Acta Scientiarum
http://periodicos.uem.br/ojs/acta
ISSN on-line: 1807-8621
Doi: 10.4025/actasciagron.v42i1.42587

CROP PRODUCTION

Variability of harvest loss in relation to physiological characteristics of cotton

Elizabeth Haruna Kazama[1*], Rouverson Pereira da Silva[2], Franciele Morlin Carneiro[2], Daniel de Bortoli Teixeira[3], Welington Gonzaga do Vale[4] and Gener Tadeu Pereira[5]

[1] Departamento de Engenharia Rural, Universidade Estadual Paulista "Júlio de Mesquita Filho", Via de Acesso Professor Paulo Donato Castelane, s/n, Jaboticabal, São Paulo, Brazil. [2]Departamento de Engenharia Rural, Universidade Estadual de São Paulo, Jaboticabal, São Paulo, Brazil. [3]Centro de Ciências Agrárias, Universidade de Marília, Marília, São Paulo, Brazil. [4]Centro de Ciências Agrárias Aplicadas, Departamento de Engenharia Agrícola, Universidade Federal de Sergipe, São Cristóvão, Sergipe, Brazil. [5]Departamento de Ciências Exatas, Universidade Estadual de São Paulo, Jaboticabal, São Paulo, Brazil. *Author for correspondence. E-mail: bethkazama@hotmail.com

ABSTRACT. Pearson's correlation and spatial variability are tools that can be used to help one understand the process of losses in the mechanical harvesting of cotton. Therefore, the objective of this study was to model the spatial distribution and map the losses of mechanical cotton harvest using geostatistics and to correlate the losses with agronomic variables using Pearson's correlation. The experiment was conducted in Itiquira and Lucas do Rio Verde, Mato Grosso State, Brazil. At each sampling point, the evaluated variables were agronomic plant variables and cotton losses in the soil and the plant (divided into lower, medium and upper thirds) and the sum total of losses. The highest losses in cotton harvest occurred in the lower third and on the soil, both of which exhibit a spatial dependence model, according to geostatistics, demonstrating that they do not occur in a randomized process and are related to the specific plant. There was a relationship between the plant populations with losses in the cotton crop. The plant population can influence the spatial dependence of losses.

Keywords: *Gossypium hirsutum*; geostatistics; precision agriculture.

Received on April 20, 2018.
Accepted on July 5, 2018.

Introduction

The quantitative and qualitative harvest losses in cotton crops diminish profits and lower the efficiency at the end of the crop cycle. This happens when the producer is expected to reap profits from the investments and efforts demanded by crop management.

Vieira et al. (2001) proposed that 10% was the maximum acceptable criteria for cotton harvest losses. Ferreira et al. (2014) observed increasing losses of 10.6 and 14.1% with mechanical harvesting of the cotton at the velocities of 3.6 and 7.2 km h^{-1}, respectively. This result represents a loss increase of 125 kg ha^{-1} between the two harvesting speeds. These authors showed that the harvester speed could interfere with cotton losses on the ground because the means were significantly different by multiple comparisons test.

Precision agriculture has emerged as a strong trend for the management of technical crops with increasing demands. It is already being used for sowing, soil management, fertilization, the application of localized inputs and yield maps in harvesting operations. Maybe it is the beginning of the discussion on the subject of precision harvesting. This issue has not been discussed in the literature. We propose that at some point it could be possible to conduct a harvest project and that adjustments could be made during the harvest. Therefore, we sought to understand the phenomenon of losses for cotton crop conditions assuming that the spatial variability of crop losses was related to plant variables.

In this context, geostatistics was a useful tool for generating more reliable and accurate maps since geographical spatial continuity is assumed and estimated by the semivariogram and interpolation by kriging, an estimator that provides the minimum variance trend. These parameters are ideal for isoline maps, allowing better visualization and interpretation of spatial patterns (Webster & Oliver, 2009). Martins, Carvalho, Andreotti, and Montanari (2009) also used geostatistical maps combined with linear correlation to study the effect of soil physics on bean productivity.

As tendencies for agriculture are increasingly related to precision, harvesting can be optimized, aiming towards the minimization of losses if there is spatial dependence on this variable. This would demonstrate that there may be continuity in space related to the attributes of the plant, which could initiate studies for future precision harvests. Additionally, the need to analyze two harvesting speeds arises, since previous studies have demonstrated that the harvesting speed can interfere in the losses of the cotton.

Given the above, the objective of this study was to analyze harvesting losses and physiological variables of cotton using Pearson's correlation method, model the spatial distribution and map the losses in cotton by mechanical harvesting in three plots, using geostatistics.

Material and methods

Experimental site

The experiment was conducted during the 2014/2015 agricultural year in Itiquira (altitude 730 m) and Lucas do Rio Verde (altitude 413 m), Mato Grosso State, Brazil. The Mato Grosso State is the main cotton producer in Brazil and has one of the most technical production systems in Brazil. The experimental sites were strong cotton producers, with a high technological level on board, distanced from each other 500 km straight and 700 km by road, on farms of different groups.

On July 13, 2015, when cotton (cultivar FM 975 WS) was in the C_n stage (the maturation point for harvest), 64 sample points were marked on the rows. Of the total points, 28 points every 50 m were harvested at 5 km h^{-1} (plot 1) and 36 points every 10 m were harvest at 7 km h^{-1} (plot 2) in a 10.5 ha area at Itiquira. The purpose of the more dense points was to better capture the spatial dependence on a smaller scale and obtain the first points of semivariograms with greater accuracy. The cultivar TMG 81 WS was used, which is characterized by a late cycle of 180 days and nematode tolerance. 48 sampling points were evaluated, with 16 being spaced every 30 m and 32 points every 5 m, harvested at 7 km h^{-1} (plot 3), in a 0.81 ha area at Lucas do Rio Verde (Figure 1).

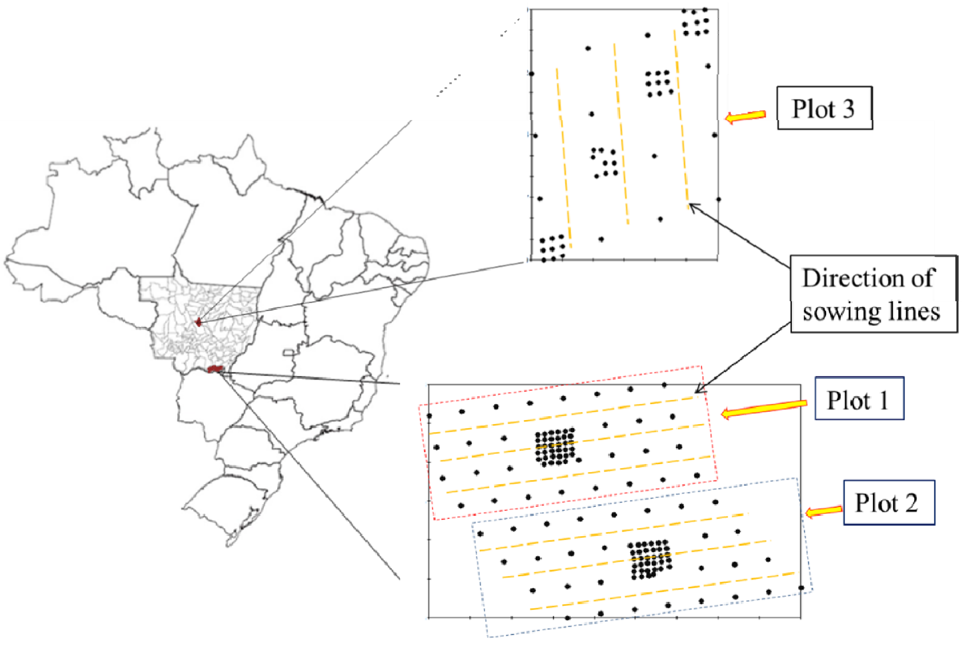

Figure 1. Study site and spatial locations of collected samples of plot 1 (V = 5 km h^{-1}), plot 2 (V = 7 km h^{-1}) in Itiquira and plot 3 in Lucas do Rio Verde, Mato Grosso State, Brazil, 2015.

The climate was seasonal tropical according to the Köppen classification. The soil of the experimental area was classified as Oxisol, with 46% of clay and 49% of sand at Itiquira and dystrophic Red Yellow Latosol, presenting a clayey textural class at Lucas do Rio Verde (EMBRAPA, 2013). The cotton was planted in the no-tillage system, spaced 0.90 m, on December 26, 2014. For Lucas do Rio Verde, the seeding was carried out on January 31 in a conventional planting system, with row spacings of 0.76 m.

The harvest was performed using a John Deere Cotton Harvester 2015, Model CP690 with a picker harvesting system, a power of 417 kW (567 hp), six harvesting rows and a platform adjusted to the 0.90 m cotton spacing, totaling 5.40 m at Itiquira. For the Lucas do Rio Verde experiment, a John Deere model 7760 harvester with a picker system, six lines, 4.5 m wide and 395 kW (537 hp) was used for cotton harvesting.

Evaluations

For the variables of productivity, only 20 samples were measured for plot characterization. For all other variables, the samples were collected according to the schematic, n = 64 and n = 48, respectively. Productivity was measured by the number cotton bolls with seeds manually harvested, without impurities, using a 5.40 and 4.50 m^2 frame, respectively, at Itiquira and Lucas do Rio Verde Mato Grosso State, Brazil.

The plant population was determined by the number of plants counted inside the frame at the time of harvest, extrapolating to hectares. The boll average mass was obtained by averaging the mass of 10 cotton bolls collected randomly at each point. The insertion height of the first fruiting branch was obtained by averaging the distance from the ground level to the insertion of the fruiting branch on three plants for each sample point. The average number of bolls per plant was determined by averaging three plants per sampling point. Plant height, the distance between the ground and plant apex, was determined by averaging the height of three plants in each sample point.

The preharvest, ground, plant and total losses were determined following the methodology described by Silva, Souza, Cortez, Furlani, and Vigna (2007). For ground losses, preharvest losses are discounted, assuming that preharvest losses were not caused by the harvesting operation. The preharvest losses were measured by collecting all cotton fallen on the ground inside the 5.40 m^2-frame area before the mechanical harvesting. After the passage of the harvester, all cotton dropped on the ground was collected manually using the 5.40 and 4.5 m^2–frame in all sample points of plots 1, 2, and 3. Plant losses were calculated by collecting all the cotton that remained on the plant after harvesting, the plants were divided into lower, medium and upper thirds (Figure 2). The total losses were the summation of the losses on the ground and on the plant. The loss percentage was given by the ratio with the average productivity/yield of plots 1, 2, and 3.

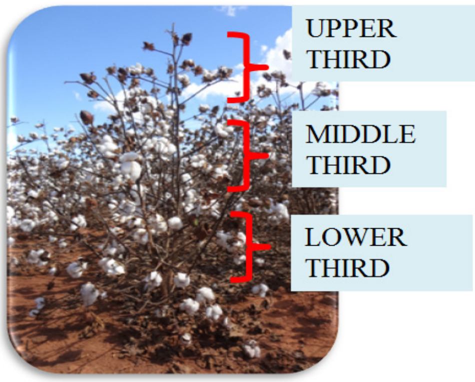

Figure 2. Schematic of losses on plant thirds.

Statistical analysis

Initially, the variabilities of plant physiological variables and losses were evaluated by descriptive statistics, calculating the mean, confidence interval, coefficient of variation, minimum, maximum, skewness and kurtosis.

The Pearson correlation between variables was used to determine the relationship between losses and plant agronomic variables.

The spatial dependence was analyzed by geostatistics, with estimates determined by experimental semivariograms. Under the assumption of the intrinsic hypothesis, the semivariograms were estimated by equation 1 (Burrough & McDonnell, 2006):

$$\hat{\gamma}(h) = \frac{1}{2\,N(h)} \sum_{i=1}^{N(h)} [z(x_i + h) - z(x_i)]^2 \quad (1)$$

where: N(h) is the number of pairs of experimental observations Z(x_i) and Z(x_i + h) separated by a distance h. The semivariogram is represented by the graph $\hat{\gamma}$(h) versus (h).

From the adjustment of a mathematical model to the values of $\hat{\gamma}$(h), the parameters were estimated from the theoretical semivariogram model (nugget effect, C_0; sill, $C_0 + C_1$; and range, a). The analysis of the relationship [C_0 / (C_0 + C_1)] was expressed according to Cambardella et al. (1994). To verify the presence of anisotropy, semivariograms were calculated for the four directions (0, 45, 90, and 135°). Experimental semivariograms were chosen based on the number of pairs involved in the calculation of semivariance, the presence of a clearly defined range, a better cross-validation coefficient (a graph showing the relationship between real and estimated values) (Landim, 2006) and a greater coefficient of determination (R^2). Anisotropy was not evident in any of the variables, so the semivariograms were assumed to be isotropic. After adjustment of the mathematical models, data interpolation was made by ordinary kriging in unsampled locations. The geostatistical analysis was performed using GS+ software and the maps were edited using Surfer software version 9. In the absence of spatial dependence, interpolation was performed by the inverse distance weighting (IDW).

Results and discussion

No spatial analysis

The average yield was 3,988 at Itiquira and 3,793 kg ha^{-1} for Lucas, close to the values of 3,911 and 4,108 kg ha^{-1} found in the literature for the FMT 701 and IMACD 408 cultivars, respectively, in the Cerrado region of Brazil (Ferreira et al., 2014). These were similar to the values of 4,124 kg ha^{-1} and 4,530 kg ha^{-1} found for the FMT 701 and Fibermax 993 cultivars, respectively, in Goiás State, Brazil (Sana, Anghinoni, Brandão, & Holzschuh, 2014).

Although higher speeds were expected to generate greater crop losses, this result was not found. In the second plot (V = 7 km h^{-1}), a total loss of 8.3% was observed in comparison to field 1 (V = 5 km h^{-1}) with a loss of 10.1% (Table 1). Kazama, Silva, Ormond, Alcantara, and Vale (2018) found that the speed (5, 6, 7, 8, and 9 km h^{-1}) did not increase losses and fiber quality when cotton was well conducted and machine adjustments were performed correctly.

Table 1. Descriptive statistics of cotton yield, physiological variables and losses for mechanical harvesting in Itiquira and Lucas do Rio Verde, Mato Grosso State, Brazil, 2015.

Variables*		Mean	CI (95%)	CV	Minimum	Maximum	Skewness	Kurtosis
		Plot 1 (V = 5 km h^{-1})						
N boll pl	-	15.5	14.5 - 16.5	26.1	9	28.7	0.82^N	0.75
Pop	pl ha^{-1}	70047	66319 - 73775	21.1	20370	107407	-0.22^N	1.31
M 1 boll	g	5.1	4.9 - 5.2	14.98	2.8	6.6	-0.52^N	0.19
Height pl	m	1.16	1.13 - 1.19	9.69	0.92	1.44	0.07^N	-0.04
Height ins	m	0.25	0.23 - 0.27	27.85	0.12	0.45	0.73^A	0.56
L_{low}	%	2.3	1.8 - 2.7	72.43	0.09	8.71	1.86^A	4.49
L_{med}	%	1.0	0.8 - 1.2	82.76	0	4.64	2.2^A	6.42
L_{up}	%	0.4	0.2 - 0.5	154.63	0	3.06	2.96^A	9.92
L_{pl}	%	3.6	3.0 - 4.2	69.57	0.743	14.84	2.42^A	7.22
L_{ground}	%	6.6	6.0 – 7.3	36	2.19	12.83	0.72^A	0.1
L_{total}	%	10.1	9.1 - 11.2	40.41	4.37	27.67	1.98^A	5.57
		Plot 2 (V = 7 km h^{-1})						
N boll pl	-	14	13.2 – 14.7	22.5	7.33	20.7	0.15^N	-0.41
Pop	pl ha^{-1}	79485	77106 – 81864	12	53704	101852	-0.42^N	0.13
M 1 boll	g	5.1	4.9 – 5.4	17.8	3.6	7.6	0.7^N	0.21
Height pl	m	1.17	1.13 – 1.20	11	0.89	1.5	0.14^N	-0.4
Height ins	m	0.26	0.24 – 0.28	23.4	0.15	0.4	0.75^A	-0.25
L_{low}	%	1.6	1.4 – 1.8	48.3	0.09	4.1	0.92^A	1.7
L_{med}	%	1.1	0.9 – 1.2	55.7	0	2.9	0.83^A	0.8
L_{up}	%	0.3	0.2 – 0.4	129.4	0	2.2	2.37^A	7.6
L_{pl}	%	2.9	2.6 – 3.2	41.6	0.19	6.5	0.44^N	0.7
L_{ground}	%	5.5	5.0 – 5.9	34.8	2.08	11.1	0.65^N	0.5
L_{total}	%	8.3	7.6 – 8.9	30.2	2	16.3	0.76^A	1.2
		Plot 3 (Lucas do Rio Verde)						
N boll pl	-	11.38	10.6 – 12.1	23.2	4.33	18.3	0.24^N	0.98
Pop	pl ha^{-1}	104120	100940 – 107301	10.5	75556	128889	0.04^A	0.04
M 1 boll	g	4.79	4.64 – 4.94	11.0	3.60	6.0	0.05^N	-0.30
Height pl	m	0.87	0.82 – 0.91	17.6	0.56	1.2	0.08^N	-0.75
Height ins	m	0.21	0.20 – 0.22	12.0	0.15	0.3	-0.04^N	-0.65
L_{low}	%	0.69	0.5 – 0.9	79.5	0.18	2.6	1.48^A	2.23
L_{med}	%	0.16	0.1 – 0.2	83.6	0.00	0.5	0.94^A	0.38
L_{up}	%	0.14	0.1 – 0.2	83.6	0.00	0.5	0.86^A	0.55
L_{pl}	%	0.99	0.8 – 1.2	60.4	0.23	3.0	1.44^N	2.73
L_{ground}	%	4.18	3.8– 4.6	34.5	1.82	8.3	0.66^N	0.50
L_{total}	%	5.17	4.7 – 5.7	32.8	2.75	11.4	1.30^A	2.62

CI: confidence interval; CV: coefficient of variation; N boll pl: number of bolls per plant; Pop: plant population; M 1 boll: mass of a boll; Height pl: plant height; Height ins: insertion height of the first fruiting branch; L_{inf}: loss in the lower third; L_{med}: loss in the medium third; L_{up}: loss in the upper third; L_{pl}: plant loss; L_{soil}: ground loss; L_{total}: total loss; ^{N}: Normal according to Kolmogorov-Smirnov Test; ^{A}: not normal; *(n = 64) for each plot.

Thus, a more detailed study of the harvesting process will be based on field plant conditions. These values were close to the maximum tolerable loss according to Vieira et al. (2001). These authors stated that losses up 10% were acceptable, but the ideal range lies between 6 and 8%, a value obtained in plot 3 (5.17%), which had half the losses in comparison to plots 1 and 2. This was due to the operator's experience in regulating the harvester, in which there is a noticeable decrease in losses. Moreover, the cultivar used in Itiquira (plots 1 and 2), FM 975 WS, presents a pyramidal structure, in which the branches of the lower third are larger than the branches in the upper third, and the platforms of the harvester were cylindrical drums. On the other hand, in area 3, the cultivar used was TMG 81 WS, which is characterized by a cylindrical structure, in which the branches have more uniform sizes and present better conformation for mechanized harvesting for the machines used.

The mean values of the cotton physiological variables were similar between plants from plots 1 and 2. However, these values differ widely from plot 3, which was expected since this plot contained another cultivar with distinct characteristics between plants. The same was proven when compared to the literature, which shows that for each cultivar, specific values were found; for example, the average plant height was 1.16 m compared to Mattioni, Figueiredo, Marcos-Filho, and Guimarães (2012) (1.70 m) and Nagashima, Miglioranza, Marur, Yamaoka, and Gomes (2007) (0.69 m). This great variability shows the complexity of cotton ecophysiology, in addition to genetic factors, and that growth was also strongly correlated with environmental factors.

The coefficients of variation (CV%) for the agronomic variables were similar for both harvesting speeds, except for plant population, which was higher for plot 1 (21.1%) compared to plot 2 (12%) and plot 3 (10.5%). CVs were very high for ground, plant, and total losses for both harvesting speeds. Likewise, Loureiro Junior, Silva, Cassia, Compagnon, and Voltarelli (2014) and Zerbato, Silva, Torres, Silva, and Furlani (2014) also reported high CV values for the mechanical harvesting losses of soybeans and peanuts, respectively, showing the great variability of the process. All loss variables had greater CVs in plot 1. Souza, Marques Júnior, Pereira, and Moreira (2004) stated that the CV serves as a preview of the spatial variability.

Confidence intervals (95%) showed that only the plant population was distinctly distributed in each plot. Therefore, this variable may have influenced the quantitative losses on the plant lower third, ground, and total since these variables had significantly different intervals.

Correlation of losses with physiological variables

Table 2 shows the simple linear correlation between losses and plant attributes. For plot 1, the plant population had moderate and negative linear correlation with losses in the lower third ($r = -0.40$, $p < 0.01$), upper third ($r = -0.22$, $p < 0.10$) and on the ground ($r = -0.23$, $p < 0.10$). Although the correlations were not strong, this showed that the plant population interfered with the plant and ground losses due to the machine-plant interactions. It has been reported that in areas where cotton populations are less dense, the remaining cotton has greater tillering and produces more bolls, interacting with the environment and compensating production. This can be demonstrated by the negative correlation of the following variable pair: plant population and number of bolls per plant ($r = -0.35$; $p < 0.01$).

The cotton plant has complex development and structural growth. The growth habit is indeterminate while the existence of two types of branches, vegetative and fruiting, gives great environmental adaptability to the plant. At the base of each leaf on the main stem, there are two or, occasionally, three buds, one of which is responsible for fruiting or vegetative branches. The second bud is usually dormant except when problems arise with the first bud, when it may lead to a new branch (Mauney, 1984). The cotton crop presents holocenotism. By this principle, there are no barriers between environmental factors and production, implying that the plants are subjected to all environmental factors at any specific time (Mota, 1976).

Thus, it is understood that some plants grow larger to compensate for neighboring plants that do not grow. However, most tillered plants tend to have greater plant losses, especially in the lower third, because the cotton bolls do not enter the harvester platform continuously and at a constant flow. The bolls are not harvested efficiently because the machine is set to a standard tillering, which does not take into account plant and insertion height variations.

This correlation of plant population with plant and ground losses was observed only for plot 1, and as seen in plots 2 and 3, there was no relationship between the population and plant losses. This can be explained, since the average plant population for FM 975 WS was approximately 70,000 plants ha^{-1} in plot 1, compared to an average of 80,000 plants ha^{-1} in plot 2. The recommendation of the seed manufacturer of this cultivar was 80 to 90,000 plants ha^{-1} while EMBRAPA recommends 80-125 thousand plants ha^{-1} (Lamas, 2008). Therefore, holocenotism occurred because plot 1 had on average 10 thousand plants below the minimum recommended, so larger plants with tillering emerged due to the compensatory behavior of cotton crops.

Table 2. Simple linear correlation between cotton physiological variables and mechanical harvesting losses in plot 1, plot 2, and plot 3 (Itiquira and Lucas do Rio Verde, Mato Grosso State, Brazil).

Plot 1 (V = 5 km h^{-1})											
Var	N boll pl	Pop	M boll	Hgt pl	Hgt ins	L_{low}	L_{med}	L_{up}	L_{pl}	L_{ground}	L_{total}
N boll pl	-	-0.35**	0.27*	ns	ns	ns	ns	ns	0.22•	ns	ns
Pop		-	ns	ns	0.41**	-0.40**	ns	-0.22•	-0.31*	-0.23•	-0.35**
M boll			-	ns	ns	ns	ns	ns	ns	ns	ns
Hgt pl				-	ns	ns	ns	ns	ns	ns	ns
Hgt ins					-	-0.32*	ns	ns	-0.26*	ns	-0.24•
L_{low}						-	0.40**	0.41**	0.89**	0.38**	0.73**
L_{med}							-	0.63**	0.74**	0.24•	0.60**
L_{up}								-	0.70**	ns	0.55**
L_{pl}									-	0.38**	0.81**
L_{ground}										-	0.82**
L_{total}											-
Plot 2 (V = 7 km h^{-1})											
Var	N boll pl	Pop	M boll	Hgt pl	Hgt ins	L_{low}	L_{med}	L_{up}	L_{pl}	L_{ground}	L_{total}
N boll pl	-	ns	ns	ns	ns	ns	ns	0.31**	ns	ns	ns
Pop		-	ns	ns	0.34**	ns	ns	ns	ns	ns	ns
M boll			-	ns	ns	ns	ns	ns	ns	-0.23•	ns
Hgt pl				-	ns	ns	0.26*	ns	ns	ns	ns
Hgt ins					-	ns	0.28*	ns	0.25*	ns	ns
L_{low}						-	ns	ns	0.75**	0.28*	0.59**
L_{med}							-	ns	0.63**	ns	0.31*
L_{up}								-	0.48**	ns	ns
L_{pl}									-	ns	0.61**
L_{ground}										-	0.87**
L_{total}											-
Plot 3 (Lucas do Rio Verde)											
Var	N boll pl	Pop	M boll	Hgt pl	Hgt ins	L_{low}	L_{med}	L_{up}	L_{pl}	L_{ground}	L_{total}
N boll pl	-	ns	ns	ns	ns	ns	-0.28•	ns	ns	ns	ns
Pop		-	ns	ns	0.40**	ns	ns	ns	ns	ns	ns
M boll			-	0.31*	ns	ns	-0.36*	ns	ns	ns	ns
Hgt pl				-	ns	ns	-0.35*	ns	ns	0.48**	0.41**
Hgt ins					-	ns	ns	ns	ns	ns	ns
L_{low}						-	ns	ns	0.95**	0.33*	0.62**
L_{med}							-	ns	0.30*	0.32*	ns
L_{up}								-	0.33*	ns	ns
L_{pl}									-	0.25•	0.57**
L_{ground}										-	0.94**
L_{total}											-

N boll pl: number of bolls per plant; Pop: plant population; M 1 boll: mass of a boll; Height pl: plant height; Height ins: insertion height of the first fruiting branch; L_{inf}: loss in the lower third; L_{med}: loss in the medium third; L_{up}: loss in the upper third; L_{pl}: plant loss; L_{soil}: ground loss; L_{total}: total loss; (•): significant at 0.10; (*): significant at 0.05; (**) significant at 0.01; (ns): not significant; *(n = 64) for each plot.

Plant density significantly alters plant architecture, the position of the fruit on the branches, the number of fruits per plant, plant height, the insertion height of the branches and the number of nodes on the main stem (Jost & Cothren, 2000; Boquet, 2005). It can be considered that when the population of plants is close to the ideal (for plots 2 and 3, the recommended population for TMG 81 WS is 105,000 plants ha^{-1}), the plants are presented in a more standardized architecture and are suitable for mechanized harvest since the regulation of the harvester is usually done in the morning, when the operator will start the operation, and for a standard plant size.

This can be proven by the correlations observed in plot 1, where the lower the plant population, the higher the number of bolls per plant ($r = -0.35$, $p < 0.01$). Cotton displays this compensation when there is a loss of some plants and the neighboring plants compensate for it, forming a larger plant with a larger number of bolls and larger sized bolls. This could be seen as the larger the number of bolls on the plant is, the greater the mass of the bolls ($r = 0.27$, $p < 0.05$), and the larger the number of bolls on the plant is, the greater the loss from the plant ($r = 0.22$, $p < 0.10$). This proved how the population of plants in the field interferes with harvest losses. This was not observed for plots 2 and 3.

The variables insertion height and loss in the lower third of the plant had a moderate negative correlation ($r = -0.32$, $p < 0.05$) in plot 1. This allows the conclusion that the greater the insertion height of the first fruiting branch, the smaller the losses in the lower third of the plant. It is noteworthy that while the machine platform height can be adjusted relative to the ground level, the height is never leveled very low as to collect those bolls with small insertion heights because the bolls harvested too close to the ground are contaminated with vegetable and mineral materials, harming fiber quality.

The insertion height of the first fruiting branch varies according to species and cotton cultivar, accounting for the genotype factor, but it can be modified by environmental conditions. The lower the insertion height is, the earlier fruiting the plant is (Souza et al., 2008). It was observed that the insertion height is also proportionally correlated with the plant population in plots 1, 2, and 3. The larger the plant population is, the greater the intraspecific competition and the insertion height of the first fruiting branch, which may also be explained by the fact that fewer auxiliary/vegetative branches emerged from buds that would break dormancy and produce more tillers.

The losses in the soil are explained by the displacement and friction of the harvester with the cotton plants, which are detached from the stem and deposited on the soil when they collide with the machine. The highest value found for losses on the soil, compared to the losses in the plant, is due to the mass of the whole bundle detaching at the moment of the friction of the machine with the plant.

A possible solution to reduce soil losses would be the genetic improvement to strengthen the receptacle and the floral peduncle (structures responsible for connecting the floral bud to the vegetative branch) so that the bud is not so sensitive as to become detached due to friction with the machine.

There is also a relationship between losses in the lower third and losses on the ground in the 3 plots ($r = 0.38$, 0.28, and 0.33, plots 1, 2, and 3, respectively). This demonstrates how important it is to harvest efficiently, mainly in the lower third of the plant, since the highest average loss is due to ground losses, followed by loss from the lower third. Even the choice of cultivars that present higher production in the medium branches of the plant and not in the lower third is related to this result.

Spatial variability

Spatial variability analysis of the results (Table 3) indicated that plant height and losses in the lower third for plot 1 and number of bolls on the plant, plant height, and plant, ground and total losses for plot 2 showed high spatial dependence ($C_0/(C_0+C_1) \leqslant 25\%$), with values ranging from 0.10 to 23.8%. The other variables showed moderate spatial dependence ($25\% < C_0/(C_0+C_1) \leqslant 75\%$) (Cambardella et al., 1994).

The total absence of spatial dependence is called the nugget effect, indicating that the spatial distribution is random or that the shortest distance between the points of the sampling grid was not sufficient to detect the spatial dependence. There is a possibility that the losses in the medium and upper thirds did not present spatial dependence due to pure nugget effects of the plant population in plots 2 and 3, which accounted for the variability in losses due to environmental conditions, as the holocenotism of cotton crops was already explained.

The range obtained by semivariograms (Figures 3 and 4) is important in relation to the limit of spatial dependence. It was observed that the estimated range for plant, ground and total losses ranged between 40 and 70 m in all plots. The other variables ranged from 25.3 m (plant height) to 82.9 m (plant population). The low range of the plant height shows the low continuity of this physiological attribute. In practical terms, the variogram range can be used to guide the sampling plan, indicating the closest to ideal spacing in the field (Montanari et al., 2012).

Table 3. Parameters of experimental semivariograms obtained for cotton physiological variables and losses in mechanical harvesting for Plot 1, Plot 2, and Plot 3, Itiquira and Lucas do Rio Verde, Mato Grosso State, Brazil.

Variables*	Model	C_0	C_1	$C_0/(C_0+C_1)$	a	SQR	R^2	CV
	Plot 1 (V = 5 km h^{-1})							
N boll pl	NE	-	-	-	-	-	-	-
Pop	Sph	1.05E+08	1.05E+08	50.0	82.9	2.75E+15	0.71	1.55+0.77x
M 1 boll	NE	-	-	-	-	-	-	-
Height pl	Sph	0.0002	0.0106	2.0	25.3	2.80E-06	0.85	0.16+0.87x
Height ins	NE	-	-	-	-	-	-	-
L_{low}	Sph	0.1340	1.033	11.5	34.5	0.016	0.94	0.20+0.96x
L_{med}	Sph	0.2001	0.201	49.9	75.0	6.23E-03	0.74	0.22+0.74x
L_{up}	Sph	0.0151	0.045	25.1	45.0	4.26E-05	0.95	0.07+0.73x
L_{pl}	Sph	0.6300	1.351	31.8	49.4	0.204	0.80	0.05+1.01x
L_{ground}	Sph	1.5650	2.775	36.7	36.7	1.100	0.63	1.49+0.78x
L_{total}	Sph	2.0700	7.317	28.3	50.6	5.06E-03	1.00	0.86+0.92x
	Plot 2 (V = 7 km h^{-1})							
N boll pl	Sph	0.0100	9.520	0.10	27.7	1.500	0.90	2.77+0.81x
Pop	NE	-	-	-	-	-	-	-
M 1 boll	NE	-	-	-	-	-	-	-
Height pl	Sph	0.0031	0.0107	22.3	33.7	5.83E-06	0.80	-0.2+1.16x
Height ins	NE	-	-	-	-	-	-	-
L_{low}	Sph	0.086	0.252	25.4	44.1	1.06E-03	0.96	0.11+0.91x
L_{med}	NE	-	-	-	-	-	-	-
L_{up}	NE	-	-	-	-	-	-	-
L_{pl}	Sph	0.276	1.174	19.0	76.1	0.064	094	0.26+0.88x
L_{ground}	Sph	0.639	2.129	23.8	51.7	0.168	0.90	0.85+0.86x
L_{total}	Sph	0.600	3.430	14.9	48.9	0.173	0.96	0.75+2.09x
	Plot 3 (Lucas do Rio Verde)							
N boll pl	NE	-	-	-	-	-	-	-
Pop	NE	-	-	-	-	-	-	-
M 1 boll	NE	-	-	-	-	-	-	-
Height pl	Sph	0.0122	0.0122	49.91	49	5.16E-06	0.94	0.11+0.86x
Height ins	Sph	0.000253	0.000275	52.10	46.7	3.46E-09	0.91	-0.01+1.05x
L_{low}	Sph	0.3324	0.2087	38.60	59.7	8.73E-03	0.82	8.04+0.78x
L_{med}	NE	-	-	-	-	-	-	-
L_{up}	NE	-	-	-	-	-	-	-
L_{pl}	NE	-	-	-	-	-	-	-
L_{ground}	Sph	0.0294	0.0834	26.06	64.7	1.94E-04	0.95	0.76+0.83x
L_{total}	Sph	0.0192	0.0592	49.98	59.5	2.72E-04	0.85	0.88+0.82x

C_0: nugget effect; $C_0 + C_1$: sill; a: range (m); $C_0/(C_0+C_1)$: spatial dependence degree (%); R^2: coefficient of determination for the adjustment; SQR: sum of squared residuals; CV: cross-validation; N boll pl: number of bolls per plant; Pop: plant population; M 1 boll: mass of a boll; Height pl: plant height; Height ins: insertion height of the first fruiting branch; L_{inf}: loss in the lower third; L_{med}: loss in the medium third; L_{up}: loss in the upper third; L_{pl}: plant loss; L_{soil}: ground loss; L_{total}: total loss. NE: pure nugget effect; Sph: spherical; Gauss: Gaussian; Exp: exponential; *(n = 64 for each plot).

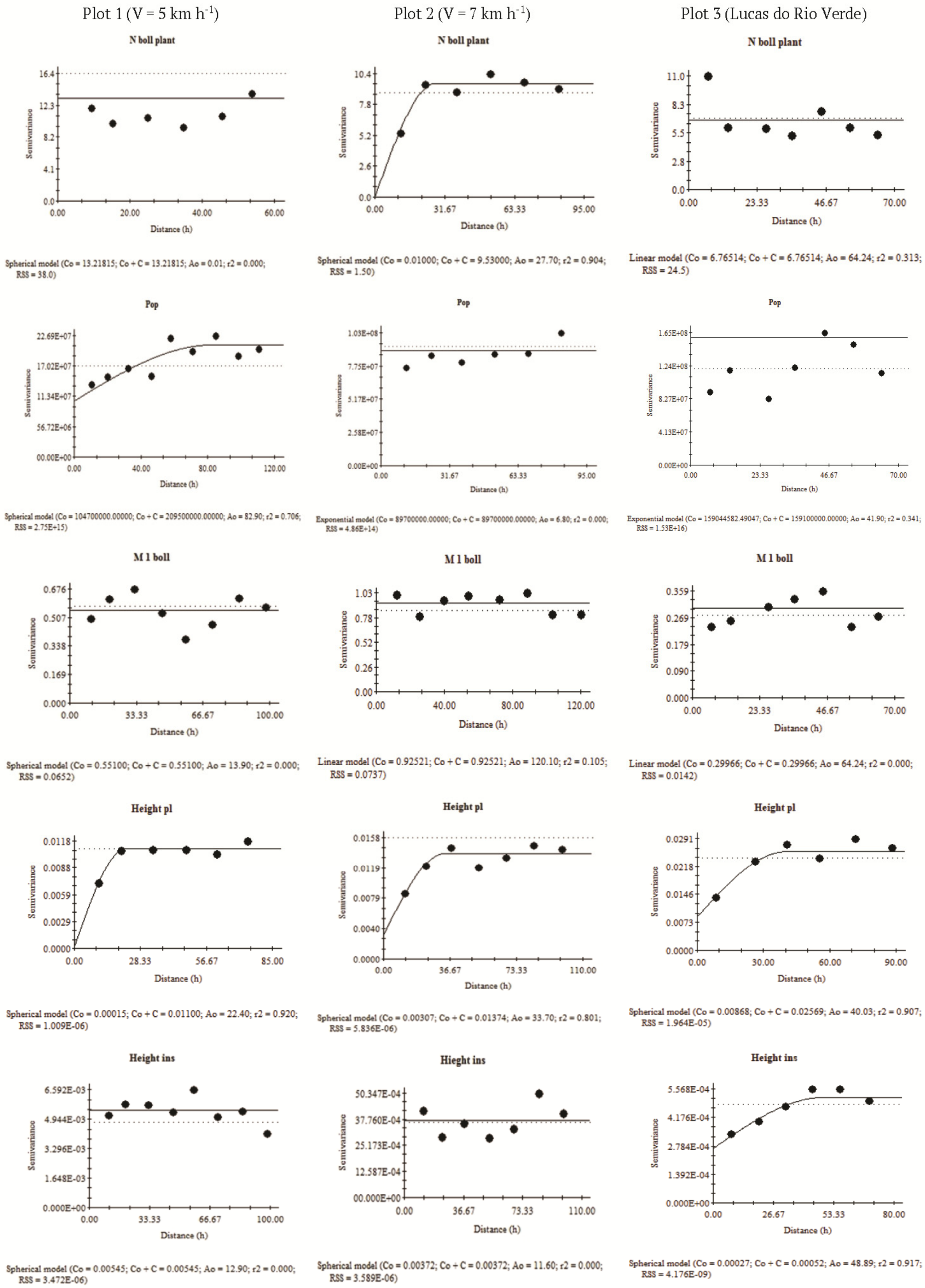

Figure 3. Semivariograms of the physiological variables of cotton. N boll: number of bolls per plant; M 1 boll: mass of a boll; Height pl: plant height; Height ins: insertion height.

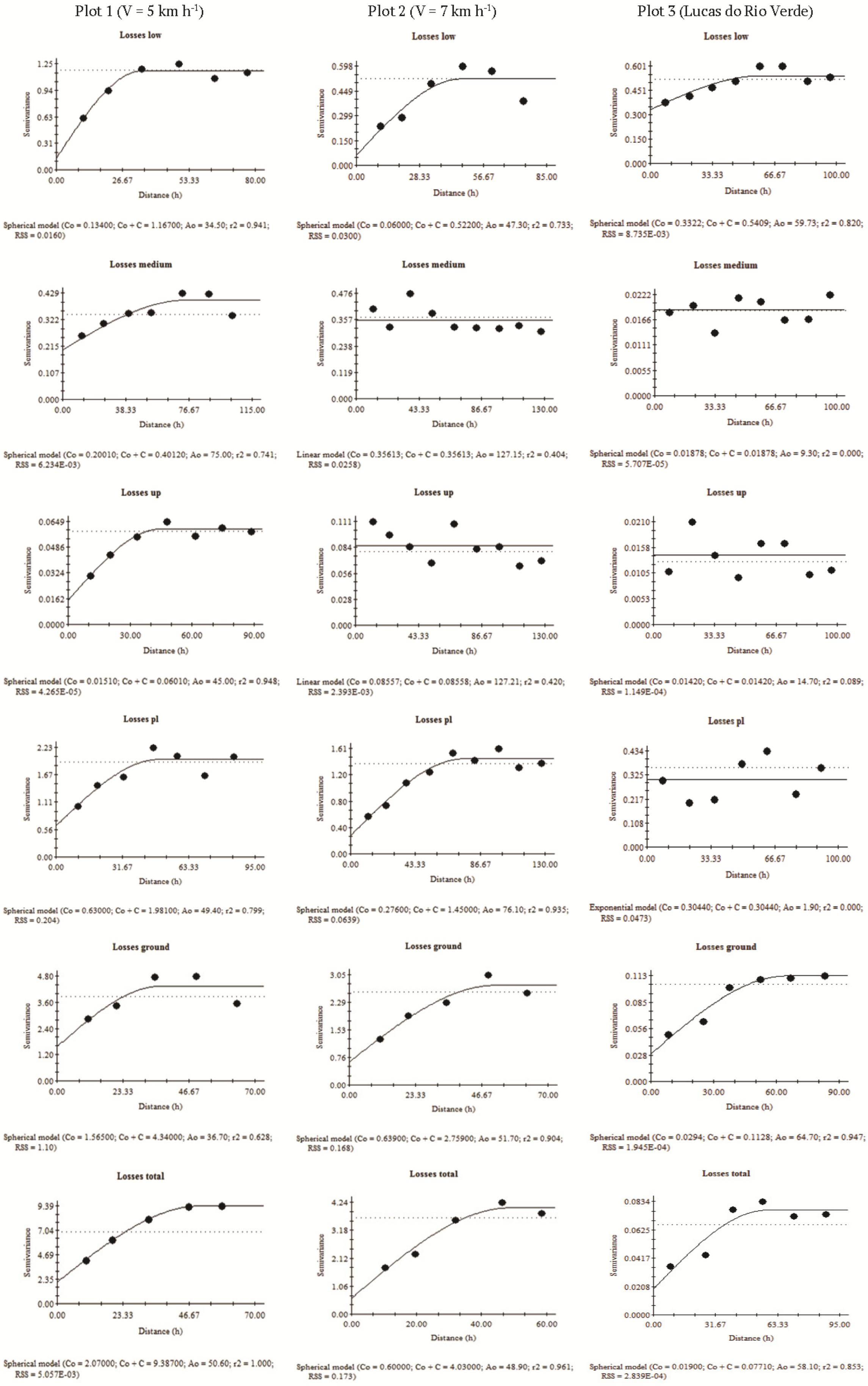

Figure 4. Semivariograms of losses from mechanical harvesting.

Losses in the lower third and on the ground present spatial dependence for all plots, and it is where the highest loss values occurred, demonstrating that losses are not a random phenomenon and may allow better precision in harvest planning if studied.

Spatial distribution maps

Figures 5 and 6 show the spatial distribution maps for cotton crop losses and physiological variables. The spatial distribution of the plant population demonstrated a clumped pattern, showing that the population may have been affected by nematodes, weevil attacks, puddles, or diseases in plot 1, where there was spatial dependence. In plots 2 and 3, the plant population behavior was more random, with no spatial dependence, reinforcing that there was no significant correlation between losses and the plant population.

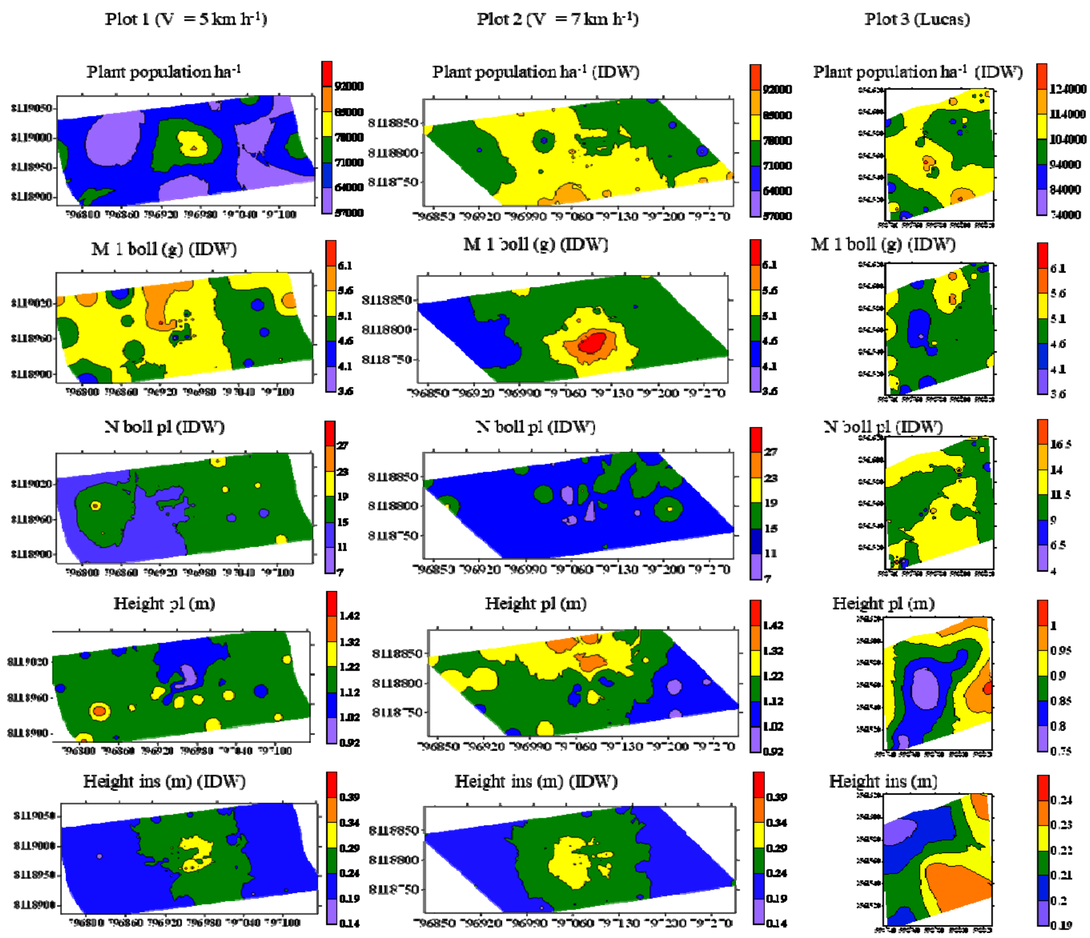

Figure 5. Spatial distribution of cotton physiological variables. N boll: number of bolls per plant; M 1 boll: mass of a boll; Height pl: plant height; Height ins: insertion height.

It was observed that the total loss in plots presented the highest variability for losses aligned in the direction of the seeding rows. That is, the harvester platform promotes the loss as it moves (in an east-west horizontal direction for plots 1 and 2, and in a north-south vertical direction for plot 3) following the row instead of randomly.

However, there were studies in which the losses presented great variability across the area with no continuity in the losses as many occurred randomly; the authors stated that it was difficult to say which factors led to this occurrence at the site (Silva et al., 2013). This result could be because of the large distances between samples (every 50 m), which hinders the precise adjustment of the semivariogram. Thus, this work shows that additional studies of loss in cotton maps presents slightly more detail on how the machine factor interacts with losses, as they are not random.

The total loss maps were similar to the ground loss maps. A possible explanation is that cotton bolls were removed whole from the plant, and instead of being harvested by the spindles, the bolls are launched whole on the ground, with husks.

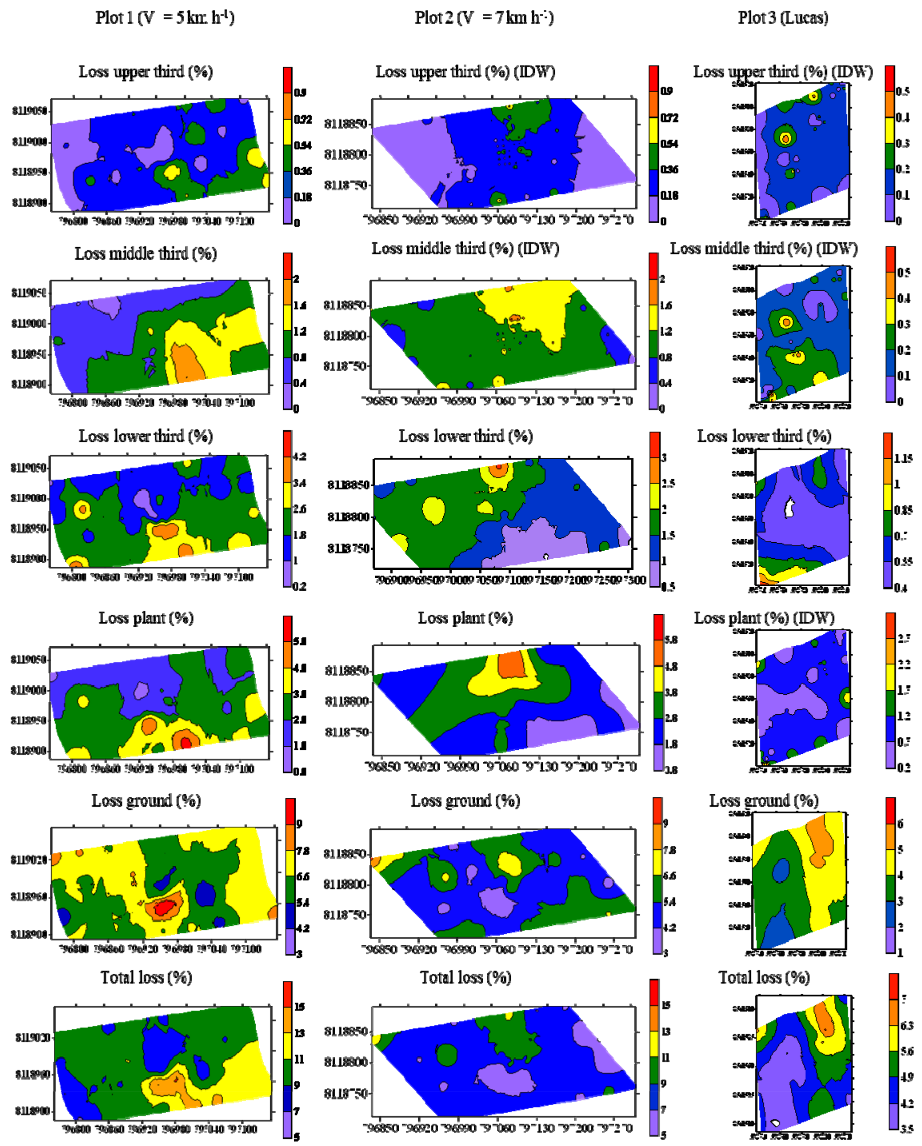

Figure 6. Spatial distribution of losses from mechanical harvesting.

Similarly, plant losses are highly correlated with losses on the lower third of the plant, as shown by the similarity in all maps. The lower third has the greatest losses due to the pyramidal architecture of the cotton plant. Therefore, cotton yield greatly depends on the plant location; 80% of the yield is defined in the lower and medium third of cotton plants, which is in the first and second fruit position with respect to the main stem (Soares, Lara, Silva, Almeida, & Wanderley, 1999).

General discussion

The present work discusses the premises of precision harvesting associated with the conditions of the plant in the field and discusses some ecophysiological mechanisms that may influence harvesting, especially the population of the cotton plants. This work aimed to analyze crop losses using Pearson's correlation and geostatistical analyses, seeking to understand the phenomenon of loss in the harvest and aiming at a minimum loss and maximum productivity. We know this is a much more complex operation that will require years of study to understand how it can be done. However, it may be the beginning of the discussion of the 'precision harvesting' theme.

Cotton produces larger fruits in positions closer to the main stem and in the lower thirds. Plants obtain more assimilates from the vegetative leaves present in the main stem, especially in the lower nodes, where the larger leaves (almost twice the size of other leaves) with longer life span are located (Wullscheleger & Oosterhuis, 1990). This fact suggests that losses in cotton crops are greater precisely where the plant is more productive. Therefore, breeding programs have been aiming to maximize harvest efficiency by studying plants with more cylindrical architecture or harvester platforms that are more efficient in the lower third than in the upper third and able to harvest cotton closer to the main stem in the first positions/insertions where the bolls are larger.

If harvester adjustments can vary throughout the plots, by using sensors that can read plant structure, harvesting could become more precise crop yield would be maximized and losses would be minimized. Studies that join efforts to understand the loss processes/steps could drive towards more technological machines able to increase productivity. In a cotton harvester with spindles, which have two drums for collecting the bolls, there is the possibility of placing a sensor between the drums to read plant losses and automatically regulate the adjustment of the second drum for more efficient fiber harvesting, especially in the lower third of the plant, the region with the greatest losses. Sensors that estimate the population of cotton plants could also be used, since this crop demonstrates a complex responsiveness to the environment, adapting the architecture of the plant as a compensatory effect for productivity. However, greater losses co-occur, and this population sensor may need to be an automatic controller for the best regulation on the harvester platform.

It is also interesting to note that the range, a geostatistical parameter, can be used as a signal for the sensors and controllers of possible machines designed for the future of cotton harvest since the range of losses was 40 to 70 m in this work and in others it was approximately 15 to 45 m (Silva et al., 2013). The sensors could perform readings and the controllers could have a response time based on the autoadjustment according to the range values studied. That is, it is known that there is a continuity of losses of up to 75 m, and the controllers can act on this precision of self-regulation in the pressure of the picking drums for a better harvest.

Pearson’s correlation and geostatistics is an innovative tool to understand the losses in mechanical cotton harvesting since it allows defining the correlation between variables and the spatial dependence of the losses, proving that the relationship between losses and plants in space is not random.

Conclusion

The highest losses in cotton harvest occur in the lower third and on the soil, both of which exhibit a spatial dependence model, according to geostatistics, demonstrating that they do not occur in a randomized process and are related to the plant.

There is a relationship between plant populations and losses in the cotton crop. The plant population can influence the spatial dependence of losses.

References

Boquet, D. J. (2005). Cotton in ultra-narrow spacing: plant density and nitrogen fertilizer rates. *Agronomy Journal*, *97*(1), 279-287. DOI: 10.2134/agronj2005.0279

Burrough, P. A., & Mcdonnell, R. A. (2006). *Principles of geographical systems.* New York, NY: Oxford University Press.

Cambardella, C. A., Moorman, T. B., Novak, J. M., Parkin, T. B., Karlen, D. L., Turco, R. F., & Konopka, A. E. (1994). Field-scale variability of soil properties in Central Iowa. *Soil Science Society of American Journal*, *58*(5), 1501-1511. DOI: 10.2136/sssaj1994.03615995005800050033x

Empresa Brasileira de Pesquisa Agropecuária [EMBRAPA]. (2013). *Sistema brasileiro de classificação de solos.* Brasília, DF: Embrapa.

Ferreira, F. M., Silva, A. R. B., Silva, P. R. A., Benez, S. H., Kroth, B. E., & Ormond, A. T. S. (2014). Pluma Perdida. *Cultivar Máquinas*, *13*(137), 34-37.

Jost, P. H., & Cothren, J. T. (2000). Growth and yield comparisons of cotton planted in conventional and ultra narrow row spacings. *Crop Science*, *40*(2), 430-435. DOI: 10.2135/cropsci2000.402430x

Kazama, E. H. K., Silva, R. P., Ormond, A. T. S., Alcantara, A. S., & Vale, W. G. (2018). Cotton and fiber quality in function of picker harvest speed. *Revista Brasileira de Engenharia Agrícola e Ambiental*, *22*(8), 583-588. DOI: 10.1590/1807-1929/agriambi.v22n8p583-588

Lamas, F. M. (2008). O agronegócio do algodão no Brasil: Manejo cultural do algodoeiro nas condições do Cerrado. In N. E. M. Beltrão, & D. M. P. Azevedo (Eds.), *O agronegócio do algodão no Brasil: Manejo cultural do algodoeiro nas condições do Cerrado* (p. 623-648). Brasília, DF: Embrapa.

Landim, P. M. B. (2006). Sobre geoestatística e mapas. *Terra e Didática*, *2*(1), 19-33. DOI: 10.20396/TD.V2I1.8637463

Loureiro-Júnior, A., Silva, R. P., Cassia, M. T., Compagnon, A. M., & Voltarelli, M. A. (2014). Influence of the sample área in the variability of losses in the mechanical harvesting of soybeans. *Engenharia Agricola*, *34*(1), 74-85. DOI: 10.1590/S0100-69162014000100009

Martins, M. V., Carvalho, M. P., Andreotti, M., & Montanari, R. (2009). Correlação linear e espacial entre a produtividade do feijoeiro e atributos físicos de um Latossolo Vermelho distroférrico de Selvíria, Estado de Mato Grosso do Sul. *Acta Scientiarum. Agronomy*, *31*(1), 147-154. DOI: 10.4025/actasciagron.v31i1.6641

Mattioni, F., Figueiredo, M. C., Marcos-Filho, A. J., & Guimarães, S. C. (2012). Vigor de sementes e desempenho agronômico de plantas de algodão. *Revista Brasileira de Sementes*, *34*(1), 108-116. DOI: 10.1590/S0101-31222012000100014

Mauney, J. R. (1984). Anatomy and morphology of cultivated cottons. In R. J. Kohel, & C. F. Lewis (Eds.), *Cotton* (p. 58-80). Madison, WI: American Society of Agronomy.

Montanari, R., Souza, G. S. A., Pereira, G. T., Marques Jr, J., Siqueira, D. S., & Siqueira, G. M. (2012). The use of scaled semivariogramas to plan soil sampling in sugarcane fields. *Precision Agriculture*, *13*(5), 542-552. DOI: 10.1007/S11119-012-9265-6

Mota, F. S. d. (1976). *Metereologia agrícola*. São Paulo, SP: Nobel.

Nagashima, G. T., Miglioranza, E., Marur, C. J., Yamaoka, R. S., & Gomes, J. C. (2007). Embebição de sementes e aplicação foliar com cloreto de mepiquat no crescimento e produção do algodoeiro. *Ciência e Agrotecnologia*, *31*(4), 1027-1034. DOI: 10.1590/S1413-70542007000400001

Sana, R. S., Anghinoni, I., Brandão, Z. N., & Holzschuh, M. J. (2014). Variabilidade espacial de atributos físico-químicos do solo e seus efeitos na produtividade do algodoeiro. *Revista Brasileira de Engenharia Agrícola e Ambiental*, *18*(10), 994-1002. DOI: 10.1590/1807-1929/agriambi.v18n10p994-1002

Silva, R. P. d., Cortez, J. W., Voltarelli, M. A., Cassia, M. T., & Furlani, C. E. A. (2013). Variabilidade espacial das perdas na colheita mecanizada do algodoeiro com diferentes armações de coleta. *Comunicata Scientiae*, *4*(3), 293-301.

Silva, R. P. d., Souza, F. G., Cortez, J. W., Furlani, C. E., & Vigna, G.P. (2007). Variabilidade espacial e controle estatístico do processo de perdas na colheita mecanizada do algodoeiro. *Engenharia Agrícola*, *27*(3), 742-752. DOI: 10.1590/S0100-69162007000400018

Soares, J. J., Lara, F. M., Silva, C. A. D., Almeida, R. P., & Wanderley, D. S. (1999). Influência da posição do fruto na planta sobre a produção do algodoeiro. *Pesquisa Agropecuária Brasileira*, *34*(5), 755-759. DOI: 10.1590/S0100-204X1999000500005

Souza, J. G., Beltrão, N. E. M., Azevedo, D. M. P d., Albuquerque, W. G., Lima, R. L. S., & Cardoso, G. D. (2008). Fisiologia. In N. E. M. Beltrão, & D. M. P. Azevedo (Eds.), *O agronegócio do algodão no Brasil* (p. 221-249). Brasília, DF: Positiva.

Souza, Z. M., Marques Júnior, J., Pereira, G. T., & Moreira, L. F. (2004). Variabilidade espacial do pH, Ca, Mg e V% do solo em diferentes formas do relevo sob cultivo de cana-de-açúcar. *Ciência Rural*, *34*(6), 1763-1771. DOI: 10.1590/S0103-84782004000600015

Vieira, C. P., Cunha, L. J. C., & Zofoli, R. C. (2001). Colheita. In Embrapa Agropecuária Oeste (Ed.), *Algodão: Tecnologia de produção* (p. 273-276). Dourados, MS: Embrapa.

Webster, R., & Oliver, M. A. (2009). *Geostatistics for environmental scientists.* Chinchester, UK: Oxford University Press.

Wullschleger, S. D., & Oosterhuis, D. M. (1990). Photosynthetic carbon production and use by developing cotton leaves and bolls. *Crop Science*, *30*(6), 1259-1264. DOI: 10.2135/cropsci1990.0011183X003000060021x

Zerbato, C., Silva, V. F. A., Torres, L. S., Silva, R. P., & Furlani, C. E. A. (2014). Peanut mechanized digging regarding to plant population and soil water level. *Revista Brasileira de Engenharia Agrícola e Ambiental*, *18*(4), 459-465. DOI: 10.1590/S1415-43662014000400015