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Agronomic and Economic Interactions between Sidedressed Nitrogen and Potassium Fertilizations on 'Atlantic' Potato

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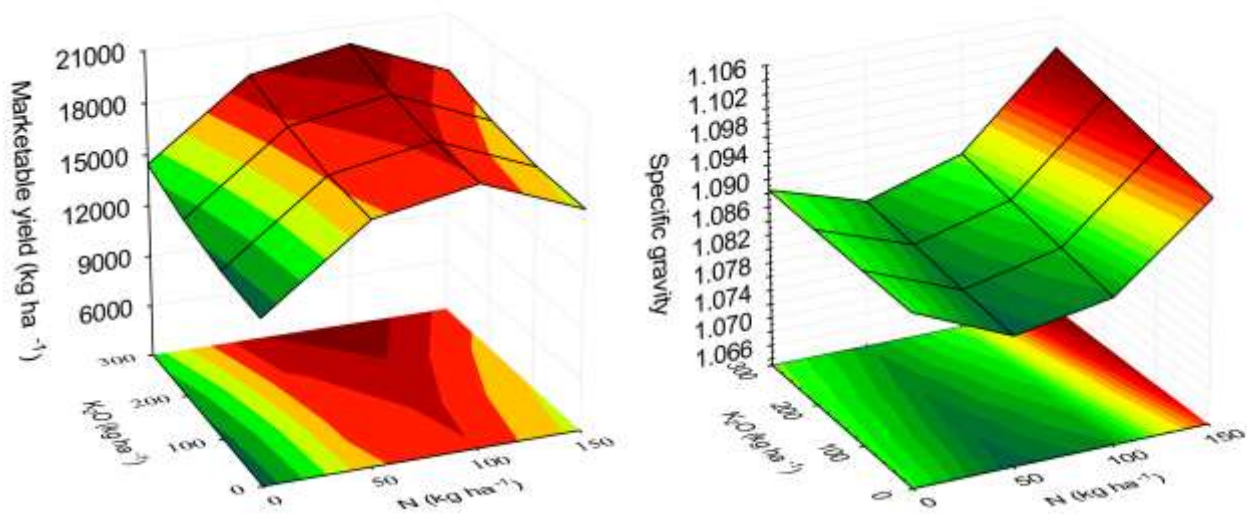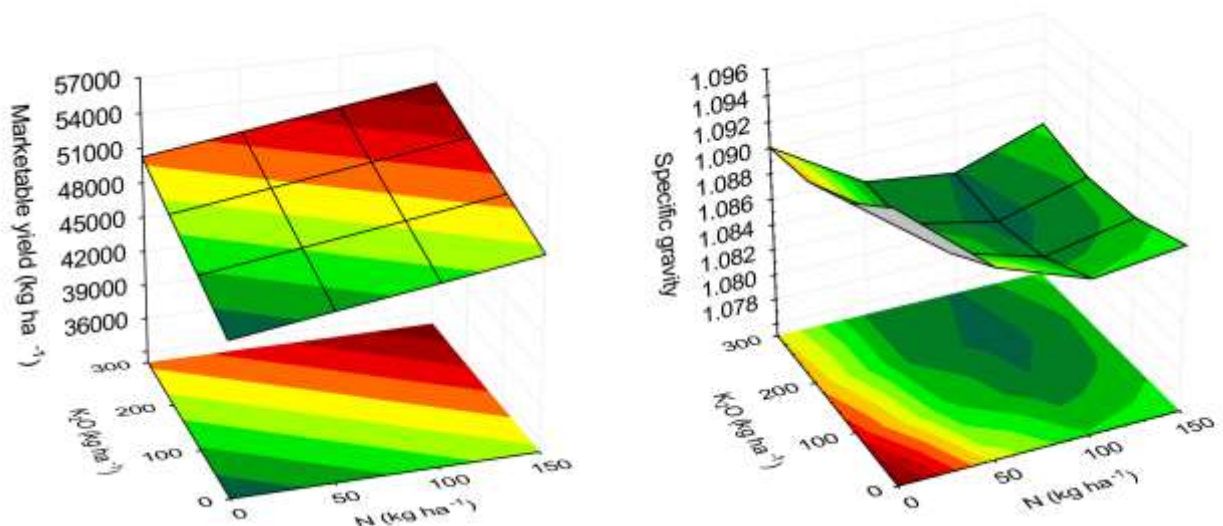*Correspondence: ryagi@idr.pr.gov.br; Tel.: +55-42-3219 9700 (R.Y.)

HIGHLIGHTS

- N and K are the nutrients taken up in greatest amounts by potato crop.

- Reported N×K interaction at planting also exists in the sidedress fertilization.

- N×K interaction in the sidedress fertilization is classified as Liebig-synergism.

- Joint N and K application as sidedressing is more profitable than their application at planting.

Abstract: Nitrogen (N) and potassium (K) in potato crop planting synergistically increase tuber yield, but there are no studies on this interaction in sidedressing. In two experiments with 'Atlantic' potato combinations of four N rates (0, 50, 100, and 150 kg ha^{-1}) with four K_2O rates (0, 100, 200, and 300 kg ha^{-1}) were applied in sidedressing in a 4×4 factorial scheme with three replications in a completely randomized design. Adjacent commercial fields were sampled to economic comparisons with experimental results. Significant interaction between N and K sidedressing rates with tuber yields increase also was confirmed and classified as Liebig-synergism. Compared to the isolated N and K applications in sidedressing, joint N and K fertilizations, respectively, increases by 11% and 48% marketable tuber yields in the summer-fall experiment, and 12% and 7% in the spring experiment. Joint N and K applications as sidedressing was more profitable than planting fertilization, mainly at higher N and K rates. The response of specific gravity of 'Atlantic' potato tubers to the N and K sidedressing rates was mediated by interactions between edaphoclimatic conditions and inputs of N and K. The combined application of N and K sidedressing rates increased specific gravity in the summer-fall experiment, but had a negative effect in the spring experiment. Therefore, our results provide strong evidence that the fertilization management for potato crop in Brazil can be modified by applying higher amounts of N and K in sidedressing to match nutritional needs of the crop.

Keywords: *Solanum tuberosum*; mineral nutrition; synergistic effect.

GRAPHICAL ABSTRACT

N×K INTERACTIONS

Summer-fall growing season

Spring growing season

INTRODUCTION

The N and K are the nutrients taken up in greatest amounts by potato (*Solanum tuberosum* L.) plants [1-3] and suitable rates at planting synergistically increase potato yield [4-8]. However, unbalanced fertilization with N and K at planting can also reduce yield [6], specific gravity (SG) [4] or dry matter (DM) content of tubers, depending on potato genotype [9]. Excessive N and K applications reduce SG due to the increased water content of tubers to cell turgor maintenance against negative osmotic salt potential [6]. Tubers with higher water content absorb greater oil amounts during frying process due to heating and water evaporation [10], and high N and inadequate K supply increase acrylamide-forming potential in fried potatoes, a probable carcinogenic substance [11].

'Atlantic' potato, the most used cultivar for the chipping industry in Brazil, takes up K and N at maximum daily accumulation rates of 5.0 and 1.8 kg ha^{-1} day^{-1}, respectively, during tuber bulking stage [2]. The dilution curves of N and K in the total DM of potato plants are proportional, indicating that the N concentration in plant tissues increases as K concentration increases and vice versa [12]. In potato plants, N is a primary component of nucleic acids, proteins and amino acids whereas K acts in the osmoregulation, in the activation of some enzyme systems, and in the translocation of carbohydrates [1]. Nitrogen × K interaction depends on the form of N supply and levels of both nutrients, existing antagonism between ammonium (NH_4^+) and exchangeable K (K^+) due to similar charges and hydrated diameters, competing to the same binding sites of

carriers [13]. Antagonistically, NH_4^+ toxicity can be diminished by K uptake, while co-operative uptake, internal transport, and utilization occurs between K^+ and nitrate (NO_3^-) [14]. On the other hand, the presence of chlorine (Cl) and magnesium (Mg) in the soil, respectively, increases NO_3^- and K^+ demands by potato plants, favoring synergistic effects of N and K on the tuber yields [4,15]. Both, N and K affect the SG of potato tubers with a synergistic effect between them, although the most pronounced effect is that of N [4]. The addition of excessive amounts of N or K, particularly as high salinity sources, like KCl, reduces the solid content in potato tubers [16]. Joint applications of N and K increased the water demand to maintain the cell turgor pressure against increasing the negative potential of solutes, and thus having an additive effect on the reduction of tuber SG [6].

Nitrogen and K also interact in the soil. On one hand, presence of N may decrease K^+ leaching due to increase of plants uptake; on the other hand, N fertilization with urea may increase K^+ leaching due to its displacement to soil solution by Ca^{2+} and Mg^{2+} also displaced by protons produced with nitrification [13]. Fertilizer recommendations for the potato crop in Brazil indicate massive applications of N and K in the planting furrows, along with all P fertilizer, and N sidedressing before hilling [17-18]. Brazilian potato farmers traditionally have used high fertilizer rates at planting (e.g., 3-4 Mg ha^{-1} 4-14-8 N-P_2O_5-K_2O, regardless of soil fertility), to prevent lack of nutrients for the plants and consequent financial profitability drop [19]. This traditional fertilization practice is not in accordance to the initial nutritional demands of the 'Atlantic' potato cultivar, which takes up only 16% N and 20% K before tuber initiation [2]. Under in vitro conditions, increasing the availability of both nutrients increased microtuber number and decrease microtuber size [20], while the large and medium tuber yields were increased and small and very small sized tuber yields were decreased in field conditions [7]. Grade tuber weight increase with increase of both N and K rates at planting but decrease peeling losses, a very important character for chipping industry [6].

Thus, we hypothesized that: a) a certain combination of N and K sidedressing rates can increase yield and quality of 'Atlantic' potato tubers, and b) rates of N and K similar to that traditionally used but distributed according to phases of nutritional requirements increase profitability. The objective of this study was to evaluate the effect of combined N and K rates as sidedressing on yield and quality of marketable tubers of 'Atlantic' potato grown in the summer-fall and spring growing seasons, as well as to compare economically similar N and K amounts in split application and in traditional full application at planting furrow.

MATERIAL AND METHODS

Site characteristics

Two field experiments were carried out in the summer-fall (January 16th to May 16th) and spring (September 08th to December 07th) growing seasons of 2013, in commercial areas of potato production. The experiments were performed, respectively, in a clayey Oxisol in Lapa (49°43'8" W, 25°46'15" S, 942 m a.s.l.) and in a sandy loam Inceptisol in Palmeira (49°59'60"W, 25°26'3"S, 867 m asl), south-central region of Paraná State, southern Brazil. According to the Köppen classification system, the region has a Cfb climate. Weather conditions were monitored from weather stations in Lapa municipality (summer-fall growing season) and Ponta Grossa municipality (distant 40 km of the experimental area in the spring growing season), representing the regional climatic conditions for the experiments (Figure 1). Before initiating each experiment, the chemical [21] and textural [22] characteristics of the topsoil (0–0.20 m depth) were evaluated (Table 1). The soil was tilled with chiseling, plowing, and light harrowing on the day before planting.
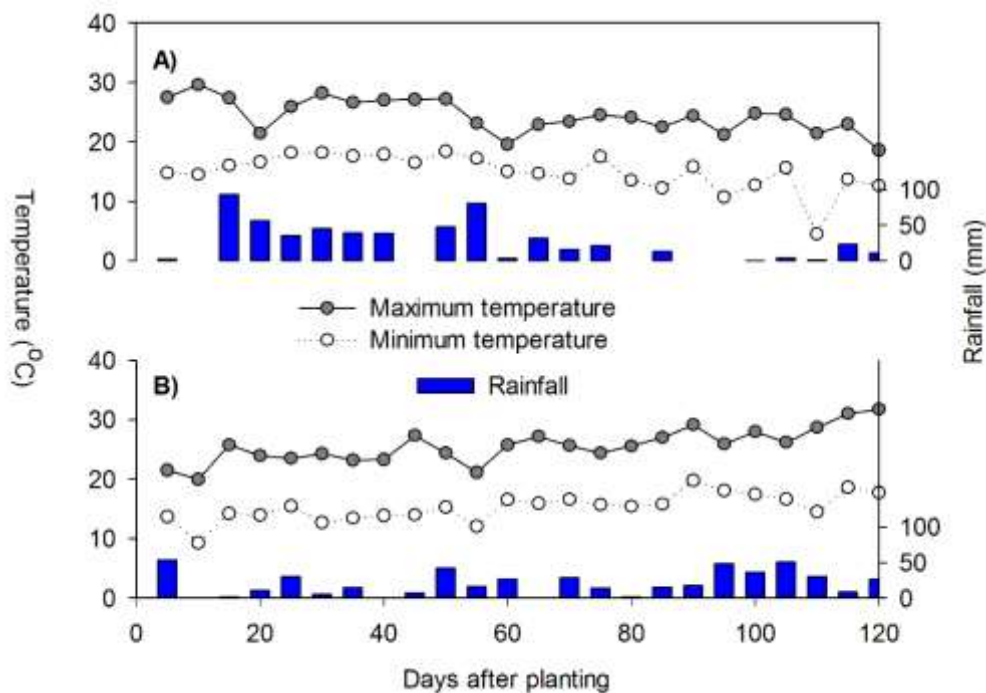
Figure 1. Maximum (grey circles) and minimum (white circles) temperature and rainfall (black bars) for each period of five days in the summer-fall (A) and in the spring (B) growing seasons from planting to harvesting dates, during February to May 2013 and September to December 2013, respectively.

Table 1. Chemical and textural characteristics of the soils at the experimental sites before the potato planting.

Growing season	pH[a]	P[b]	C[c]	Ca[d]	Mg[d]	K[d]	V[e]	Clay	Sand
		mg dm^{-3}	g dm^{-3}	——— cmol$_c$ dm^{-3} ———			%	——— g kg^{-1} ———	
Summer-fall	5.1	27.5	33.4	7.8	3.7	0.16	62	451	356
Spring	5.1	42.2	18.6	5.8	1.2	0.26	63	244	642

[a]1:2.5 soil/CaCl$_2$ suspension 0.01 mol L^{-1} CaCl$_2$ extractor; [b] Mehlich-1 extractor; [c]Walkley and Black method; [d]KCl 1 mol L^{-1} extractor; [e]V is base saturation index.

Crop management, treatments, and measurements

Planting were mechanically carried out on 16 January 2013 in the summer-fall growing season and on 10 August 2013 in the spring growing season, with 0.80-m spacing between furrows. Uncut type III seed tubers (approximately 35 g in mass) of cultivar Atlantic were hand planted with 0.35 m apart between seed tubers within rows. At planting, all plots received 1.4 Mg ha^{-1} of 6-30-6 NPK fertilizer (84 kg ha^{-1} N, 420 kg ha^{-1} P$_2$O$_5$, and 84 kg ha^{-1} K$_2$O) in both growing seasons. Phosphorus rate was based on the P$_2$O$_5$ rate traditionally used by Brazilian potato growers (420 kg ha^{-1} P$_2$O$_5$ in 3.0 Mg ha^{-1} of 4-14-8 NPK fertilizer). Thus, the N and K planting rates in this study were consistent with the potato crop recommendations in Paraná State, Brazil [18], but less than the traditionally fertilizer usage of 120-160 kg ha^{-1} N and 240-320 kg ha^{-1} K$_2$O used by Brazilian potato growers [19].

Plots consisted of four 5.0-m-long rows, and the three central rows were considered for data collection; the 0.5 m at each end of each row and the two outer rows of the plot were considered borders. At 30 and 35 days after planting (DAP), respectively, in the summer-fall and spring seasons, a combination of four N rates (0, 50, 100, and 150 kg ha^{-1}, as ammonium sulfate) and four K$_2$O rates (0, 100, 200, and 300 kg ha^{-1}, as potassium chloride) were weighed, pre-mixed, and uniformly sidedressed by hand immediately before hilling. Ammonium sulfate was used because it is the major N source preferred on 'Atlantic' potato by farmers and in the studies with potato crop in Brazil [23-25], and considering the low demands of 7 to 8 kg ha^{-1} S by cultivar Atlantic [2].

Irrigation was not used and diseases and insect control followed the technical recommendations for the crop and the criteria adopted by the growers. Potato vine killing was performed using the herbicide Diquat (330 g a.i. ha^{-1}) at 90 DAP and 95 DAP for the experiments in summer-fall and spring growing season, respectively. In both experiments, the two centermost rows were machine harvested at 120 DAP. Tubers were weighed and marketable tuber (> 45 mm diameter) yield (MY) was separated from unmarketable tubers

(< 45 mm diameter), with the aid of a scale and a classification table. From each plot, 10 randomly marketable tubers were sampled to estimate the average SG [SG = weight in air / (weight in air strength – weight in water)]. In each growing season four replicates of plots of same dimensions were randomized collected in adjacent commercial fields, in order to compare the MY in conventionally fertilized plants. In these areas, traditional fertilization criteria, with 3.0 Mg ha^{-1} of 4-14-8 NPK and 60 kg ha^{-1} ammonium sulfate-N as sidedressing, were used.

Calculations and statistical analysis

In both experiments, the experimental design was a randomized complete block with a 4 × 4 factorial scheme and three replications. Data analysis was performed separately for each experiment because soil attributes (Table 1) and weather conditions (Figure 1) in each experiment were very different. The N and K fertilizer rates were considered fixed effects. The blocks and all of the block interactions were considered random effects. Dependent variable results were fitted to surface responses with multiple regressions according to determination coefficients and P values, using Sigmaplot 12.0 software.

The interaction between N and K sidedressing rates in both growing seasons was evaluated according to the equation 1 [26].

$$\frac{MY_{NK}}{MY_0} = \frac{MY_N}{MY_0} \times \frac{MY_K}{MY_0} \qquad (1)$$

$$\text{(C)} \qquad \text{(A)} \qquad \text{(B)}$$

Where MY_{NK} = marketable tuber yield with optimal N and K sidedressing rates; MY_0 = marketable tuber yield in the control treatment; MY_N = marketable tuber yield with only optimum N sidedressing rate and MY_K = marketable tuber yield with only optimum K sidedressing rate. The N×K interaction with sidedress fertilization was classified as synergism, antagonist, zero-interaction or Liebig-synergism if respectively C>A+B, C<A+B, C=A+B and C>A+B with C≈A or C≈B.

With the yields from adjacent commercial fields, where the fertilization was 180 kg ha^{-1} N, 420 kg ha^{-1} P_2O_5 and 240 kg ha^{-1} K_2O, extrapolations were made based on the equations from the surface responses (i.e., 96 kg ha^{-1} N and 156 kg ha^{-1} K_2O). Thus, MY with similar NPK amounts and with best combinations of N and K rates sidedressing were economically compared between experiments and adjacent commercial fields. This referred to the differences between total N and K_2O used in commercial fields and of these elements (84 kg ha^{-1} each) applied at planting time, in both experiments. Economic calculations were made based on the values paid, or received, by the potato farmers for the different fertilizer formulas, as of R$ 1,360.00 Mg^{-1} for 4-14-8 NPK, R$ 1,800.00 Mg^{-1} for 6-30-6 NPK, R$ 1,365.72 Mg^{-1} for ammonium sulphate, R$ 1,900.11 Mg^{-1} for potassium chloride, and R$ 1,300.00 Mg^{-1} as price of marketable tubers sold.

RESULTS AND DISCUSSION

Marketable tuber yield

The average MY was 68% lower in the summer-fall (15,924 kg ha^{-1}; Figure 2A) compared to the spring growing season experiment (49,844 kg ha^{-1}; Figure 2B). In the spring growing season, mean temperatures and rainfall volumes were 13% and 26% higher, respectively, after 40 DAP (i.e., tuberization period) than for the summer-fall experiment (Figure 1). This may explain the differences found for MY. Yorinori [3] also observed larger (48%) total yield of 'Atlantic' potato tubers in the spring experiment (35,500 kg ha^{-1}) than in the summer-fall experiment (24,000 kg ha^{-1}), with higher demand for N in the spring, and higher for K in the summer-fall experiment, respectively.

A)

$$MY = 12353 + 123.23x + 1.30y - 0.67x^2 - 0.0018xy + 0.02y^2$$
$$R^2 = 0.80*$$

B)

$$MY = 42726 - 43.11x - 5.24y - 0.39x^2 - 0.031xy + 0.06y^2$$
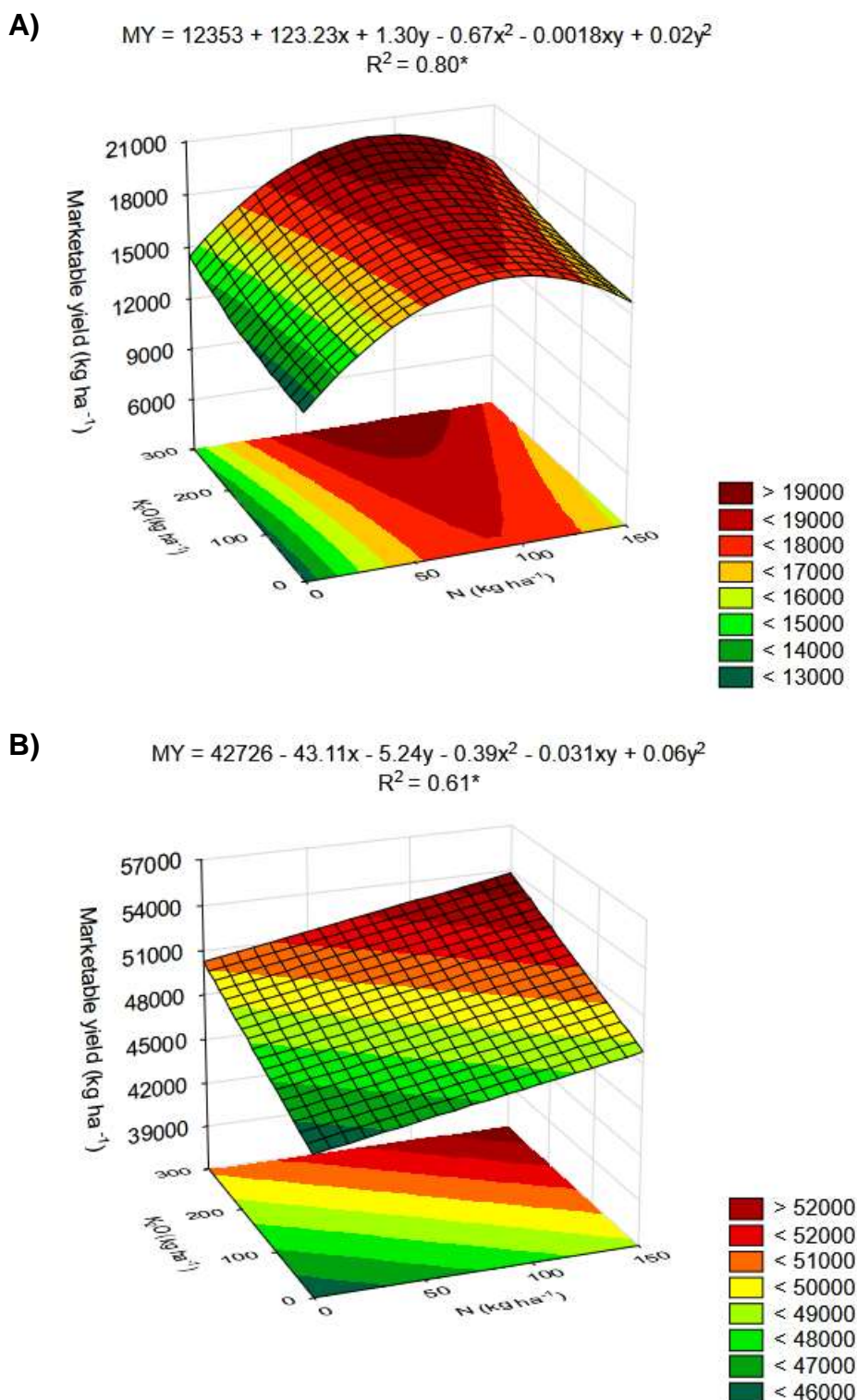$$R^2 = 0.61*$$

Figure 2. Marketable tuber yield (MY) of 'Atlantic" potato as affected by sidedressed N and K fertilization rates in the summer-fall (A) and spring (B) growing seasons. *: significant at 5% probability.

Compared to control treatment (no sidedressed N or K application), isolated N sidedressing rates increased MY by 53% (6,466 kg ha^{-1}) up to 91 kg ha^{-1} N in the summer-fall experiment (Figure 2A; Table 2) and 8% (3,705 kg ha^{-1}) with the highest rate (150 kg ha^{-1} N) in the spring experiment (Figure 2B; Table 2). According to response surfaces for summer-fall experiment, the rates from 60 to 90 kg ha^{-1} of sidedressed N as ammonium sulfate, commonly used by Brazilian 'Atlantic' potato growers, resulted in increases from 47% to 53% in MY, respectively; however, no effect was observed in the spring experiment (Figure 2). The greater volume of rainfall in the summer-fall experiment, especially between 20 and 60 days after planting (Figure 1), probably enhanced the response to the N fertilization. On the other hand, the spring experiment, in addition

to having less rainfall and probably less N leaching, it also presented a higher MY even without sideressed N fertilization. The sidedressed N rate that promoted the maximum MY was lower in the summer-fall than in the spring experiment, which may also be related to the higher temperatures and rainfall in the initial phase of potato cycle in the summer-fall growing season. Rens and coauthors [27] also did not observe increments in MY increasing sidedressed N rates at 'Atlantic' potato tuber initiation in seven experiments over three years. Studying ammonium sulfate rates at planting of 'Atlantic' potato in the summer-fall season under tropical conditions, Fontes and coauthors [24] and Fontes and coauthors [28] observed respectively maximum MY values of 33,305 kg ha^{-1} (18% increase or 5,043 kg ha^{-1}) with 175 kg ha^{-1} N, and 37,985 kg ha^{-1} (32% increase or 9,150 kg ha^{-1}) with 205 kg ha^{-1} N. However, high N rates at the tuber initiation also may decrease MY and also to result in higher residual soil mineral N at the end of the cycle [29].

Table 2. Marketable tuber yield increases and relative tuber yields (in parenthesis) both in relation to control treatment with sidedressed N and/or K fertilization to the 'Atlantic' potato crop.

Growing season	N	K	NK
Summer-fall	6,466 kg ha^{-1} (1.53)	1,959 kg ha^{-1} (1.16)	8,425 kg ha^{-1} (1.69)
Spring	3,705 kg ha^{-1} (1.08)	5,806 kg ha^{-1} (1.13)	9,511 kg ha^{-1} (1.21)

The isolated K sidedressing rates increased MY in 16% (1,959 kg ha^{-1}) and 13% (5,806 kg ha^{-1}) up to the highest K rate applied as sidedressing (300 kg K_2O ha^{-1}), respectively, in the summer-fall and spring experiments (Figures 2A and 2B; Table 2). In sandy soils, the 'Atlantic' potato did not have tuber yield increase in response to KCl rates at planting for four years [30]. In a clayey Oxisol with medium exchangeable K (summer-fall experiment) and in a sandy loam Inceptisol with high exchangeable K (spring experiment) (Table 1), the recommended K_2O rates to the maximum MY values achieved would be 151-200 and 201-250 kg ha^{-1}, respectively [18]. These K rates at planting are on average 54% and 41% lower than the maximum rate of 384 kg ha^{-1} K_2O applied in both experiments (22% at planting and 78% at sidedressing). This suggests that higher rates of split K fertilization at planting and sidedressing can be applied under these edaphoclimatic conditions.

In both experiments, the MY was higher with combined application of N and K at sidedressing in comparison to the isolated application of each of these nutrients (Figures 2A and 2B; Table 2). Compared to control treatment (no sidedressed N or K application), MY was increased by 69% (8,425 kg ha^{-1}) with 91 kg ha^{-1} N plus 300 kg ha^{-1} K_2O in the summer-fall experiment (Figure 2A; Table 2) and by 21% (9,511 kg ha^{-1}) with 150 kg ha^{-1} N plus 300 kg ha^{-1} K_2O in the spring experiment (Figure 2B; Table 2). The MY increases obtained with the combined optimal N and K rates were, respectively, 11% or 46% higher in the summer-fall experiment and 157% or 64% higher in the spring experiment, compared to the maximum increases of MY obtained with the optimal isolated N or K fertilization rates. Thus, our results confirm the hypothesis that the classic interactive effect of planting-applied N and K increasing potato tuber yield [4-8] also occurs with combined application of these nutrients as sidedressing before hilling. According to the criteria described by Rietra and coauthors [26], this interaction would be Liebig-synergistic because relative tuber yields with optimum N and K rates in both growing seasons were similar to the product between the relative tuber yields with isolated N or K fertilization (Table 2). This type of synergy occurs when adding one of the nutrients does not affect yield whereas addition of both nutrients shows an increase [26].

The interactive effect of sidedressed N and K cannot be explained by competitive uptake between N and K forms in plasma membrane level [26]. Although K^+ is not metabolized by plants it is crucial to protein synthesis [13,14], but NH_4^+ competes for uptake and inhibits K translocation by high affinity transporters [13]. Tubers are the main N and K sink in potato plants, accumulating 72% of N and 52% of K taken up by the Atlantic cultivar [2]. Nitrogen × K interaction synergistically increases the vegetative growth of potato plants, extending the tuber setting duration and increasing size, weight, and amounts of N and K removed by the tubers [8]. The presence of available N and K increases number and size of potato microtubers with the action of phytohormones in laboratory conditions [20] as well in the tuber size in field [7,8].

Planting *versus* sidedressing N and K rates

Besides being significant, N × K interaction with sidedressing-applied rates was more profitable than with planting-applied rates (Table 3). As typically used by Brazilian potato farmers, adjacent commercial fields had received 3.0 Mg ha^{-1} 4-14-8 N-P_2O_5-K_2O at planting plus 60 kg N ha^{-1} in sidedressing (i.e., 67%, 100%, and 100% of total rates of 180, 420, and 240 kg ha^{-1} N, P_2O_5, and K_2O, respectively, were applied at potato planting). Having similar N-P_2O_5-K_2O total rates but with 53% of N and 65% K applied as sidedressing

fertilization, there was a cost saving of 8.1% with profit increases of R$ 277.41 ha^{-1} (29.4%) in the summer-fall and R$ 235.63 (7.1%) in the spring growing seasons. These results reflect the higher tuber yields with application of N and K rates in times of higher nutritional demands by potato crop, such as tuberization and tuber bulking [1-3]. In comparison with commercial fields (traditional fertilizer management), similar rates of N and K applied most as sidedressing increased MY by 20.9% (3,220 kg ha^{-1}) and 5.9% (2,693 kg ha^{-1}) in the summer-fall and spring growing sesons, respectively (Table 3). Optimum sidedressed N and K rates promoted MY 33.7% (5,179 kg ha^{-1}) and 20.9% (9,522 kg ha^{-1}) higher than the commercial fields, in the summer-fall and spring growing seasons, respectively. As a result, profits also increased by 46.0% (R$ 434.78 ha^{-1}) in the summer-fall and by 22.6% (R$ 754.34 ha^{-1}) in the spring growing season (Table 3).

Table 3. Nitrogen and potassium fertilizer rates applied at planting (PL) and in sidedressing (SD) to 'Atlantic' potato crop with traditional fertilization used in the adjacent commercial fields and in the experiments (Exp) with similar total rates or with the optimum combinations of fertilizer rates, and respective marketable yields and economic results.

Fertilization management[a]	N		K_2O		Marketable yield	Costs	Profit
	PL	SD	PL	SD			
	——————— kg ha^{-1} ———————				kg ha^{-1}	——— R$ ha[-1] ———	
Summer-fall							
Traditional	120	60	240	0	15,375	273.72	944.84
Similar rates (Exp)	84	96	84	156	18,595	251.52	1,222.25
Optimum rates (Exp)	84	91	84	300	20,554	249.44	1,379.62
Spring							
Traditional	120	60	240	0	45,543	273.72	3,335.87
Similar rates (Exp)	84	96	84	156	48,236	251.52	3,571.51
Optimum rates (Exp)	84	150	84	300	55,065	274.00	4,090.21

Tuber quality

Marketable-tuber SG responded in an opposite way to the combined application of N and K sidedressing rates in each growing season (Figure 3). The SG was increased by 1.6% (0.018 units) in summer-fall experiment (Figure 3A) and decreased by 1.3% (0.014 units) in spring experiment (Figure 3B), with the application of the highest N and K sidedressing rates. These contradictory results can be attributed to the edaphoclimatic conditions of each growing season, since lower level of K^+ and higher levels Ca^{2+} and Mg^{2+} in the soil (Table 1) as well as greater volumes of rainfall (Figure 1) during the tuber bulking phase in the summer-fall experiment favored the positive response of marketable-tuber SG to sidedressed N and K fertilization, in contrast to the spring experiment. These results corroborate the findings that there is interaction between N and K inputs and their levels in the soil [16] and were in line with the synergistic [4] and antagonistic [16] effects reported for N and K interactions to potato crop. The application of N rates at planting of 'Atlantic' potato also increased, linearly or quadratically, the SG in three of five experiments in Florida-EUA, although the magnitude of those increases were lower, in the order of 0.001 to 0.003 units [27]. Despite the reported negative effects of the N fertilization on tuber SG, increases of this parameter with sidedressed N application may be associated with the reduction in water absorption with increase of NH_4^+-N uptake by plants [16].

A)

$$SG = 1.087 - 0.2057x - 0.0028y - 0.0017x^2 + 0.00003xy + 0.0001y^2$$
$$R^2 = 0.74*$$

B)

$$SG = 1.096 - 0.0001x + 0.00004y - 0.0000007x^2 + 0.00000006xy + 0.0000001y^2$$
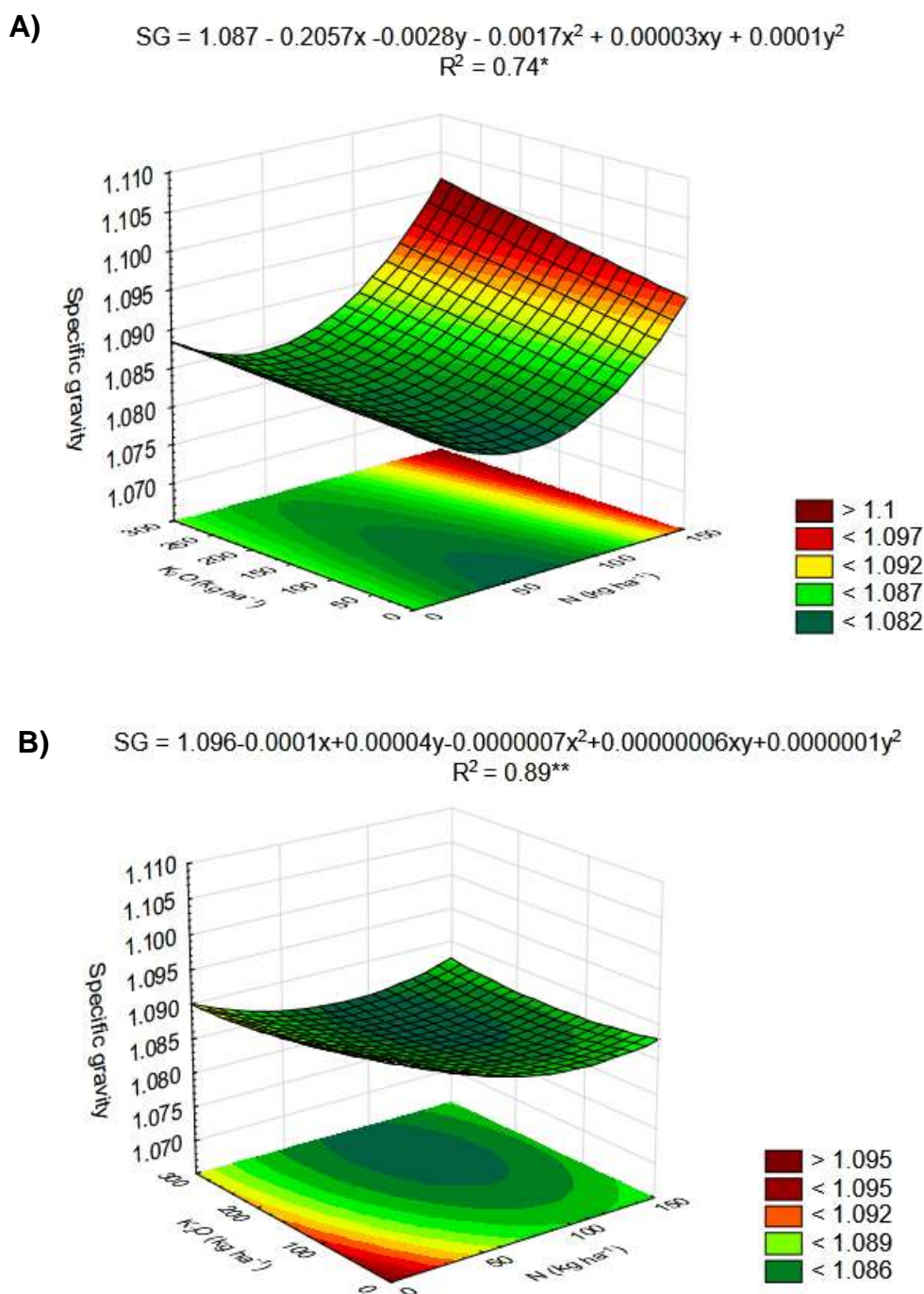$$R^2 = 0.89**$$

Figure 3. Specific gravity (SG) of marketable tubers of 'Atlantic' potato as affected by sidedressed N and K fertilization rates in the summer-fall (A) and spring (B) growing seasons. ** and *: significant at 1% and 5% probability.

CONCLUSIONS

Significant interaction between N and K sidedressing rates with tuber yields increase also was confirmed and classified as Liebig-synergism. Compared to the isolated N and K applications in sidedressing, joint N and K rates, respectively, increases 11% and 48% marketable tuber yields in the summer-fall experiment, and 12% and 7% in the spring experiment. Joint N and K applications as sidedressing was more profitable than their application at planting, mainly at higher N and K rates. The response of specific gravity of 'Atlantic' potato tubers to the N and K sidedressing rates was mediated by interactions between edaphoclimatic conditions and inputs of N and K. The combined application of N and K sidedressing rates increased specific gravity in the summer-fall experiment, but had a negative effect in the spring experiment.

Conflicts of Interest: The authors declare no conflict of interest.

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