An Acad Bras Cienc (2021) 93(1): e20191338 DOI 10.1590/0001-3765202120191338
Anais da Academia Brasileira de Ciências | *Annals of the Brazilian Academy of Sciences*
Printed ISSN 0001-3765 I Online ISSN 1678-2690
www.scielo.br/aabc | www.fb.com/aabcjournal

ENGINEERING SCIENCES

Maximum length of subsurface drip irrigation laterals subjected to backpressure

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Abstract: To achieve a better SDI system design, the emitters' hydraulic characteristics and the flowrate uniformity along lateral lines under backpressure influence must be known. The objective of this study was to evaluate the effect of backpressure on the maximum length of irrigation laterals using two types of emitters (pressure-compensating and nonpressure-compensating) in different situations. Data from a field experiment combined with information obtained from a previously published paper was used, that tested driplines hydraulics behavior influenced by backpressure. The lateral dripline design technique based on statistical approach developed by Anyoji & Wu 1987 was used to calculate the maximum length. The variables that most influenced the maximum length of the laterals were the terrain slope and permissible flowrate variation. For nonpressure-compensating emitters, the maximum length of the irrigation laterals is up to 5% greater in subsurface applications than in surface applications. For pressure-compensating emitters operating under the influence of backpressure, there is an increase in the discharge exponent due to the small difference in flowrate between the surface and subsurface conditions, which also increases the influence of pressure variations on the flowrate thus, the surface laterals are up to 8% longer than the subsurface ones.

Key words: Discharge exponent, dripline, flow rate coefficient of variation, irrigation line hydraulics, lateral design, microirrigation.

INTRODUCTION

The use of subsurface drip irrigation (SDI) has grown due to its advantages over surface drip irrigation, such as its greater use and application efficiency of both water and fertilizers, as a result of reduced soil water evaporation by keeping the soil surface dry, therefore increasing the quality of the agricultural products (Jordan et al. 2014, Ren et al. 2018).

However, the physical properties and spatial variability of soil can affect the hydraulics of SDI systems, causing fluctuating and reduced flow from emitters (Ren et al. 2018). Such issues occur because soils with low water redistribution capacity reduce the emitter flowrate due to the backpressure phenomenon (Shani et al. 1996), which happen when the application rate of the buried emitter exceeds the infiltration capacity of the soil.

According to Lazarovitch et al. 2006 it is possible to avoid the formation of backpressure in soils with low water flow capacity by inserting pressure compensating emitters closer to each other and operating at low inlet pressure. Ben Gal et al. 2004 suggest changing the cavity around the emitter by inserting a highly water conductive material such as gravel, while Shaviv & Sinai 2004, recommend the injection of conditioners in the irrigation system to stabilize the soil around the emitters but both techniques are hardly viable.

There are several methods for designing irrigation laterals, and in most cases, only the pressure variations along the lateral caused by head losses and local topography are considered. Thus, a common practice when designing laterals is to assume a maximum flowrate variation along the line of 10% (Baiamonte 2018). Still according to this author, this criterion is also recommended by manufacturers, which often set the maximum length of the lateral line according to the nominal pressure, flowrate, emitter spacing and dripline diameter. However, these conditions are often not applicable in the field because they are the results of tests performed under perfect emitter working conditions and on flat surfaces.

Anyoji & Wu 1987 developed a method to determine the maximum length of drip laterals using statistical approach and considering the flowrate variations caused by the hydraulic and constructive effects of emitters.

Gomes et al. 2010 argued that for a drip system to function efficiently, it is necessary for the project design to consider the maximum pressure variation because it is used to determine the maximum length of the lateral lines.

The effect of backpressure is often also neglected when designing irrigation laterals. Gil et al. 2011 and Reis et al. 2017 showed that flowrate variation occurs when using the same dripper in surface and subsurface drip systems because of backpressure. Additionally, Thebaldi et al. 2016 observed a change in the discharge exponent of emitters (used to characterize the flow regime) and consequently a variation in the flowrate of the emitters due to the variation in their operating pressure.

The effect of backpressure on emitters in SDI systems must be studied because it can contribute to pressure variation along the laterals, consequently affecting their maximum length and the irrigation system design. Therefore, the present study evaluated the maximum length of irrigation laterals in dripline systems under different backpressures.

MATERIALS AND METHODS

The emitters used in this study was the NaanDanJain TalDrip dripline which is described as nonpressure-compensating and has a nominal flowrate of 1.7 L h^{-1}, pressure range between 50 and 300 kPa, a nominal external diameter of 0.017 m and an internal diameter of 0.0158 m, with each emitter at 0.30 m spacing; and the Rivulis D5000 dripline which is characterized as pressure compensating and has a nominal flowrate of 2.0 L h^{-1}, a nominal external diameter of 0.016 m, an internal diameter of 0.0138 m and a pressure range between 50 and 350 kPa and spacing between emitters of 0.75 m.

To obtain the mean subsurface flowrate of the emitters, driplines were tested in field condition at the University of California at Davis at Campbell Tract field station of the Department of Land, Air and Water Resources. The driplines were installed at depths of 0.10 and 0.20 m in Yolo loam soil and operated at three irrigation time intervals: 0.5, 1.0 and 3.0 h, with three replications each. The textural properties and hydraulic parameters of the Yolo Loam soil are shown in Table I.

For this study, information on TalDrip and D5000 dripline hydraulics (including parameters related to their surface and subsurface behavior) under the effect of backpressure (determined in submerged conditions) was used from the flow-pressure equations presented by Thebaldi et al. 2016 (Table II).

The flowrate of the entire driplines was measured by an Omega Engineering FL-46.302 flowmeter, with measuring interval between 24 and 240 L h^{-1} for an accuracy of ± 5% and,

Table I. Textural properties and hydraulic parameters of the Yolo Loam soil.

Attribute	Layer	
	0 – 0.30 m	0.30 – 0.60 m
ρs (kg m^{-3})	1436	1407
K_{sat} (cm h^{-1})	1.78	0.55
α (cm^{-1})	0.0072	0.0064
n	1.5712	1.6020
m	0.364	0.376
θ_s (m^3 m^{-3})	0.4030	0.4070
θ_r (m^3 m^{-3})	0.0685	0.0683
Sand (%)	28.0	26.0
Silt (%)	49.0	52.0
Clay (%)	23.0	22.0

ρs – soil bulk density; k_{sat} – soil saturated hydraulic conductivity; θ_s – saturated water content; θ_r – residual water content, α, m and n – van Genuchten – Mualem Soil Water Retention Curve (Van Genuchten 1980) fitting parameters.

using the information presented in Table II, the backpressures in field condition were calculated. The measured average surface and subsurface flowrate values under field conditions and calculated backpressure values for the two emitter types are shown in Table III.

Additionally, simulated subsurface flowrates of the emitters were obtained by considering backpressures of 0.49, 1.47, 2.45, 4.41 and 6.37 kPa, calculated using the flow-pressure mathematical models presented by Thebaldi et al. 2016 (Table II) for each dripline and, also, considering an emitter inlet pressure (h_0) value of 145 kPa, the same delivered by the pumping system on the field essays (Table IV). The selected backpressures were within the range used by Thebaldi et al. 2016 on their work.

To calculate the maximum length of laterals using these driplines, we used the design technique based on the statistical approach, of Anyoji & Wu 1987. Simulations were performed for three coefficients of variation of emitter flowrate CV(q), which is design designated, of

Table II. Flow-pressure mathematical models of TalDrip and D5000 driplines at surface and subsurface conditions.

Emitter	Surface	Subsurface
TalDrip	$Q = 0.247 \times h_0^{0.4154}$	$Q = 0.271 \times (h_0 - h_s)^{0.394}$
D5000	$Q = 1.2739 \times h_0^{0.1053}$	$Q = 1.120 \times (h_0 - h_s)^{0.132}$

h_0: pressure in the emitter inlet, kPa; h_s: backpressure, kPa.

5%, 10% and 20%. Lateral slope situations were also considered: ascending slopes of 2% and 5%, horizontal, and descending slopes of 2% and 5%.

Thus, the coefficient of variation of the emitter flowrate can be expressed by Equation 1 (Anyoji & Wu 1987):

$$CV(q) = \frac{\left\{\left[CV(k)\right]^2 + x^2 \cdot \left[CV(H)\right]^2\right\}^{0.5}}{1 + \frac{1}{2} \cdot \left[CV(H)\right]^2 \cdot (x-1) \cdot x} \quad (1)$$

where

CV(q): flowrate coefficient of variation, dimensionless;

CV(H): pressure head coefficient of variation along the lateral, dimensionless;

CV(k): manufacturing coefficient of variation CVm, dimensionless; and

x: discharge exponent of the emitter in the flow-pressure equation under surface or subsurface conditions, dimensionless.

For the use of Equation 1, we adopted a flowrate uniformity criterion, CV(q), based on which CV(H) was calculated. The pressure head variance along the lateral was obtained by combining the pressure head variances resulted from the head loss and by the slope, and by determining the interaction between these two factors. Thus, the coefficient of variation of the pressure head along the lateral line of Equation 2 was obtained by equating the ratio between the square root of the variance of the pressure head along the lateral line and the mean pressure head in the lateral line.

Table III. Surface and subsurface flowrates at an inlet pressure of 145 kPa and calculated backpressure acting on the buried emitters.

Emitter	$Q_{surface}$ (L h^{-1})	$Q_{subsurface}$ (L h^{-1})	Calculated backpressure (kPa)
TalDrip	1.91 ± 0.02	1.84 ± 0.04	14.99
D5000	2.15 ± 0.06	2.12 ± 0.07	16.86

$$CV(H) = \frac{\left\{8.2735 \cdot 10^{-2} \cdot hf_F^2 + 8.3335 \cdot 10^{-2} \cdot \Delta Z^2 + 15.439 \times 10^{-2} \cdot hf_F \cdot \Delta Z\right\}^{0.5}}{H - \frac{m+1}{m+2} \cdot hf_F - \frac{1}{2} \cdot \Delta Z} \quad (2)$$

where

hf_F: major head loss in the lateral line corrected by Christiansen's F factor (mH_2O);

ΔZ: difference in the level of the lateral, negative for a descending slope (m);

H: operating pressure of the emitters (mH_2O); and

m: flowrate exponent in Darcy-Weisbach's head loss equation (m = 2).

The head loss in the lateral line was calculated by combining the Darcy-Weisbach head loss equation (Equation 3) with the Swamee-Jain 1976 equation to calculate the friction factor f (Equation 4). The kinematic viscosity of water with a value of 1.01 x 10^{-6} m^2 s^{-1} was considered for calculating the Reynolds number (Re).

$$hf = f \cdot \frac{L}{d_i} \cdot \frac{v^2}{2 \times g} \quad (3)$$

$$f = \frac{0.25}{\left[\log\left(\frac{e}{3.7 d_i} + \frac{5.74}{\mathrm{Re}^{0.9}}\right)\right]^2} \quad (4)$$

where

L: lateral line length (m);

d_i: internal pipe diameter (m);

v: water flow velocity (m s^{-1});

g: gravitational acceleration (m s^{-2}); and

To determine the real lateral head loss (hf_F Equation 5), the head loss reduction factor F (Christiansen 1942) was used for a number of emitters in the lateral line greater than 20 in all cases, as shown in Equation 6.

$$hf_F = hf \cdot F \quad (5)$$

$$F = \frac{1}{m+1} \quad (6)$$

The length of the lateral line was numerically adjusted in Equation 3 to make the CV(H) in Equation 1 and 2 equals. In this evaluation, the minor head loss caused by the emitters in the lateral line was disregarded.

To determine the manufacturing coefficient of variation (CVm), we performed tests with driplines containing 15 emitters on a hydraulic test bench. The volumes individually applied

Table IV. Subsurface flowrate simulated at an inlet pressure of 145 kPa for different backpressures acting on the buried driplines.

Backpressure (kPa)	$Q_{subsurface}$ (L h^{-1})	
	TalDrip	D5000
0.49	1.923	2.159
1.47	1.918	2.157
2.45	1.912	2.155
4.41	1.902	2.151
6.37	1.892	2.147

by each emitter were collected by cylindrical plastic containers with a diameter of 80 mm and a height of 102 mm. Four replications were carried out, each with a duration of two minutes, at nominal operating pressure of each dripline. Then, CVm was calculated with Equation 7:

$$CVm = 100 \times \left(\frac{S}{V_m} \right) \quad (7)$$

where

S: standard deviation of the sampling volume (L); and

V_m: average volume collected, considering all containers (L).

The CVm values obtained for the TalDrip and D5000 driplines were 1.67 and 2.78%, respectively.

RESULTS AND DISCUSSIONS

The maximum simulated lengths of the TalDrip and D5000 lateral driplines operating in surface and subsurface conditions are shown in Figure 1, with an inlet pressure of 145 kPa, different slopes, a certain allowed flowrate variation and different backpressures.

For the TalDrip dripline, the longest simulated lateral line length was 214.4 m for the irrigation lateral with a descending slope of 5%, an allowed flowrate variation coefficient of 20%, and a backpressure equal to 14.99 kPa (subsurface irrigation). Comparatively, under these same conditions but for surface irrigation, the maximum calculated length was 204.5 m, i.e., 9.9 m shorter.

Based on the analysis of the results, the shortest lateral line length was obtained for a flowrate coefficient of variation of 5%, an ascending slope of 5%, and a backpressure of 0.49 kPa (76.4 m for subsurface irrigation and 73.9 m for surface irrigation). This scenario featured

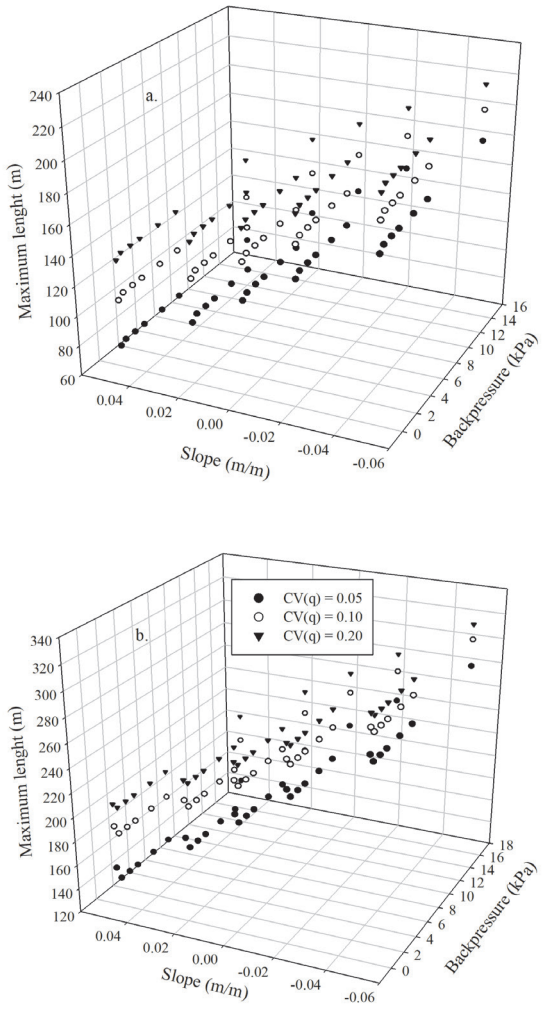

Figure 1. Maximum lengths of the TalDrip (a) and D5000 (b) lateral driplines in surface and subsurface applications with an operating pressure of 145 kPa for different flowrate coefficients of variation, slopes and backpressures.

the smallest difference between the maximum length of the surface and subsurface lines, i.e., 2.5 m.

Thus, an increase in the permissible flowrate coefficient of variation, CV(q) also increases the difference between the maximum laterals lengths because it allows greater energy variation in the pipeline, both due to head loss and as a function of the geometric gradient. Thus, a lower flowrate in the laterals leads to a

lower head loss and less pressure head variation, which, together with a steep descending slope, increases the difference between the maximum lengths for different lateral flowrates. The opposite situation results in shorter lengths and smaller differences in maximum lengths between surface and subsurface applications.

In the case of the pressure-compensating D5000 dripline, the maximum lateral line lengths in subsurface applications are shorter. The largest difference between lengths was obtained for an ascending slope of 5%, a flowrate coefficient of variation of 5% and a backpressure of 0.49 kPa, and the difference was equal to 11.6 m (140.6 m subsurface and 152.2 m surface). The contrast in the maximum lateral line lengths between the TalDrip and D5000 driplines is due to the minor influence of the variation in pressure head and terrain slope on the flowrate on pressure-compensating emitters.

In general, the maximum lateral line lengths increased with increasing backpressure for both driplines. This trend occurred because the increase in backpressure reduced the flowrates of the emitters, which resulted in greater maximum length values.

This finding agrees with the results obtained by Yao et al. 2011 and Shani et al. 1996, who observed that the presence of backpressure results in decreased dripline discharge in subsurface conditions, especially in nonpressure-compensating emitters operating at low pressures. This decrease was evidenced in this study because the greatest difference in maximum lengths in the comparison between the highest and lowest backpressures occurred in the nonpressure-compensating TalDrip dripline, with a difference of 6.5 m. Under the same conditions, the difference was 3.7 m for the D5000 dripline.

For the D5000 dripline with a 5% descending slope, a flowrate variation of 20% and a backpressure of 16.86 kPa, the maximum lengths of the surface and subsurface laterals were 312.7 and 312.7 m, respectively. Therefore, in this case, the decrease in the flowrate of the pressure-compensating emitter was so significant that the length of the subsurface lateral became equal to the length of the surface lateral.

The correlation between the surface and subsurface lengths of the TalDrip and D5000 driplines is shown in Figure 2.

As shown in Figure 2, the lengths of the surface and subsurface laterals have a good correlation. The greater the surface lateral length is, the greater the subsurface lateral

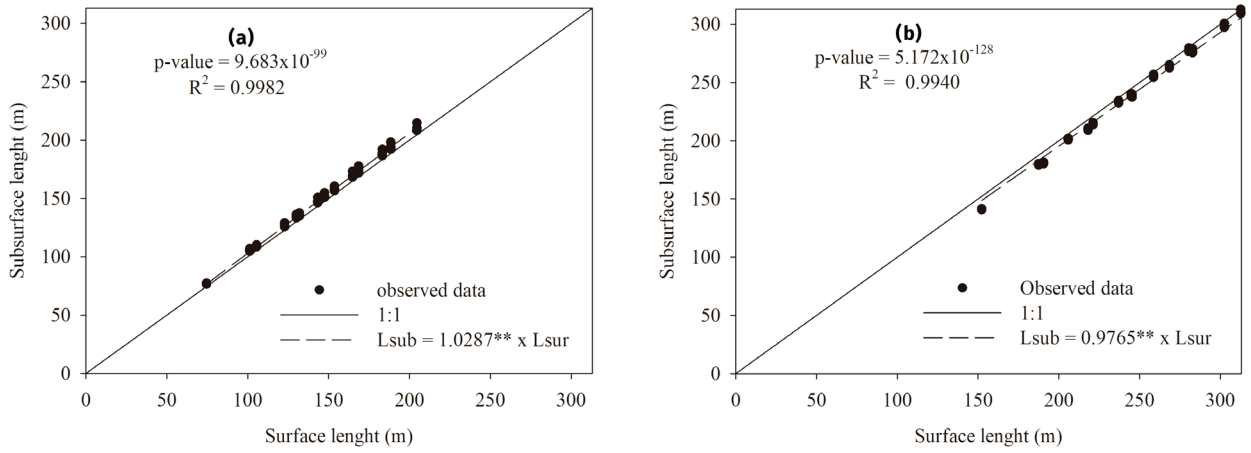

Figure 2. Correlation between the maximum surface and subsurface lengths obtained for the TalDrip (a) and D5000 (b) driplines under the different evaluated scenarios.

length for both driplines with steep descending slopes and permissible flowrate coefficients of variation. This result is not due to possible differences between discharge exponents but is related to the surface or subsurface installation conditions.

However, as previously observed, for the nonpressure-compensating emitter, the maximum subsurface length is longer than the maximum surface length, whereas for the pressure-compensating emitter, the subsurface length is shorter than the surface length. This difference can be explained by the change in the discharge exponent of the emitters between surface or subsurface conditions.

The flowrate of the emitters is a function of the operating pressure, which is elevated by the discharge exponent, and the closer it is to zero, the weaker is the influence of pressure on the emitter flowrate, which directly increases the lateral line length. Pressure-compensating drippers have a small discharge exponent, i.e., closer to zero, which hydraulically allows longer lateral lines (Prado et al. 2014), thus agreeing with the results found in this study.

According to Gil et al. 2008, nonpressure-compensating drippers, when used in subsurface conditions, tend to display behavior similar to flowrate compensation due to the backpressure.

Such behavior was observed by Thebaldi et al. 2016 in a study on the effect of backpressure on the hydraulics of subsurface drip emitters, in which the discharge exponent of the nonpressure-compensating TalDrip dripline decreased from 0.4154 to 0.394 with the presence of backpressure. The opposite behavior was found for the pressure-compensating D5000 dripline, which exhibited a discharge coefficient of 0.1053 in surface applications and 0.1320 in subsurface applications.

However, Gil et al. 2008 reported that, at a constant operating pressure, the variation in CV(q) in buried emitters depends not only on CVm but also on the presence of backpressure, in case of soils with low permeability the CV(q) is controlled mostly by physical and hydraulic characteristics. The relationship between the CVm and backpressure leads to smaller CV(q) values for nonpressure-compensating emitters in subsurface applications than those in surface applications, because they tend to self-regulate the flow rate.

Table V. Pearson's Correlation Indexes of subsurface driplines maximum length with slope, backpressure and CV(q).

Emitter	Slope	Backpressure	CV(q)
TalDrip	0.905	0.001	0.387
D5000	0.833	0.051	0.521

Thus, the behavior of the pressure head variation along a lateral, expressed by CV(H), is not as expected, thereby affecting the calculation of the maximum length of subsurface laterals and potentially resulting in erroneous values. It is necessary to know the flow-pressure curve, the technical information on the emitters in subsurface conditions, and the interaction between the emitters and the soil in order to design better irrigation lines in these cases.

In addition, in Table V are presented the Pearson's Correlation Indexes of maximum lateral lengths in subsurface condition of the studied driplines with the hydraulic variables slope, backpressure and CV(q).

As shown by the calculated Pearson's Correlation Indexes (Table V), the increase in backpressure does not influence the maximum length of the lateral lines as much as the slope and the permissible flowrate variation, given that the largest differences between the highest and lowest backpressures were obtained for the situations with the steepest descending slope and highest permissible CV(q). In contrast, under

the conditions with the steepest ascending slope and lowest CV(q), the differences between lengths were less than 1 m for both driplines.

According to the Pearson's Correlation Indexes obtained (Table V), the variation of the backpressure does not directly promote a great influence on the maximum length of the lateral lines of the studied driplines. However, the action of burying the drippers promotes a change in their discharge exponent, which leads to a change in the general hydraulic behavior of the lateral lines, explained by the flow-pressure relation of the driplines, as already discussed.

Additionally, the slope of the terrain influences the maximum length of the lateral lines of the TalDrip dripline compared to the D5000 (Table V), precisely because the first is nonpressure-compensating, which makes pressure variations more significantly affect the flowrates. On the other hand, due to its pressure-compensating constructive aspect, the design permission for greater flow variations along the lateral line, expressed by the CV(q), is less important for the D5000 dripline than for the TalDrip, when determining the maximum length drip irrigation lateral lines must have, in order to respect the designer-defined hydraulic variables.

CONCLUSIONS

The variables that most strongly influence the maximum length of lateral lines are, in order, terrain slope and permissible flowrate variation. The longest lateral lengths for the surface and subsurface irrigation conditions were obtained under steeper descending slope and higher CV(q) conditions. In contrast, under conditions with the steepest ascending slope and lowest CV(q), the shortest lengths were obtained for both cases.

For the evaluated scenarios and conditions of this study, the greatest variations in length were observed for the conditions with a descending slope of 5%, a CV(q) of 20% and the highest backpressure, with values of 5% for the TalDrip and zero for the D5000 driplines. Under conditions with an ascending slope of 5%, a CV(q) of 5% and the lowest backpressure, there was a variation of 3% and 8% for the TalDrip and D5000 driplines, respectively.

In the case of nonpressure-compensating emitters, the maximum lateral line length is longer in subsurface applications than in surface applications. However, for pressure-compensating emitters, in irrigation under the influence of backpressure, there is an increase in the discharge exponent due to the small flowrate difference between the surface and subsurface conditions. Thus, the surface laterals may be longer than the subsurface ones.

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How to cite
THEBALDI MS, RODRIGUES KV & TAMBO FLR. 2021. Maximum length of subsurface drip irrigation laterals subjected to backpressure. An Acad Bras Cienc 93: e20191338. DOI 10.1590/0001-3765202120191338.

Manuscript received on October 10, 2019;
accepted for publication on April 7, 2020

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Michael Silveira Thebaldi carried out the field experimentation, as well as the writing of the text, which was done with the contribution of the author Karina Vilela Rodrigues. Fidel Luís R. Tambo contributed to the production of graphic elements. All authors contributed to the data interpretation and analysis, discussion of results and production of graphic elements, in addition to approving the final version of the manuscript.