	15.8
	Number of bolls	13.5
Main criterion for topping decision[b]	Flowering	54.2
	Calendar-based (days after planting)	29.2
	Height of cotton plants	16.6

[a] Main advantage cited for those who had already practiced topping (113).
[b] For those who made a proposal (48/113). The name in square brackets corresponds to a variable included in the final PLS model.

surveyed had already experimented with cotton topping. One third of the growers who had already carried out topping gave the length of fruit-bearing branches as the main advantage, followed by seed-cotton yield, reduced pest incidence and number of bolls. The main decision criterion for topping was flowering, but it can also be based on the calendar, or the size of the cotton plants.

3.2. Description of cotton focal plots

Growers involved in setting up experimental plots included two women and 198 men (Table 2). The average age of the farmers surveyed was 48.5 years. The average cultivated area per farm was 15.7 ha, including 5.9 ha of cotton. Apart from cotton, the main crops grown on the farms were maize, groundnuts, sorghum, and millet. The cotton plots on which the experimental sub-plots were set up averaged 2.5 ha in size, and almost half had sandy soils (Table 2). Trees were present in the cotton plots at a generally low density and diversity (on average 12.1 trees and 1.7 species per ha), but highly variable (0–142 trees and 0–18 species per ha), with shea trees present in more than three out of four plots.

The main crops grown in rotation with cotton were maize, sorghum, millet, and groundnuts (Table 2). Even so, we found nearly 7% of plots with cotton as a previous crop. Before plowing, almost half of all farmers applied organic manure. Most plots were plowed with an animal-drawn plow or a tractor or rototiller. Some farmers simply scraped the soil with a hoe. Planting occurred mainly in June (between May 4 and July 26). Most growers used a seed drill. Several varieties were sown (NTA MS334, NTA L88, STAM 279A, and G 440) depending on the production zone, and more than one grower in two treated the seeds before planting. All farms grow cotton as a pure crop, as the use of herbicides and insecticides does not allow other crops to be combined with it. The average number of manual weeding operations carried out before ridging was 1.5. The vast majority of growers applied a herbicide before or just after planting. When the cotton plants were removed, the plots received an average of 121 kg/ha of cotton complex (14N-18P_2O_5-18K_2O+6S+1B_2O_3). The plots received an average of 29 kg/ha of urea (46N) at the time of ridging. Topping was carried out mainly in August (between July 27 and September 18), averaging 68 days after planting (DAS) but with considerable variability (34–97 DAS). Low to medium weed cover was observed in rows from topping to first boll opening. The number of insecticide treatments was moderate (4.3 on average), which shows that the schedule is not fully respected (6–8 treatments recommended depending on planting date). The incidence of pests in topped plots was moderate overall but variable, with an average of 11% of plants showing symptoms of fruiting body attack by bollworms, 30% of plants infested by jassids, 20% of plants infested by whiteflies, and 8% of plants infested by aphids. Natural enemies were observed on an average of 10% of plants.

Rainfall from planting to the first boll opening (708 mm on average) varied widely, from 367 to 962 mm per plot, depending on site and planting date. Rainfall from topping to first boll opening (set at 110 JAS) varied widely, from 36 to 510 mm per plot. Semi-natural elements of the landscape (trees, rangeland, and open forest), quantified within a 1 km radius of the plots (Fig. S1), varied from 0 to 92% of the surface (on average 49% of the surface). The compositional diversity (Shannon Index) of these land-use classes within a 1000 m radius varies from plot to plot, ranging from 0.1 to 1.5 (average 0.7).

3.3. Response to topping

The response to topping was evaluated in terms of yield and incidence of pests and natural enemies (Fig. 2). The overall effect of topping on seed cotton yield was positive (+25%), with a significant increase in the number of bolls per plant (+27%), with no change in average boll weight (Fig. 2A and B). It also reduced the incidence of critical pests such as bollworms (−23% of plants showing damage to fruiting bodies) and

Table 2
Description of the sample of observation plots (N = 200 producers surveyed).

Variables	Measurement	Mean	[Min – Max]
Exploitation			
Age of farmers	years	48.5	[22–98]
Farm area	ha	15.7	[1.25–70]
Cotton area	ha	5.9	[0.5–30]
Main crops			
Maize	% citations	92.0	
Peanut	% citations	80.5	
Sorghum	% citations	70.0	
Millet	% citations	49.5	
Characteristics of the cotton plot			
Area	ha	2.5	[0.5–14.0]
Soil type (defined by the farmer)			
Sandy	%	46.5	
Loamy	%	30.0	
Clayey	%	23.5	
Fertility [*Fertilite*]	score 1-3	1.8	[1–3]
Trees and shrubs	number per ha	12.1	[0–142]
Species of trees and shrubs	number per ha	1.7	[0–18]
Shea tree occurrence	%	76.9	
African locust bean occurrence	%	20.6	
Baobab occurrence	%	11.0	
Opérations culturales et état du milieu			
Previous crop			
Maize	%	50.5	
Sorghum	%	17.2	
Millet	%	13.1	
Peanut	%	9.1	
Cotton	%	6.6	
Manure supply [*Fumier*]	%	45.5	
Soil preparation			
Plowing harness	%	44.0	
Plowing tractor or rototiller	%	42.4	
Hoe scraping	%	13.1	
Planting date [*Semis_JJ*]	JJ (Julian days)	161.2	[124–207]
Variety			
NTA MS334	%	49.5	
STAM 279A	%	25.0	
NTA L88	%	12.5	
G 440	%	12.5	
Seed treatment	%	60.3	
Intercropping	%	0	
Herbicide treatment	%	91.0	
Weeding before ridging	number	1.5	[0–3]
Quantity of NPK applied [*Q-NPK_ha*]	Kg/ha	120.6	[0–250]
Quantity of urea applied [*Q_uree_ha*]	Kg/ha	28.9	[0–100]
Plant density [*Nb_plts_m2*]	number/m^2	4.4	[2.0 _ 8.8]
Insecticide treatment	number	4.3	[0–8]
Topping date	JJ (Julian days)	228.8	[208–261]
Topping date [*Ecimage_JAS*]	JAS (days after planting)	67.6	[34–97]
Post-topping weed cover [*Enherb_apecim*]	% ground cover	17.6	[0–60]
Post-topping pest incidence[a]			
Bollworms [*Deg_che_NE*]	% damaged plants	14.0	[0–52.7]
Jassids	% infested plants	36.9	[0–92.0]
Whiteflies	% infested plants	27.0	[0–63.4]
Aphids	% infested plants	13.7	[0–53.3]
Piercing-sucking pests [*Piq_NE*]	% infested plants	25.9	[4.7–62.8]
Post-topping incidence of natural enemies	% colonized plants	11.9	[0–29.3]
Environmental data			
Rainfall (one rain gauge per village)			
From planting to boll opening	mm	708	[367–962]
From topping to boll opening [*Plu_ecim_110jas*]	mm	276	[36–510]
Landscape context	within a 1 km radius		
Number of tree patches [*Np_tree_1000*]	number	691	[202–1482]
Rangeland area	area (ha)	94	[0–264]
Open forest area	area (ha)	24	[0–284]

(*continued on next page*)

Table 2 (*continued*)

Variables	Measurement	Mean	[Min – Max]
Lowland area	area (ha)	1.5	[0–29]
Semi-natural area [*Ca_semnat_1000*]	area (ha)	156	[54–288]
Diversity of semi-natural habitats [*Shdi_500*]	H' index	0.7	[0.1–1.5]

[a] Non-topped plots. Names in square brackets correspond to variables included in the final PLS model.

sucking pests (from −20% to −44% of plants infested by jassids and aphids, respectively). Fewer natural enemies were observed in topped plots (−18%) compared to non-topped plots, with more prey.

The response to topping in terms of yield, while very positive overall, was close to 0 (<5%) or negative for 20% of the plots (N = 188) in the experimental set-up (Fig. 3).

The focal cotton plots were chosen to be at least 1 km apart, but this criterion was not always met, as some of the growers who volunteered to conduct the experiment had their plots quite close together. However, Moran's spatial autocorrelation test showed that yield response to topping (LRR) was not significantly autocorrelated in space for all study

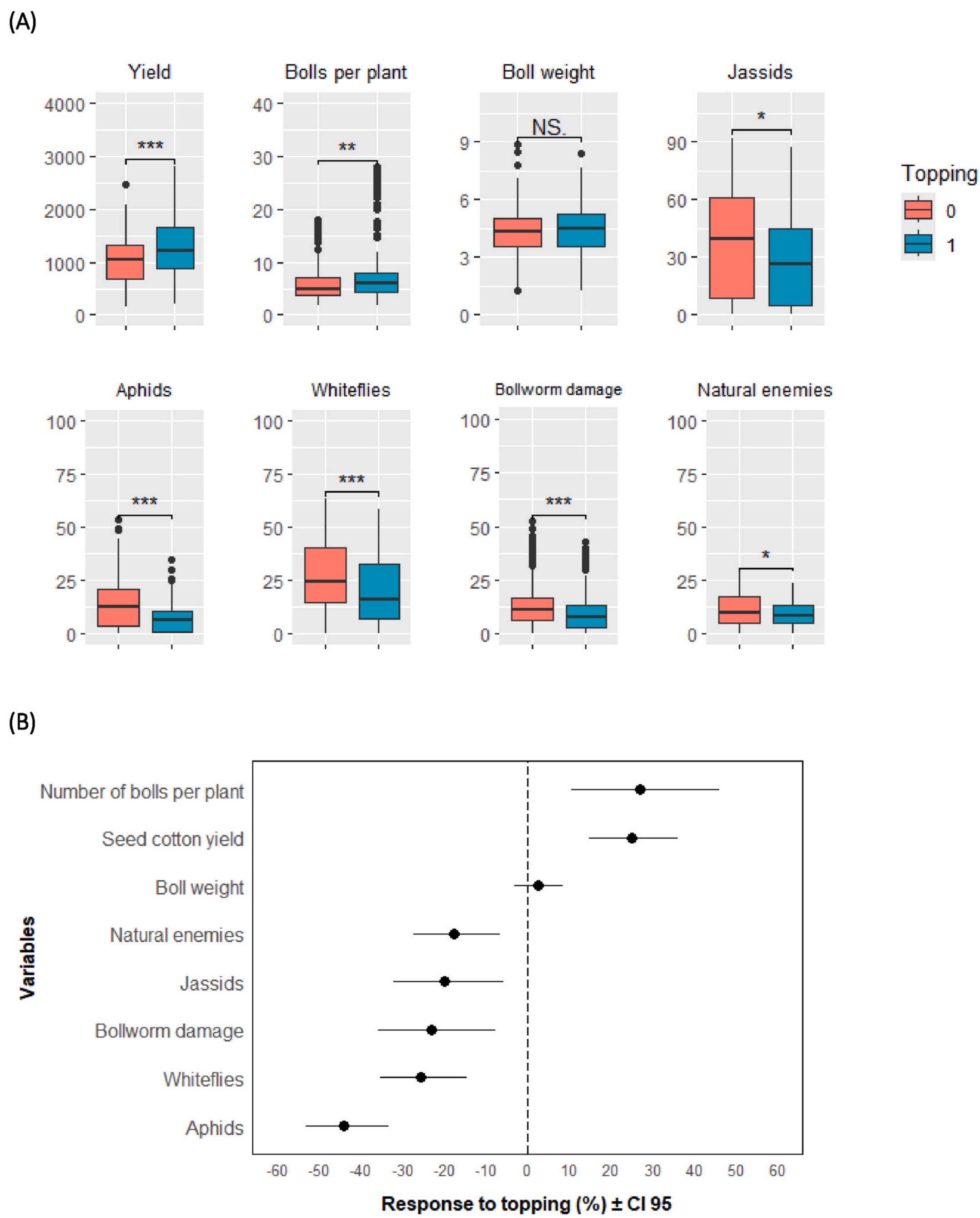

Fig. 2. Response to topping of seed cotton yield (kg/ha) and its components (number of bolls per plant, boll weight in g), and incidence of pests (percentage of plants infested by jassids, whiteflies and aphids, and proportion of plants with fruiting bodies damaged by bollworms) and their natural enemies. (A) Boxplots of variables in non-topped vs. topped cotton paired plots. Significant differences between non-topped and topped plots were assessed using Wilcoxon paired tests (*P < 0.05; **P < 0.01; ***P < 0.001). (B) Percent change or response of variables ad a function of topping. Points and bars represent mean values and 95% confidence intervals, respectively. The mean effects of topping are considered significant when the confidence intervals do not overlap the horizontal axis of value 0 (P < 0.05).

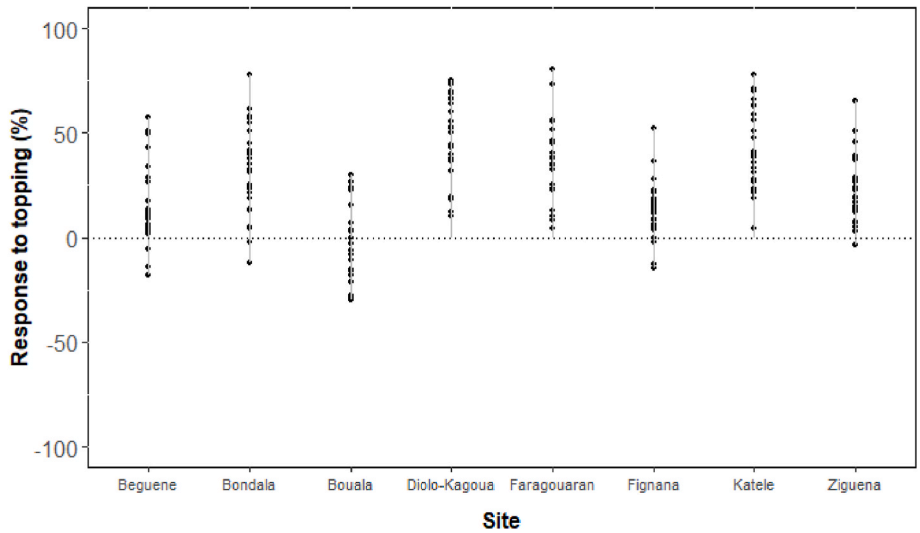

Fig. 3. Yield response to cotton topping in plots at the eight study sites (N = 188). Points represent the seed cotton yield response for a given subplot of topped cotton compared with the corresponding subplot of non-topped cotton. No comparison between sites can be done as experiments were conducted in 2021 or 2022.

sites (Moran's Index I between −0.10 and −0.03, $P > 0.05$), except Katele (−0.10, $P = 0.022$).

3.4. Drivers of seed cotton yield response to topping

The choice of local explanatory variables (12) to be included in the PLS regression model was made according to their relevance to meet the main hypotheses of yield response to topping (Tables 1 and 2), such as a context of low soil fertility (*Fertilite*, *Q_uree_ha*, *Q-NPK_ha*, *Fumier*), planting density lower than recommendations (*Nb_plts_m2*), and variable pest pressure (*Piq_NE, Deg_che_NE*). The incidence of natural enemies was not taken into account in the regression because it is highly correlated with pest incidence (Fig. S2). It was also expected that the response to topping would be affected by the availability of water resources (*Plu_ecim_110jas*), the planting date (*Semis_JJ*), competition with weeds (*Enherb_apecim*), but also by compliance with the intervention date (*Ecimage_JAS*) and the expertise of producers (*Experience_ecim*). Three landscape variables (*Np_tree_1000*, *Shdi_500*, *Ca_semnat_1000*) were preselected according to the results of a first PLS model to determine the most determining variables and buffers. The areas of semi-natural habitats included the classes of trees, open forest, lowlands and rangelands. The final regression model (PLS) on the 15 variables identified eight influential variables (VIP >0.8) (Table S1). The model explained 30% of the variance of the LRR response variable. The standardized coefficients indicated that rainfall after topping (*Plu_ecim_110jas*), the incidence of sucking pests after topping (*Piq_NE*), and manure application (*Fumier*) had a positive effect on the response of seed cotton yield to topping. Conversely, the response was reduced in the case of late planting (*Semis_JJ*) and late topping in the crop cycle (*Ecimage_JAS*), increasing plant density (*Nb_plts_m2*) and nitrogen fertilizer inputs (*Q_uree_ha*). We did not find any significant effect of knowledge of the topping technique by producers or of the landscape structure around the cotton plot on the topping performance, nor of the plot's fertility level according to farmers' perception (Table S1). The generalized linear mixed-effects model (GLMM) showed a significant effect ($P < 0.05$) of rainfall after topping (*Plu_ecim_110jas*), incidence of piercing-sucking insects after topping (*Piq_NE*), planting date (*Semis_JJ*) and topping date (*Ecimage_JAS*), on the performance of topping in terms of cotton

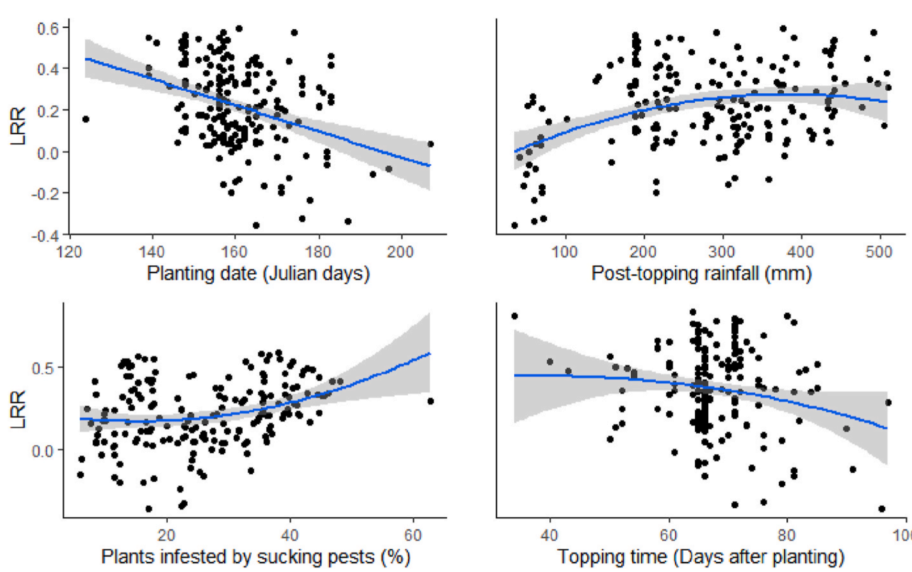

Fig. 4. Effect of planting date, incidence of piercing-sucking insects, topping date in JAS, and rainfall after topping on yield response to topping. LRR: logarithm of yield response ratio to topping.

seed crop yield (Fig. 4, Table S2).

Furthermore, there was a positive correlation between the amount of rainfall after topping or the area of semi-natural elements around the plots and the incidence of piercing-sucking insects and a negative correlation between the incidence of piercing-sucking insects after topping and the cotton seed yield (Fig. S2). There was also a negative effect of late planting date and weed cover after topping on the yield response to topping. Finally, weed cover had a positive effect after topping on bollworm damage and the incidence of natural enemies (Fig. S2).

4. Discussion

Since 2013, the Compagnie Malienne de Développement et des Textiles (CMDT) has developed capacity-building programs through cascading training. More than one in two of the 200 farmers who participated in the on-farm experiment had already tested cotton topping. While on-station experiments have shown a reduction in the incidence of pests following the topping of cotton plants (Renou et al., 2011; Maiga et al., 2024), it is primarily for an increase in yield, mainly linked to the increase in the number of bolls, that these producers declared having adopted the technique. The main advantages mentioned by producers in a survey conducted by Diarra et al. (2020) in Mali were “increased income” linked to “higher yields.” Monitoring a network of 200 pairs (topped vs. non-topped) of farmers' plots made it possible to empirically confirm an overall gain in seed cotton yield (+25%) enabled by topping cotton plants through a significant increase in the number of bolls per plant, without impact on the boll weight. Other studies have shown that this technique allowed an increase in yield by producing an increased number of bolls per plant and, in some cases, an increase in boll weight (Obasi and Msaakpa, 2005; Chaudhari et al., 2021; Nie et al., 2021; Dai et al., 2022; Zhu et al., 2022; Wu et al., 2023). This can be explained by the re-allocation of nutrients in the plant following the inhibition of vegetative growth in favor of reproductive growth (Yang et al., 2008; Nie et al., 2021; Dai et al., 2022; Zhu et al., 2022; Wu et al., 2023). Zhu et al. (2022) reported that higher boll production per plant comes from higher boll retention rates and increased fruiting branch length. Cotton topping is widespread in China, often combined with removing vegetative branches, senescent leaves, and fruitless fruiting branches (plant training) to increase boll retention rate and weight (Dai and Dong, 2014). In addition to a similar order of magnitude improvement in seed cotton yield in their 2018 trials in Bangladesh (a decrease in the 2019 trials) due to higher boll numbers per plant, Alam et al. (2024) reported an increase in fiber quality, independently of the genotypes tested.

While topping to improve cotton yield has been the subject of several publications, little attention has been paid to the effect of topping on pests. In the present study, a depressive impact on the incidence of critical pests such as bollworms (−23% of plants with damage to fruiting bodies) and piercing-sucking moths (−20 to −44% of plants infested by jassids and aphids, respectively) was observed. These results confirm those of Renou et al. (2011), who, in a series of twelve experiments in Mali, observed a reduction in bollworm infestations (−50%) on topped cotton plants. In a greenhouse experiment, Llandres et al. (2023) observed that topping reduced the number of aphids (−45%) on topped cotton plants compared to control cotton plants. Topping could be a very interesting biotechnical method for the control of jassids, in particular *Amrasca biguttula*, responsible for significant yield losses in 2022 in West Africa (Kouadio et al., 2024). In India, Shwetha et al. (2009) also observed lower populations of aphids, jassids, and thrips on topped plants than on non-topped plants of Bt cotton. Similarly, surveys conducted over several years in village farms in India showed that topping reduced the oviposition of populations of the noctuid *H. armigera* (Sundaramurthy, 2002).

Surprisingly, no significant increase in seed cotton yield was observed in the on-station topping trials under insecticide protection conducted by Renou et al. (2011) or Maiga et al. (2024) in Mali. In farmers' plots, the increase in yield following the topping of cotton plants results from a greater number of bolls per plant. We had put forward three non-exclusive hypotheses to explain the increase in the number of bolls per plant following the topping of cotton plants in peasant plots, which our surveys support: (H1) generally earlier planting, (H2) generally lower planting densities, and (H3) insufficient insecticide protection due to several insecticide treatments lower than recommended. Our analysis showed that the performance of topping in farmers' plots depends on cultivation practices and the state of the environment. Topping performance increased with (i) the earliness of planting (H1), which would allow the crop to take full advantage of the peak of mineralization of the organic matter for the vegetative development of cotton plants (Amonmidé et al., 2020) and a higher production of bolls on the first positions of the first fruiting branches (Sekloka et al., 2016), which topping probably helps to maintain by an increased retention rate compared to non-topping. It is noted that planting in farmers' plots is often earlier (here, 75% of plots were already sown on June 15) than in on-station trials, with planting between June 17 and July 21 in the six trials conducted by Maiga et al. (2024). A recent study in Mali confirms that early planting yields higher yields than late planting (Kassambara et al., 2024). In addition, early planting allows for the establishment of bolls before the population of bollworms peaks (Karavina et al., 2012; Brévault et al., 2019). Topping trials conducted by Maiga et al. (2024) showed that the percentage of damaged fruiting bodies significantly increased with the planting date expressed in Julian days ($r = 0.91$). Topping performance also increased with (ii) the cumulative rainfall received after topping, an important factor for boll retention and maturation, regardless of the planting date (Snowden et al., 2014; Wang et al., 2016). Finally, topping performance increased with the incidence of piercing-sucking insects (H3) in a context where the number of insecticide treatments is lower than recommended, with an average of 4.3 insecticide treatments carried out compared to 6–8 treatments, depending on the planting date, in the calendar protection program recommended in Mali. Piercing-sucking attacks after topping (flowering-fruiting stage of cotton), here negatively correlated with yield, can significantly reduce the retention rate of bolls or the elongation of fruiting branches (Shreevani et al., 2013; Shera et al., 2020). In contrast, we did not observe any effect of bollworm pressure on topping performance, although topping significantly reduced damage to fruiting organs. It is likely that this reduction in damage concerned fruiting organs on non-topped cotton plants that do not ultimately contribute to yield (e.g., flower buds on fruiting branches at the top of the plant). Our study also showed that topping performance decreased when topping was initiated too late relative to the cotton plant development stage, probably due to a lack of water resources at the end of the cycle when topping was carried out too late after the planting date (negative correlation between topping date after planting and amount of rainfall received after topping). This confirms the importance of not topping too late to catch the benefits of the practice (Alam et al., 2024). Finally, a positive relationship between manure application and topping performance was noted. Organic fertilization may contribute, via the increase in soil fertility, to the increase of the retention rate of bolls (Blaise et al., 2005). On the other hand, no effect of the level of fertility according to farmers' perception or the level of mineral fertilization (NPK and urea) on topping performance was observed. To a lesser extent (important variables identified in the final PLS model but not significant in the GLMM), the PLS regression showed a negative relationship between the density of plants per unit area and the topping performance. This indicates that yield response to topping should be more expressed in the context of planting densities lower than the recommendations (H2) due to lesser competition between plants for limited resources in water, nutrients, and light. The average density of plants observed in farmers' plots was 4.4 plants/m^2 (2.0–8.8), which is well below the densities tested (8–10 plants/m^2) in the trials of Maiga et al. (2024). Experiments by Obasi and Msaakpa (2005) showed that reducing plant density increased the number of fruiting sites per branch, boll retention, boll weight, and seed cotton yield. At low plant density, competition for light and nutrients is likely less than at recommended densities, which might promote the development of lateral branches or the retention of fruiting organs. In this sense, Gu et al. (2024) showed the superiority of chemical topping over manual topping for light interception by reducing competition thanks to the reduced length of the internodes of the fruiting branches. Sapkota et al. (2023) showed, for their part, that when plant density is low, compensation is mainly achieved by an increase in the number of bolls per cotton plant. Topping could, therefore, provide a yield gain under low plant density conditions where there are more bolls to maintain per plant. In contrast, Dai et al. (2022) reported a positive effect of topping on seed cotton yield of 10–14 and 15–18% at densities of 6–9 plants per m^2, respectively, but not at three plants per m^2. Therefore, the yield response to topping, depending on plant density conditions, is likely highly dependent on available resources. Topping would increase yield compared to non-topping when resources are limited. Lastly, we did not find any significant effect of the grower's knowledge of the topping technique, nor of the landscape structure surrounding the cotton plots, which could have affected the success of topping as a favorable habitat for pests or natural enemies of pests.

5. Conclusion

The interest of topping in farming systems lies above all in the increase in boll production in resource conditions that are often limiting (e.g., soil fertility) to achieve the agronomic potential of varieties in cropping systems generally designed in semi-controlled on-station experiments. Its performance increased with the earliness of planting, the cumulative rainfall received after topping, regardless of the planting date, the supply of manure, and the pressure of piercing-sucking insects, which it significantly reduces by suppressing resources or inducing plant defense reactions.

The integration of topping into cotton-growing systems in Mali should be associated with other technical levers (e.g., early planting, intake of manure, phytosanitary treatments based on thresholds, and use of specific biopesticides to reduce the pesticide load and unintended effects on natural enemies) and take into account the socio-technical obstacles to the dissemination of innovation (labor, cost, complexity, etc.), within the framework of the participatory design of new sustainable cotton production strategies.

CRediT authorship contribution statement

Daouda S. Maïga: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Writing – original draft, Writing – review & editing. **Ahmadou Sow:** Data curation, Formal analysis, Writing – review & editing. **Moribo Coulibaly:** Investigation, Methodology, Writing – review & editing. **Idrissa Tereta:** Conceptualization, Funding acquisition, Methodology, Writing – review & editing. **Romain Loison:** Formal analysis, Validation, Writing – review & editing. **Thierry Brévault:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Supervision, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors would like to thank the technical assistants of Institut d'Economie Rurale (IER), who participated in field sampling and data handling. This research was carried out with the financial support of the "Projet d'appui à la transition agroécologique en zone cotonnière du Mali" (AgrECo CML1430) signed between Agence Française de Développement (AFD) and the Government of Mali.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cropro.2025.107160.

Data availability

Data will be made available on request.

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