http://journal.unoeste.br/index.php/ca/index
DOI: 10.5747/ca.2022.v18.n4.a504
ISSN on-line 1809-8215

Colloquium Agrariae

Submetido: 30/11/2021 Revisado: 26/10/2022 Aceito: 16/11/2022

Fertilization recommendation for *Brassica oleracea* using Bulletin 100 is still valid after more than two decades

Milton de Albuquerque do Canto e Silva[1], Felipe Quartucci[2]

[1]Faculdade de Ensino Superior Santa Bárbara – FAESB, Tatuí, SP (in memorian). [2]Faculdade de Ensino Superior Santa Bárbara – FAESB, Tatuí. E-mail: prof.felipe.quartucci@faesb.edu.br

Abstract

The 4R Nutrient Stewardship is a concept that aims to optimize fertilization of agricultural crops, encompassing social, economic and environmental aspects. This concept involves 4 scientific principles (the right source of fertilizer, the right rate, the right timing and the right place) that should be defined based on local conditions and knowledge. This study aimed at determining best fertilization practices for broccoli in the region of Tatuí-SP in Brazil, using the 4R nutrient stewardship principles. Four experiments were installed, each one referring to a 4R principle, comparing the standard fertilization applied in the region with different management options. The recommended rate by the fertilization bulletin outperformed other rates we tested. An increase or decrease by 25% in the bulletin recommended rate led to a reduction in broccoli productivity. Mineral fertilizer source promoted highest growth, followed by a combination of mineral and organic. In regard to timing, the standard practice applied in the region, which is applying 100% of N and K at planting, did not differ from splitting the dose in 3 parcels. Lastly, applying the fertilizer in the planting row promoted better growth than broadcasting on the soil surface. The standard fertilization practiced in the region promoted the highest growth, although there are other possibilities in terms of timing and placement that also resulted in similar growth, and the decision should be made according to the reality of each farmer.

Keywords: broccoli; placement; rate; source; timing.

Recomendação de fertilização para *Brassica oleracea* usando o Boletim 100 ainda é válida após mais de duas décadas

Resumo

O Manejo de Nutrientes 4C é um conceito que visa otimizar a fertilização de culturas agrícolas, englobando aspectos sociais, econômicos e ambientais. Este conceito envolve 4 princípios científicos (a fonte certa de fertilizante, a dose certa, a época certa e o local certo) que devem ser definidos levando em conta condições e conhecimentos locais. Este estudo teve como objetivo determinar as melhores práticas de fertilização para brócolis na região de Tatuí-SP no Brasil, utilizando os princípios do manejo de nutrientes 4C. Foram instalados quatro experimentos, cada um referindo-se a um princípio 4C, comparando a fertilização padrão aplicada na região com diferentes opções de manejo. A dose recomendada pelo boletim de fertilização superou as outras doses testadas. Um aumento ou diminuição de 25% na dose causou uma redução na produtividade dos brócolis. A fonte que promoveu o maior crescimento foi a mineral, seguida por uma combinação de mineral e orgânico. Em relação à época, a prática padrão aplicada na região, que é aplicar 100% de N e K no plantio, não diferiu da divisão da dose em 3 parcelas. Por fim, a aplicação do fertilizante na linha de plantio promoveu melhor crescimento do que a aplicação na superfície do solo. A fertilização padrão praticada na região promoveu o maior crescimento, embora existam outras possibilidades em termos de época e local que também resultaram em crescimento semelhante, e a decisão deve ser tomada de acordo com a realidade de cada agricultor.

Palavras-chave: brócolis; dose; época; fonte; local.

1 Introduction

A great part of Brazilian soils is characterized by low natural fertility (COELHO *et al.*, 2014; POPPIEL *et al.*, 2019; PRADO *et al.*, 2012). In order to guarantee adequate nutrition for crops in such soils, there is a need to apply an external source of nutrient (BERNARDI; MACHADO, 2005). This is especially true for vegetables, due to their comparatively greater nutritional demand in a short period of time (SIMONNE *et al.*, 2017; TEI *et al.*, 2020). For broccoli (*Brassica oleracea*), the rates of accumulation of nitrogen (N) and potassium (K) are 110 and 85 kg ha^{-1} in less than 100 days, respectively, considering a density of 25,000 plants ha^{-1} (CECÍLIO FILHO *et al.*, 2017; MELO, 2015).

General recommendation sources are useful as a starting point for a fertilization plan, but they do not account for the whole plant nutrition system complexity. The 4R Nutrient Stewardship concept provides that the application of fertilizers should be employed at the right rate, with right source, the right timing and right place, aligning economic, social and environmental aspects of food production (BRUULSEMA *et al.*, 2009).

The right source implies that the fertilizer choice must take into consideration the crop needs and soil properties. Attention should be taken to the interaction of nutrients and their equilibrium in the soil. Moreover, the right source implies that the fertilizer should be easily available for the farmer and that takes production specificities into consideration, as for the case of organic farmers. The right rate means applying the dose demanded by the plant. Lower doses may be the main cause of reduced productivity, whereas over doses can also reduce productivity and result into environmental problems. The right time refers to providing nutrients to plants throughout their cycle according to their needs, that is, considering the peaks and avoiding losses during periods of reduced absorption. Finally, the right place means applying the fertilizer within a zone where plants can absorb. Soil-nutrient interactions and roots development must be taken into consideration in order to minimize fertilizer losses (CASARIN; STIPP, 2013; FIXEN, 2011; JOHNSTON; BRUULSEMA, 2014). Mikkelsen (2011) emphasizes that the adoption of specific practices and the recommendation of each of the 4Rs should be adjusted to individual field conditions, combining the scientific knowledge with local expertise.

The overall benefits of observing the 4R concept goes beyond an increase in plant productivity. The reduction of fertilizer rates can have a positive economic impact for the farmer, since fertilizer is one of the inputs responsible for the highest share of production costs (ARTUZO *et al.*, 2018; SOUZA; GARCIA, 2013). Further, appropriate fertilizer management can bring environmental benefits at a local and global scale. At the local scale, the adjustment of timing and placement can reduce the environmental impacts by decreasing the nutrients leaching (CLARK; TILMAN, 2017; GONZÁLEZ-CENCERRADO *et al.*, 2019). At the global scale, the sustainable use of fertilizer can contribute towards mitigation of climate change due to two main reasons: 1) N_2O emitted after nitrogen fertilization has a warming potential almost 300 times higher than CO_2, and a small reduction in the rate applied can contribute significantly to reduce emissions (MAZZETTO *et al.*, 2020; MONTOYA *et al.*, 2021) and, 2) the production of mineral fertilizer is highly energy demanding and the main source of energy where the fertilizer is produced is natural gas, thus promoting a high carbon footprint (WALLING; VANEECKHAUTE, 2020).

The sources of information for fertilization recommendation in Brazil are regional. In São Paulo, the state with the highest planted area with broccoli, bulletin 100 is the most common source of recommendation (MELO, 2015; RAIJ *et al.*, 1997). Bulletin 200 is an updated source, with inclusion of different crops, even though some were left out, as the example of broccoli (AGUIAR *et al.*, 2014). In the first one, the recommendation of nutrient rates is based on soil nutrient content ranges, whereas in the second one there is a more generalist recommendation that does not relate dose to a specific soil nutrient content.

Therefore, the available source of information that land managers and technicians employ is more than 2 decades old, and might not promote the highest productivity. Based on that, the general objective of this study was to determine best fertilization practices for broccoli in the region of Tatuí-SP. Aligned with 4R Nutrient Stewardship concept, specific objectives of this work were: 1) to determine the right dose of the macronutrients N, P and K; 2) to compare the growth response of broccoli to mineral, organic and interaction of both sources of fertilizers; 3) to test the effectiveness of splitting N and K in different ratios throughout the broccoli life cycle and; 4) to test the effect of different fertilizer placement on broccoli growth.

2 Material and Methods

The study was conducted in Tatuí-SP, Brazil. The Köppen climate classification is Cfa, with a mean annual precipitation of 1215 mm and a mean annual temperature of 19.8 °C (ALVARES *et al.*, 2013). The soil texture is 63.2% clay, 16.8% silt and 20.0% sand and the chemical characteristics before the experiment were: pH-$CaCl_2$ 5.1, aluminum 0 $mmol_c$ dm^{-3}, organic matter 34 g dm^{-3}, phosphorous (resin) 41 mg dm^{-3}, calcium 29 $mmol_c$ dm^{-3}, magnesium 17 $mmol_c$ dm^{-3}, potassium 3.1 $mmol_c$ dm^{-3}, cation exchange capacity 98.2 $mmol_c$ dm^{-3} and base saturation 50%.

The area had been long planted with banana, which was removed and remained in fallow during one year prior to the experiment establishment. We prepared the soil with harrowing, followed by subsoiling and then a leveling harrowing. We applied 3.2 mg ha^{-1} of dolomitic lime (90 effective calcium carbonate equivalents ECCE) 30 days prior to planting (before leveling harrowing) in order to achieve 80% base saturation (TRANI *et al.*, 1997).

We conducted four experiments, each one representing a R of the 4R nutrient stewardship concept (rate, source, timing and placement). All four experiments were carried out in a randomized block design, with five repetitions per treatment. The experimental plot had an area of 6.0 m², distributed in three rows with 5 plants, totaling 15 plants, at a spacing of 0.8 m between rows and 0.5 m between plants. Each experiment occupied 120 m² of land., and all four experiments totaled 480 m². All the experimental plots were planted on 30/05/2020 with seedlings produced in 128-cell trays, using the hybrid BRO 68 single inflorescence broccoli (*Brassica oleracea* var. *Italica*), which is the most common hybrid planted in the region due to its high potential productivity.

We tested different management alternatives in relation to the standard fertilization management applied by farmers in the region in four experiments, each one referring to one of the 4Rs. The standard fertilization rate was based on Bulletin 100 (TRANI *et al.*, 1997), the standard source of fertilizer was mineral, timing was the application of 100% of the dose at planting and placement was uniform spread of fertilizer along the planting row.

Experiment 1 referred to the right rate and the treatments were: 1) no fertilization (control); 2) full rate; 3) 75% of the recommended rate and; 4) 125% of the recommended rate. Experiment 2 referred to the right source and the treatments were: 1) no fertilization (control); 2) mineral fertilizers only; 3) organic source for P and K and mineral source for N; 4) organic sources only. Experiment 3 referred to the right timing. Phosphorous was applied 100% at planting and we split N and K in the following treatments: 1) 100% of the rate at planting; 2) 50% of the rate at planting and 25% at 15 and 30 days after planting; 3) 40% of the rate at planting and 30% at 15 and 30 days after planting; 4) 25% of the rate at planting and 25% at 15, 30 and 45 days after planting. Lastly, experiment 4 evaluated the placement R and the treatments were: 1) an individual dose applied in a 5-10 cm pit close to the plant; 2) an individual dose applied in the planting bed under the plant; 3) distributed uniformly in the planting row and; 4) broadcasted uniformly on the soil surface.

The fertilization rate used was 50 kg ha^{-1} of N, 350 kg ha^{-1} of P_2O_5 and 180 kg ha^{-1} of K_2O, based on Trani *et al.* (1997). The source of N, P and K was urea (45% N), simple superphosphate (18% P_2O_5) and potassium chloride (61% K_2O), respectively. In experiment 2, the source in treatment 3 was an organic formula 00-21-06 produced by Paulivida and urea as N source. In treatment 4, the same organic formula and castor bean cake as N source.

The experiments were sprinkler irrigated three times a week with 15 mm in days when there was no rainfall. We performed three manual weeding during the experiment. The harvest took place every second day from 08/20/2020 to 08/26/2020 with one experiment being harvested per day, in the following order: rate, source, timing and placement. The central three plants of the central row in each plot were cut and we measured the inflorescence green mass using a digital scale and the head diameter in the longest section using a caliper. We then calculated the inflorescence productivity by multiplying the inflorescence average mass by the plant population. Normality test was performed with Shapiro-Wilk test and all variables of experiment 1 and green mass and productivity of experiment 2 presented non-normal distribution, which were transformed according to Templeton (2011). We then performed ANOVA and *post hoc* Tukey test in order to determine statistical difference among the treatments within each experiment. All analysis were performed in SPSS version 28 at 5% significance level.

3 Results and Discussion

3.1 Right rate

The standard fertilization rate (100%) resulted in the higher average productivity, reaching 39,850 kg ha^{-1}. An increase by 25% in the rate resulted in an average productivity of 30,242 kg ha^{-1}, statistically different from the standard rate. Likewise, a reduction in 25% in the fertilization rate differed statistically from the full rate with 33,192 kg ha^{-1}. All treatments were statistically higher than the control, whose average reached 9,325 kg ha^{-1} (Figure 1). The results of green mass and diameter followed the same statistical pattern of productivity, where the full rate promoted the highest growth, followed by the treatments where there was a variation of 25% in the fertilization rate, whereas the broccoli in the control had the smallest growth (Table 1).

Figure 1. Broccoli productivity (kg ha^{-1}) according to the rate of fertilizer used. Error bars are ± 1 standard deviation. Different letters indicate statistically different averages (Tukey p<0,05).

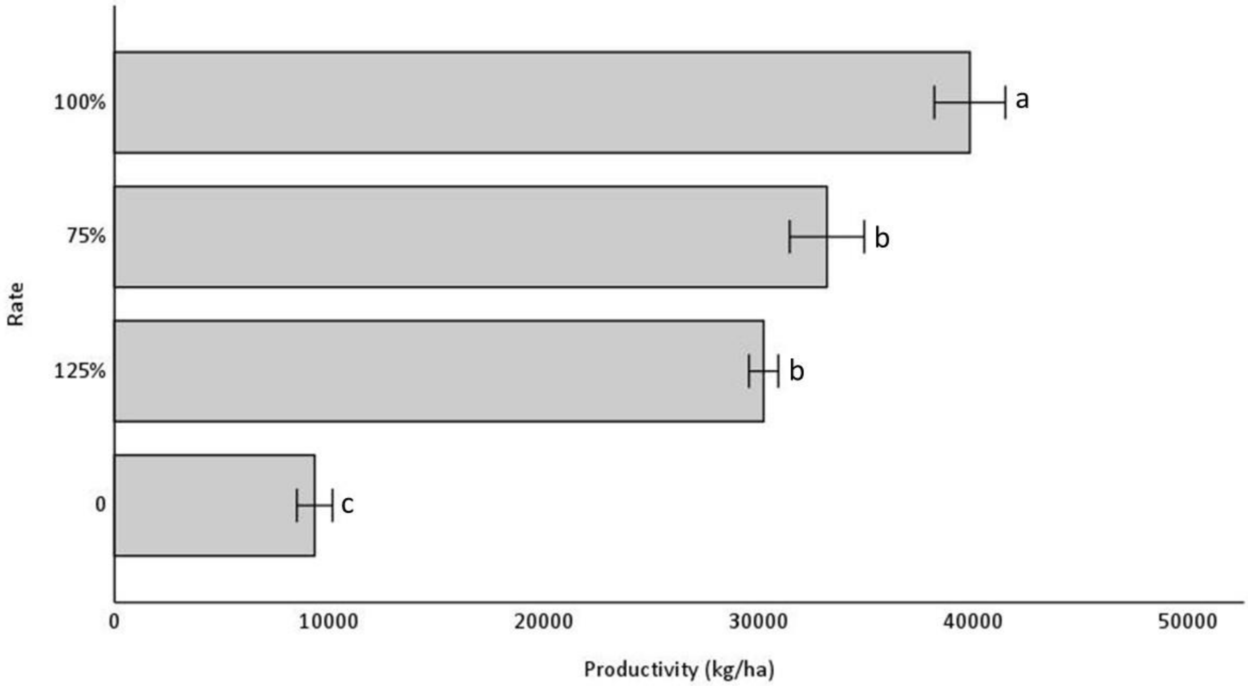

Table 1. Inflorescence green mass (g plant^{-1}) and diameter (cm) of broccoli according to the rate of fertilizer used. Averages followed by the same letter do not differ statistically column-wise (Tukey p<0.05).

Rate	Green mass (g plant^{-1})	Diameter (cm)
0	373 a	13.6 a
100%	1594 c	21.3 c
75%	1328 b	18.5 b
125%	1210 b	18.3 b
CV%	13.9	5.8

The most common sources of information for fertilization recommendation in the state of São Paulo are the bulletin 100 (RAIJ *et al.*, 1997), published in 1997 and its actualization bulletin 200 which is currently in the seventh version, published in 2014 (AGUIAR *et al.*, 2014).

However, in the bulletin 200 there is not recommendation for broccoli, and farmers mostly rely on bulletin 100. Interestingly, this recommendation of more than two decades ago resulted in the higher growth for broccoli. Genetic improvements in the last decades made broccoli achieve higher productivity (CHAVES JÚNIOR *et al.*, 2021; TREVISAN *et al.*, 2003; VIDAL NETO *et al.*, 2009) and one could expect higher nutrient demand. It could be that genetic improvements resulted into higher nutrient use efficiency, making the standard dose of decades ago still the most suitable.

Oliveira *et al.* (2016) tested four N doses (0, 150, 300 and 450 kg ha^{-1}) in broccoli in a clayish soil and found that the average green mass was higher in the dose of 150 kg ha^{-1}, with a small reduction in the 300 kg ha^{-1} dose and a high reduction in the 450 kg ha^{-1} dose. Even though the soil texture is similar from our study, the organic matter content was much lower (23 g dm^{-3}) than ours, which might explain the better results of our experiment with a much lower dose (50 kg ha^{-1}). In regard to K, Silva *et al.* (2016) found that the maximum broccoli yield was reached with a K_2O dose of 160 kg ha^{-1}, very close to our experiment that used the dose of 180 kg ha^{-1}.

The probability of a crop to respond to an increase in nutrient rate application depends on soil test levels (BORING *et al.*, 2018). In our study, the soil level of K and P prior to the experiment was high and medium, respectively (RAIJ, 2011a, 2011b). Likewise, organic matter levels were considered adequate, which might explain the absence of response to an increase in N dose (SOUSA; LOBATO, 2002).

3.2 Right source

Mineral fertilization promoted the highest productivity, reaching 36,797 kg ha^{-1}, followed by the combination of organic (P and K) and mineral sources (N). Applying only organic sources increased broccoli growth compared to no fertilization, but resulted in lower growth than mineral sources or a combination of organic and mineral (Figure 2). Broccoli green mass was 2.9, 3.4 and 4.2 times higher than control when organic, organic + mineral and mineral sources were applied, respectively. The diameter followed the same statistical pattern, with 21.3 cm for mineral and 17.2 cm for organic sources (Table 2).

Figure 2. Broccoli productivity (kg ha^{-1}) according to the source of fertilizer used. Error bars are ± 1 standard deviation. Different letters indicate statistically different averages (Tukey p<0,05).

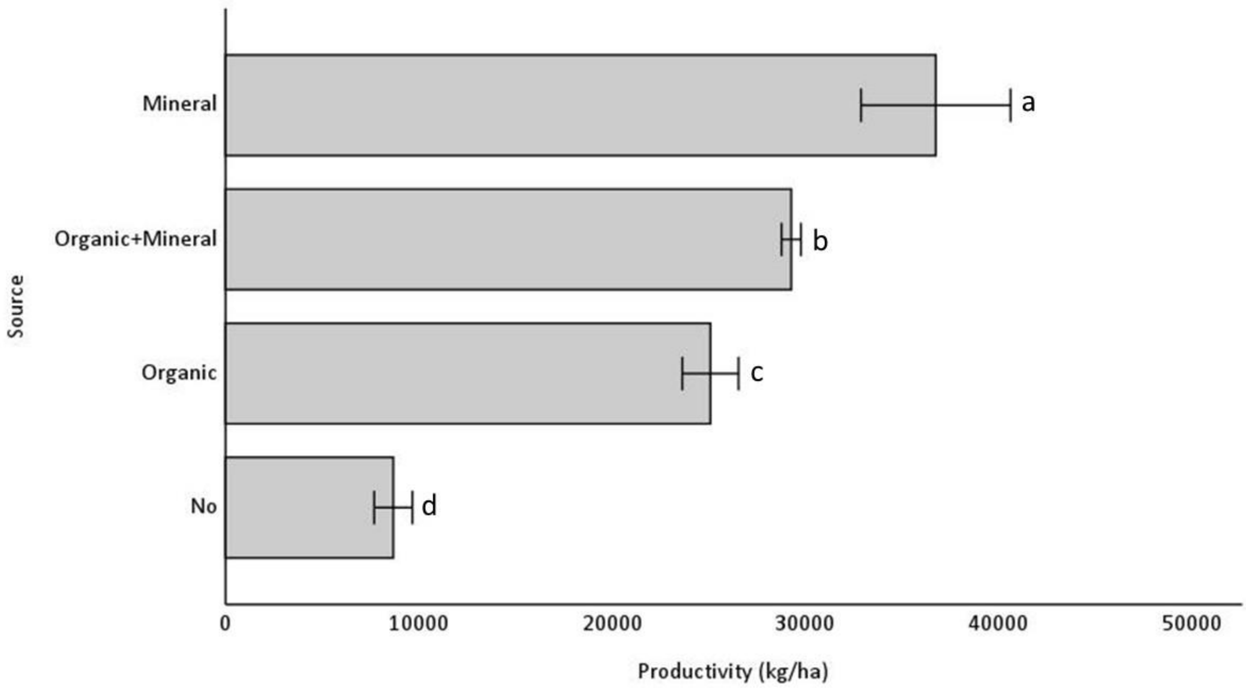

Table 2. Inflorescence green mass (g plant^{-1}) and diameter (cm) of broccoli according to the source of fertilizer used. Averages followed by the same letter do not differ statistically column-wise (Tukey $p<0.05$).

Source	Green mass (g plant^{-1})	Diameter (cm)
No	347 a	13.6 a
Mineral	1471 d	21.3 d
Organic+Mineral	1171 c	19.0 c
Organic	1004 b	17.2 b
CV%	12.5	3.3

There is not a clear trend on the response of broccoli to the source of fertilization applied. Sanwal *et al.* (2006) tested different organic fertilizers in broccoli and found higher head weight and diameter when cow, poultry or pig manure are used, in comparison to synthetic N fertilizer. On the other hand, Ouda and Mahadeen (2008) found that the fertilization with 40, 60 or 80 t ha^{-1} of manure did not increase productivity when compared to no fertilization. However, the combination of inorganic fertilizer at intermediate dose (30 kg ha^{-1} of N) with organic fertilizer had the same effect of high mineral N dose (60 kg ha^{-1}). Also, Cardoso *et al.* (2019) found a positive interaction when combining organic composts with mineral fertilizer, denoting their synergistic effect. In our work, the combination of organic PK and mineral N resulted in higher green mass than only organic source, but lower than only mineral sources. Since K is the second most demanded nutrient in broccoli (CECÍLIO FILHO *et al.*, 2017), the highest growth with only mineral source might have been due to the fastest and highest release of K from the mineral fertilizer (potassium chloride). Moreover, soil K content at the beginning of the experiment was considered intemediate, and crops respond to further addition of this nutrient in such cases (RAIJ, 2011a; RAIJ *et al.*, 1997).

Other factors rather than productivity must be taken into account when choosing the source of fertilizer and the residual effect on soil properties might help this decision. In broccoli, Sanwal *et al.* (2006) found higher organic matter content and pH when cow or poultry manure are applied, in comparison with synthetic N fertilizer. Ouda and Mahadeen (2008) found that the application of organic manure at 80 or 60 t ha^{-1} increased soil organic matter content and that mineral fertilizer did not have an effect on organic matter content. Yet, Cardoso *et al.* (2019) found that the application of organic compost in broccoli raised pH, in addition to increasing P, K and Ca contents. Chivenge *et al.* (2011) in a meta-analysis to evaluate the effects of organic, mineral and combined N sources on maize, found that the residual soil organic carbon (SOC) was 17% and 12% higher when organic and combined organic and mineral sources were used, respectively, compared to the control (no fertilization). On the other hand, mineral fertilization did not promote an increase in SOC.

3.3 Right timing

Applying 40% of fertilizer at planting and 30% at 15 and 30 days resulted in the highest productivity (42,425 kg ha^{-1}), although without statistical difference from applying 100% at planting or 50% at planting and 25% at 15 and 30 days after. Splitting the rate in 4 four times (0, 15, 30 and 45 days) did not prove to be a good timing strategy, since it differed statistically from the other treatments (Figure 3). Regarding diameter, there was no statistical difference among any timing regime applied (Table 3).

Figure 3. Broccoli productivity (kg ha^{-1}) according to the fertilization timing. Error bars are ± 1 standard deviation. Different letters indicate statistically different averages (Tukey p<0,05).

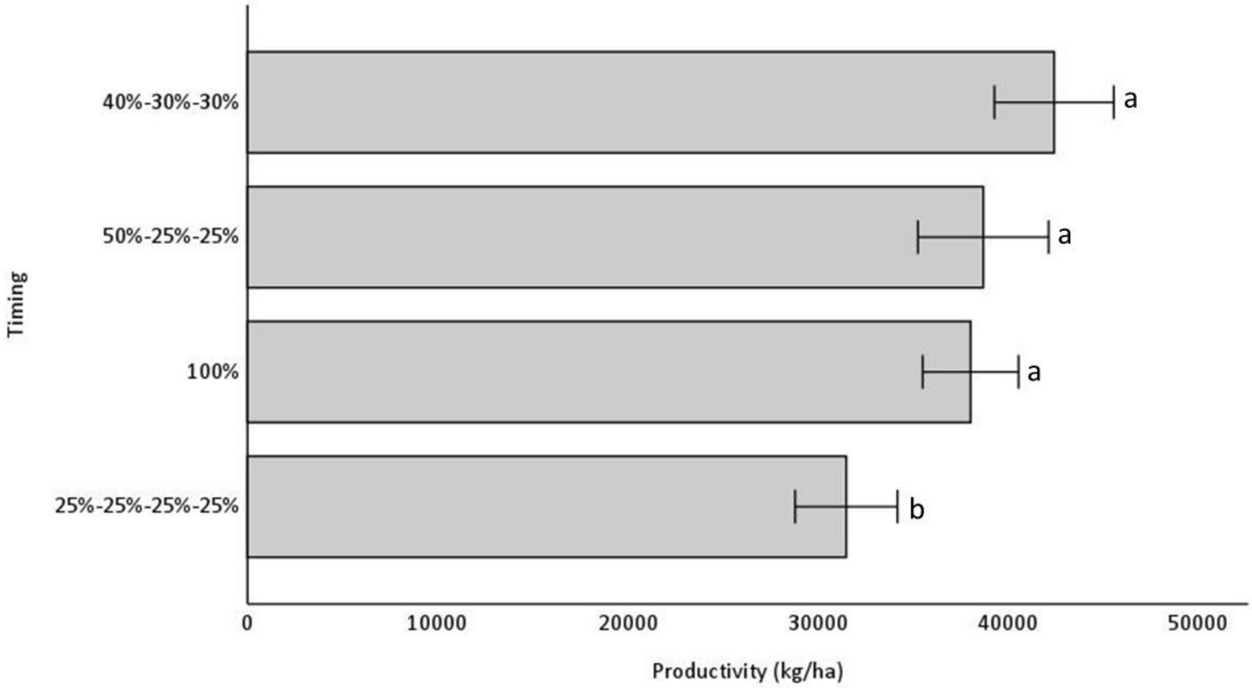

Table 3. Inflorescence green mass (g $plant^{-1}$) and diameter (cm) of broccoli according to the fertilization timing. Averages followed by the same letter do not differ statistically column-wise (Tukey p<0.05).

Timing	Green mass (g $plant^{-1}$)	Diameter (cm)
100%	1521 a	22.7 a
50%-25%-25%	1548 a	22.5 a
40%-30%-30%	1697 a	23.1 a
25%-25%-25%-25%	1260 b	21.6 a
CV%	6.2	3.2

The standard timing adopted was combining base and dressing fertilizer rates in only one application at planting. It seems that there is a trend towards higher productivity when splitting the fertilization in three times, even though it did not differ from the full rate at planting. Nevertheless, splitting the fertilization in four times resulted in lower productivity and inflorescence green mass. Even though there is a demand for K at the end of the broccoli life cycle due to the growth of the inflorescence, the total K demand remains stable after 55 days of planting (CECÍLIO FILHO *et al.*, 2017). Since K is a nutrient with high mobility within the plant (MEURER, 2006), the K demand from the inflorescence might have come from other parts of the plant. This might explain the lower productivity when a late application was performed (at 45 days in the 25-25-25-25 treatment).

Responsiveness to split application might depend on site conditions. Spackman *et al.* (2019) found that splitting N doses promoted a higher maize growth on a coarse-textured soil when compared to a fine-textured. In our study, the soil with high clay content might have avoided N losses through leaching in the single application treatment (100%), providing nutrients throughout the broccoli life cycle and thus maintaining a high productivity when compared to 3 times split application.

3.4 Right placement

Applying the fertilizer uniformly in the planting row or an individual dose in a pit 5-10 cm close to the plant resulted in the highest productivity, with 38,450 and 37,975 kg ha^{-1}, respectively. On the other hand, broadcasting the fertilizer on the soil surface resulted in the lowest productivity. Applying an individual dose in the planting bed under the plant did not differ from the other treatments (Figure 4). In regard to the diameter, the distribution of the fertilizer on the soil surface differed from the other treatments (Table 4).

Figure 4. Broccoli productivity (kg ha^{-1}) according to the fertilization placement. Error bars are ± 1 standard deviation. Different letters indicate statistically different averages (Tukey p<0,05).

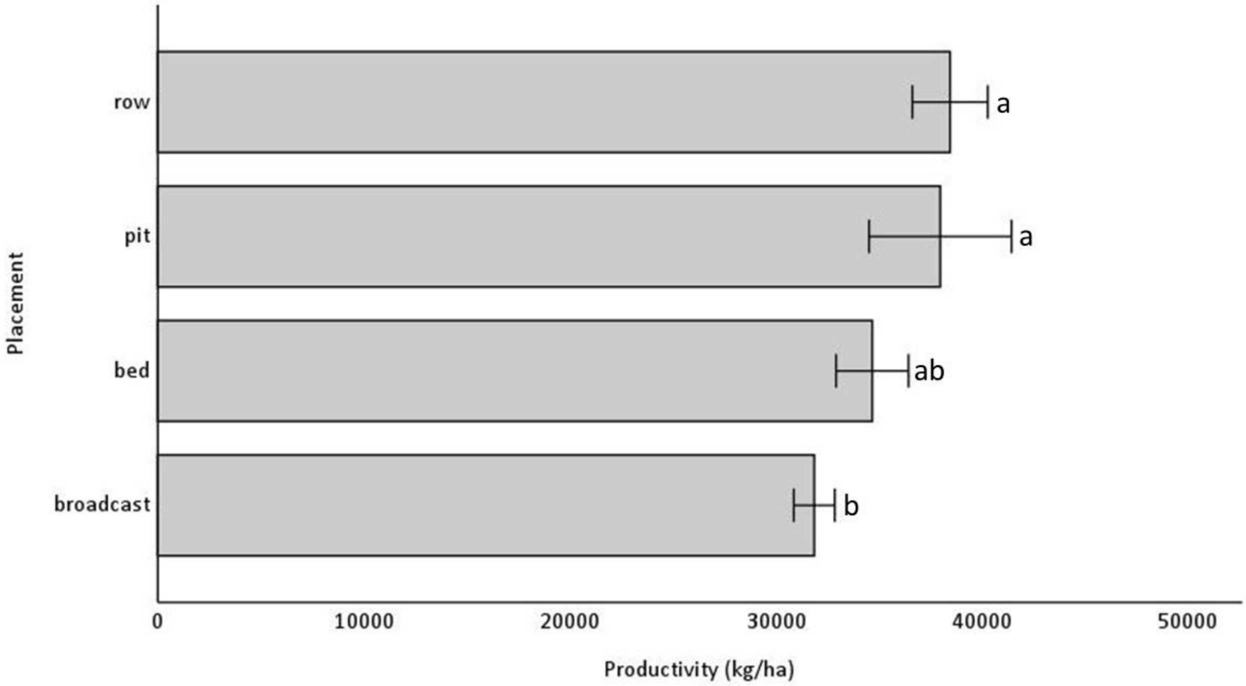

Table 4. Inflorescence green mass (g $plant^{-1}$) and diameter (cm) of broccoli according to the fertilization placement. Averages followed by the same letter do not differ statistically column-wise (Tukey test, p<0.05).

Placement	Green mass (g $plant^{-1}$)	Diameter (cm)
Pit	1519 a	22.6 a
Bed	1387 ab	22.5 a
Row	1538 a	21.4 a
Broadcast	1274 b	19.8 b
CV%	7.9	5.2

Fertilizer placement is usually an overlooked factor by land managers, even though it has an impact on nutrient acquisition and plant productivity (NKEBIWE *et al.*, 2016). Nasielski *et al.* (2020) found that placement was the factor with highest impact of N losses in maize, when compared with timing and source.

For vegetables, localized application have been recommended as an alternative to broadcast application as a way to increase productivity and improve environmental aspects, such as leaching and water bodies nitrification (SIMONNE *et al.*, 2017). Our study showed broadcasting fertilizers on the soil surface was not a good strategy, since broccoli productivity was lower than any other placement management. On the other hand, Weingartner *et al.* (2018) found no differences between fertilization applied in the planting row or broadcasted on the soil for onion, showing that fertilizer placement management dependents on several factors such as type of soil, climatic conditions, type of fertilizer used and species (ALMEIDA *et al.*, 2003; BARBOSA *et al.*, 2015;

SANTOS *et al.*, 2008).

Broadcasting P fertilizer can be used as an alternative when the goal is to build P soil, even though the doses required are higher (GRANT; FLATEN, 2019). However, in our study, broadcast fertilization caused a reduction in the broccoli growth probably due to reduced P availability, since the P application on the soil surface might have increased P fixation due to the higher contact of the fertilizer with the soil particles (ALMEIDA *et al.*, 2003; NOVAIS *et al.*, 2007; RAIJ, 2011b; URRUTIA *et al.*, 2013).

4 Conclusion

We applied the 4R nutrient stewardship concept for broccoli in a clayish soil by conducting four experiments, each one referring to a R (right rate, source, timing and placement). The recommendation based on the most common bulletin in the region proved to be the right rate. An increase or decrease by 25% in the rate reduced broccoli growth. Mineral fertilizer promoted the highest growth. Although the broccoli growth was lower when a combination of organic and mineral sources was used, it has the potential to improve soil characteristics. In regard to the right timing, any treatment that applied at least 40% of the total rate at planting resulted in higher growth. Broadcasting the fertilizer on the soil surface caused a reduction on growth and should be avoided. In general, the standard management applied in the region resulted in the highest productivity, although there is room for a refinement regarding source and timing, which can maintain the current productivity while improving ecological aspects such as nutrient leaching and lower carbon emissions, thus contributing to climate change mitigation.

Acknowledgements

This study is dedicated to Milton de Albuquerque do Canto e Silva (*in memorian*), the first author of this paper who is no longer with us. Milton have dedicated his life with passion and enthusiasm to the agriculture. We would also like to thank Wyclife Oluoch Agumba for the English review of the manuscript and for relevant technical comments. Finally, we thank the anonymous reviewer and editor for valuable comments.

References

AGUIAR, A. T. E.; GONÇALVES, C.; PATERNIANI, M. E. A. G. Z.; TUCCI, M. L. S.; CASTRO, C. E. F. **Boletim 200 - Instruções Agrícolas para as Principais Culturas Econômicas**. 7. ed. Campinas, SP: Instituto Agronômico de Campinas IAC, 2014. p.452.

ALMEIDA, J. A.; TORRENT, J.; BARRÓN, V. Cor de solo, formas do fósforo e adsorção de fosfatos em Latossolos desenvolvidos de basalto do extremo-sul do Brasil. **Revista Brasileira de Ciência do Solo**, v.27, n.6, p.985–1002, 2003. https://doi.org/10.1590/S0100-06832003000600003

ALVARES, C. A.; STAPE, J. L.; SENTELHAS, P. C.; GONÇALVES, J. L. M.; SPAROVEK, G. Köppen's climate classification map for Brazil. **Meteorologische Zeitschrift**, v.22, n.6, p.711–728, 2013. https://doi.org/10.1127/0941-2948/2013/0507

ARTUZO, F. D.; FOGUESATTO, C. R.; SOUZA, A. R. L.; SILVA, L. X. Costs management in maize and soybean production. **Revista Brasileira de Gestao de Negocios**, v.20, n.2, p.273–294, 2018. https://doi.org/10.7819/rbgn.v20i2.3192

BARBOSA, N. C.; ARRUDA, E. M.; BROD, E.; PEREIRA, H. S. Distribuição vertical do fósforo no solo em função dos modos de aplicação. **Bioscience Journal**, v.31, n.1, p.87–95, 2015. https://doi.org/10.3390/agronomy8090195

BERNARDI, A. C. C.; MACHADO, P. L. O. A. Uso agrícola dos solos do Brasil e balanço de nutrientes. *In*: NIELSON, H.; SARUDIANSKY, R. **Minerales para la agricultura en Latinoamérica**. Buenos Aires: CEPS, 2005. p.127–133.

BORING, T. J.; THELEN, K. D.; BOARD, J. E.; BRUIN, J. L.; LEE, C. D.; NAEVE, S. L.; ROSS, W. J.; KENT, W A.; RIES, L. L. Phosphorus and potassium fertilizer application strategies in corn–soybean rotations. **Agronomy**, v.8, n.9, p.1–12, 2018. https://doi.org/10.3390/agronomy8090195

BRUULSEMA, T.; LEMUNYON, J.; HERZ, B. Know your fertilizer rights. **Crops & Soils**, v.42, n.2, p.13–18, 2009.

CARDOSO, A. I. I.; SILVA, P. N. L.; COLOMBARI, L. F.; LANNA, N. B.L.; FERNANDES, D. M. Phosphorus sources associated with organic compound in broccoli production and soil chemical attributes. **Horticultura Brasileira**, v.37, p.228–233, 2019. https://doi.org/10.1590/s0102-053620190215

CASARIN, V.; STIPP, S. R. Quatro medidas corretas que levam ao uso eficiente dos fertilizantes. **Informações Agronômicas**, n.142, p.14–20, 2013.

CECÍLIO FILHO, A. B.; CARMONA, V. M. V.; SCHIAVON JUNIOR, A. A. Broccoli growth and nutrient accumulation. **Científica**, v.45, n.1, p.95–104, 2017. https://doi.org/10.15361/1984-5529.2017v45n1p95-104

CHAVES JÚNIOR, O. J.; ZEFFA, D. M.; CONSTANTINO, L. V.; GIACOMIN, R. M.; SIQUEIRA, R. G.B.; SILVA, G. A.B.; NOGUEIRA, A. F.; GONÇALVES, L. S.A.; VENTURA, M. U. Genetic variability among broccoli genotypes based on biochemical and molecular traits. **Horticultura Brasileira**, v.39, n.3, p.288–293, 2021. https://doi.org/10.1590/s0102-0536-20210307

CHIVENGE, P.; VANLAUWE, B.; SIX, J. Does the combined application of organic and mineral nutrient sources influence maize productivity? A meta-analysis. **Plant and Soil**, v.342, n.1–2, p.1–30, 2011. https://doi.org/10.1007/s11104-010-0626-5

CLARK, M.; TILMAN, D. Comparative analysis of environmental impacts of agricultural production systems, agricultural input efficiency, and food choice. **Environmental Research Letters**, v.12, n.6, p.064016, 2017. https://doi.org/10.1088/1748-9326/aa6cd5

COELHO, M. R.; FONTANA, A.; SANTOS, H. G.; PEREZ, D. V. O solo e a sustentabilidade agrícola no Brasil: um enfoque pedológico. **Boletim Informativo da SBCS**, p.30–37, 2014.

FIXEN, P. E. Balanço de nutrientes em terras cultivadas: um desafio global para o setor de fertilizantes. **Informações agronômicas**, n.133, p.1–6, 2011.

GONZÁLEZ-CENCERRADO, A.; RANZ, J. P.; JIMÉNEZ, M. T. L.F.; GAJARDO, B. R. Assessing the environmental benefit of a new fertilizer based on activated biochar applied to cereal crops. **Science of the Total Environment**, v.711, p.134668, 2019. https://doi.org/10.1016/j.scitotenv.2019.134668

GRANT, C. A.; FLATEN, D. N. 4R Management of Phosphorus Fertilizer in the Northern Great Plains. **Journal of Environmental Quality**, v.48, n.5, p.1356–1369, 2019. https://doi.org/10.2134/jeq2019.02.0061

JOHNSTON, A. M.; BRUULSEMA, T. W. 4R nutrient stewardship for improved nutrient use efficiency. **Procedia Engineering**, v.83, p.365–370, 2014. https://doi.org/10.1016/j.proeng.2014.09.029

MAZZETTO, A. M.; STYLES, D.; GIBBONS, J.; ARNDT, C.; MISSELBROOK, T.; CHADWICK, D. Region-specific emission factors for Brazil increase the estimate of nitrous oxide emissions from nitrogen fertiliser application by 21%. **Atmospheric Environment**, v.230, p.117506, 2020. https://doi.org/10.1016/j.atmosenv.2020.117506

MELO, R. A. C. **A cultura do brócolis**. Brasília: Embrapa, 2015.

MEURER, E. J. Potássio. *In*: FERNANDES, M. S.; SOUZA, S. R. DE; SANTOS, L. A. **Nutrição mineral de plantas**. Sociedade Brasileira de Ciência do Solo, 2006. p.281–298.

MIKKELSEN, R. L. The “4R” nutrient stewardship framework for horticulture. **HortTechnology**, v.21, n.6, p.658–662, 2011. https://doi.org/10.21273/HORTTECH.21.6.658

MONTOYA, M.; VALLEJO, A.; CORROCHANO-MONSALVE, M.; AGUILERA, E.; SANZ-COBENA, A.; GINÉS, C.; GONZÁLEZ-MURUA, C.; ÁLVAREZ, J. M.; GUARDIA, G. Mitigation of yield-scaled nitrous oxide emissions and global warming potential in an oilseed rape crop through N source management. **Journal of Environmental Management**, v.288, p.112304, 2021. https://doi.org/10.1016/j.jenvman.2021.112304

NASIELSKI, J.; GRANT, B.; SMITH, W,; NIEMEYER, C.; JANOVICEK, K.; DEEN, B. Effect of nitrogen source, placement and timing on the environmental performance of economically optimum nitrogen rates in maize. **Field Crops Research**, v.246, p.107686, oct. 2020. https://doi.org/10.1016/j.fcr.2019.107686

NKEBIWE, P.M.; WEINMANN, M.; BAR-TAL, A.; MÜLLER, T. Fertilizer placement to improve crop nutrient acquisition and yield: A review and meta-analysis. **Field Crops Research**, v.196, p.389–401, 2016. https://doi.org/10.1016/j.fcr.2016.07.018

NOVAIS, R. F.; SMYTH, T. J.; NUNES, F. N. Fósforo. *In*: NOVAIS, R. F.; VENEGAS, V. H. A.; BARROS, N. F.; FONTES, R. L. F.; CANTARUTTI, R. B.; LIMA, J. C. **Fertilidade do solo**. Sociedade Brasileira de Ciência do Solo, 2007. p.471-537.

OLIVEIRA, F. C.; GEISENHOFF, L. O.; ALMEIDA, A. C. S.; LIMA JUNIOR, J. A.; NIZ, A. I. S.; BARBIERO, D. F. Produtividade do brócolis de cabeça sob diferentes doses de adubação nitrogenada. **Revista Agrarian**, v.9, n.34, p.326–333, 2016.

OUDA, B. A.; MAHADEEN, A. Y. Effect of fertilizers on growth, yield, yield components, quality and certain nutrient contents in broccoli (*Brassica oleracea*). **International Journal of Agriculture and Biology**, v.10, n.6, p.627–632, 2008.

POPPIEL, R. R.; LACERDA, M. P.C.; SAFANELLI, J. L.; RIZZO, R.; OLIVEIRA, M. P.; NOVAIS, J. J.; DEMATTÊ, J. A.M. Mapping at 30 m resolution of soil attributes at multiple depths in midwest Brazil. **Remote Sensing**, v.11, n.24, 2019. https://doi.org/10.3390/rs11242905

PRADO, R. B.; BENITES, V.M.; POLIDORO, J. C.; GONÇALVES, C. E.; NAUMOV, A. Mapping soil fertility at different scales to support sustainable Brazilian agriculture. **International Journal of Biological, Biomolecular, Agricultural, Food and Biotechnological Engineering**, v.6, n.9, p.137–145, 2012.

RAIJ, B.V; CANTARELLA, H.; QUAGGIO, J.A.; FURLANI, A.M.C. **Recomendações de adubação e calagem para o Estado de São Paulo.** 2. ed. rev. atual. Campinas: Instituto Agronômico/Fundação IAC, 1997. p.285.

RAIJ, B.V. Potássio. *In*: RAIJ, B.V. **Fertilidade do solo e manejo de nutrientes**. Piracicaba: International Plant Nutrition Institute IPNI, 2011a. p.249–264.

RAIJ, B.V. Fósforo. *In*: RAIJ, B.V. **Fertilidade do solo e manejo de nutrientes**. Piracicaba: International Plant Nutrition Institute IPNI, 2011b. p.217–248.

SANTOS, D. R.; GATIBONI, L. C.; KAMINSKI, J. Fatores que afetam a disponibilidade do fósforo e o manejo da adubação fosfatada em solos sob sistema plantio direto. **Ciencia Rural**, v.38, n.2, p.576–586, 2008. https://doi.org/10.1590/S0103-84782008000200049

SANWAL, S. K.; LAXMINARAYANA, K.; YADAV, D. S.; RAI, N.; YADAV, R. K. Growth, yield, and dietary antioxidants of broccoli as affected by fertilizer type. **Journal of Vegetable Science**, v.12, n.2, p.13–26, 2006. https://doi.org/10.1300/J484v12n02_03

SILVA, A. L. P.; CECÍLIO FILHO, A. B.; MENDOZA-CORTEZ, J. W.; LIMA JUNIOR, J. A. Potassium fertilization of cauliflower and broccoli in a potassium-rich soil. **Ciencia e Investigacion Agraria**, v.43, n.1, p.151–157, 2016. https://doi.org/10.4067/S0718-16202016000100014

SIMONNE, E. H.; GAZULA, A.; OZORES-HAMPTON, M.; DEVALERIO, J.; HOCHMUTH, R. C. Localized application of fertilizers in vegetable crop production. *In*: TEI, F.; NICOLA, S.; BENINCASA, P. **Advances in research on fertilization management of vegetable crops**. Cham: Springer, 2017. p.149–181. https://doi.org/10.1007/978-3-319-53626-2_6

SOUSA, D. M. G.; LOBATO, E. **Cerrado: correção do solo e adubação**. Planaltina: Embrapa Cerrados, 2002. p.416.

SOUZA, J. L.; GARCIA, R. D. C. Custos e rentabilidades na produção de hortaliças orgânicas e convencionais no Estado do Espírito Santo. **Revista Brasileira de Agropecuária Sustentável**, v.3, n.1, p.11–24, 2013. https://doi.org/10.21206/rbas.v3i1.183

SPACKMAN, J. A.; FERNANDEZ, F. G.; COULTER, J. A.; KAISER, D. E.; PAIAO, G. Soil texture and precipitation influence optimal time of nitrogen fertilization for corn. **Agronomy Journal**, v.111, n.4, p.2018–2030, 2019. https://doi.org/10.2134/agronj2018.09.0605

TEI, F.; NEVE, S.; HAAN, J.; KRISTENSEN, H. L. Nitrogen management of vegetable crops. **Agricultural Water Management**, v.240, p.106316, jan. 2020. https://doi.org/10.1016/j.agwat.2020.106316

TEMPLETON, G. F. A two-step approach for transforming continuous variables to normal: Implications and recommendations for IS research. **Communications of the Association for Information Systems**, v.28, n.1, p.41–58, 2011. https://doi.org/10.17705/1CAIS.02804

TRANI, P. E.; TRANI, P. E.; PASSOS, F. A.; TAVARES, M.; AZEVEDO FILHO, J A. Brócolos, couve-flor e repolho. In: RAIJ, B.; CANTARELLA, H.; QUAGGIO, J.A.; FURLANI, A.M.C. **Recomendações de adubação e calagem para o Estado de São Paulo**. Campinas: IAC, 1997. p.175.

TREVISAN, J. N.; MARTINS, G. A. K.; DAL'COL LÚCIO, A.; CASTAMAN, C.; MARION, R. R.; TREVISAN, B. G. Rendimento de cultivares de brócolis semeadas em outubro na região centro do Rio Grande do Sul. **Ciência Rural**, v.33, n.2, p.233–239, 2003. https://doi.org/10.1590/S0103-84782003000200009

URRUTIA, O.; GUARDADO, I.; ERRO, J.; MANDADO, M.; GARCÍA-MINA, J. M. Theoretical chemical characterization of phosphate-metal-humic complexes and relationships with their effects on both phosphorus soil fixation and phosphorus availability for plants. **Journal of the Science of Food and Agriculture**, v.93, n.2, p.293–303, 2013. https://doi.org/10.1002/jsfa.5756

VIDAL NETO, F. DAS C.; BERTINI, C. H. C. de M.; ARAGÃO, F. A. S.; CAVALCANTI, J. J. V. O melhoramento genético no contexto atual. **I Simpósio Nordestino de Genética e Melhoramento de Plantas**. Fortaleza-CE: Sociedade Brasileira de Melhoramento de Plantas – Regional Ceará; Embrapa Agroindústria Tropical, 2009. p. 210.

WALLING, E.; VANEECKHAUTE, C. Greenhouse gas emissions from inorganic and organic fertilizer production and use: A review of emission factors and their variability. **Journal of Environmental Management**, v.276, p.111211, 2020. https://doi.org/10.1016/j.jenvman.2020.111211

WEINGARTNER, S.; GATIBONI, L. C.; DALL'ORSOLETTA, D. J.; KURTZ, C.; MUSSI, M. Rendimento de cebola em função da dose e do modo de aplicação de fósforo. **Revista de Ciencias Agroveterinarias**, v.17, n.1, p.23–29, 2018. https://doi.org/10.5965/223811711712018023