Doi: https://doi.org/10.17584/rcch.2022v16i2.13559

Agronomic and economic responses of the potato (*Solanum tuberosum* subsp. *andigena*) to differential fertilization in four environments in Nariño, Colombia

Respuesta agronómica y económica de papa (*Solanum tuberosum* subsp. *andigena*) a la fertilización diferencial en cuatro ambientes de Nariño, Colombia

CARLOS ALBERTO MARCILLO-PAGUAY[1]
CARLOS ANDRÉS BENAVIDES-CARDONA[2]
HOUSSEMAN STEVEN RAMOS-ZAMBRANO[1]
JUAN VICENTE ROMERO[1, 3]

Agronomic responses of potatoes to fertilization.

Photo: C.A. Marcillo-Paguay

ABSTRACT

Due to the importance of potato cultivation in Nariño, Colombia and the high participation of fertilizer in production costs (25%), as well as the great variability of soils in the region, we evaluated three fertilizer levels for six cultivars of *Solanum tuberosum* subsp. *andigena* in four homogeneous production environments. We recorded physiology and yield of the potatoes in experimental plots in a randomized complete block design with three replications in each environment. Analysis of variance, comparison of means for yield components, and discriminant analysis of principal components were performed for all variables. For the economic analysis we used the partial budget net benefit methodology. The environments generated differential responses in the cultivars. Between fertilization levels there were significant differences; however, there was no interaction between levels and environments. The cultivars 'ICA Única', 'Pastusa Suprema', 'Parda Bilingüe', and 'Roja Huila', showed the highest yields with the application of 262, 600, and 538 kg ha^{-1} of N, P_2O_5, and K_2O (level L3). 'Diacol Capiro' and 'Superior' did not show yield differences between levels. Economically, the alternative that would generate the highest return on investment was fertilization with level L2 (N 180, P_2O_5 400, K_2O 358 kg ha^{-1}) in 'Diacol Capiro', 'Superior', and 'ICA Única' cultivars. For 'Roja Huila' and 'Parda Bilingüe' the highest return was level L1 (N 150, P_2O_5 200, K_2O 100 kg ha^{-1}). In the case of 'Pastusa Suprema' the Marginal Rate of Return was 18.5% with the L2 fertilization level.

[1] Corporación Colombiana de Investigación Agropecuaria (Agrosavia), Pasto (Colombia). ORCID Marcillo-Paguay, C.A.: 0000-0001-9100-2463; ORCID Ramos-Zambrano, H.S.: 0000-0001-7959-9834; ORCID Romero, J.V.: 0000-0002-4857-608X

[2] Universidad de Nariño, Facultad de Ciencias Agrícolas, Pasto (Colombia). ORCID Benavides-Cardona, C.A.: 0000-0002-9144-6168

[3] Corresponding author. jvromero@agrosavia.co

Additional key words: Andisols; nutrient availability; growth index; yield; costs; plant nutrition.

RESUMEN

Debido a la importancia del cultivo de papa en Nariño, Colombia, la alta participación de fertilizantes en los costos de producción (25%) y la gran variabilidad de suelos en la región, se evaluaron agronómica y económicamente tres niveles de fertilización para seis cultivares de *Solanum tuberosum* subsp. *andigena* en cuatro ambientes homogéneos de producción. Variables fisiológicas y de rendimiento fueron registradas en parcelas experimentales con un diseño de bloques completamente al azar con tres repeticiones en cada ambiente. Se realizaron análisis de varianza, comparación de medias para componentes de rendimiento y análisis discriminante de componentes principales con todas las variables. En el análisis económico se usó la metodología de presupuesto parcial de beneficio neto. Los ambientes generaron respuestas diferenciales en los cultivares. Entre niveles de fertilización hubo diferencias significativas, sin embargo, no hubo interacción entre niveles y ambientes. Los cultivares 'ICA Única', 'Pastusa Suprema', 'Parda Bilingüe', y 'Roja Huila' presentaron los mayores rendimientos con la aplicación de 262, 600 y 538 kg ha^{-1} de N, P_2O_5 y K_2O (nivel L3). 'Diacol Capiro' y 'Pastusa Suprema' no presentaron diferencias de rendimiento entre niveles. Económicamente, la alternativa que generaría mayor retorno por la inversión fue la fertilización con el nivel L2 (N 180, P_2O_5 400, K_2O 358 kg ha^{-1}) en los cultivares 'Diacol Capiro', 'Superior', and 'ICA Única', mientras que para 'Roja Huila' y 'Parda Bilingüe' fue el nivel L1 (N 150, P_2O_5 200, K_2O 100 kg ha^{-1}). En el caso de 'Pastusa Suprema', la tasa de retorno marginal fue de 18,5% con el nivel L2 de fertilización.

Palabras clave adicionales: Andisoles; disponibilidad de nutrientes; índice de crecimiento; rendimiento; costos, nutrición vegetal.

Received: 27-10-2021 Accepted: 25-03-2022 Published: 03-05-2022

INTRODUCTION

The potato crop in Colombia for 2019 represented 3.3% of the agricultural gross domestic product (AGDP). The departments of Cundinamarca, Boyaca, and Nariño contributed 85% of production and 84% of the area planted (*Ministerio de Agricultura y Desarrollo Rural* [Colombia MADR], 2021). In the same year, 24,906 ha were cultivated in Nariño with a production of 569,163 t (Colombia MADR, 2021), involving about 25 thousand families, 3,600,000-day laborers and 350,000 indirect jobs (Colombia Gobernación de Nariño, 2020), so the crop represents great economic, social, and cultural importance in the department.

In Nariño four zones or homogeneous environments for potato production are delimited and described with different biophysical and climatic characteristics, but each one is similar to the others. However, we identified common attributes associated with the productive system among other attributes. These were soil fertilization distributed in two seasons and the low use of soil analysis (Benavides *et al.*, 2021; Marcillo *et al.*, 2021).

The soils of the potato producing zone in Nariño show variability in the content and distribution of their chemical characteristics. Strong to moderately acid soils predominate with pH between 4.7 and 6.1, medium to high contents of phosphorus and potassium with values higher than 20 mg kg^{-1}, and 0.3 $cmol_{(+)}$ kg^{-1}. In the case of the bases, calcium contents are between 1.6 and 10.9 $cmol_{(+)}$ kg^{-1}, although values between 3 and 6 $cmol_{(+)}$ kg^{-1} prevail, while magnesium contents are low (less than 1.5 $cmol_{(+)}$ kg^{-1}). Greater variability is observed in organic matter content with respect to the other characteristics. The organic matter range varies between 2.6 and 32.6% (Marcillo *et al.*, 2021).

The items associated with inputs within the production costs for Nariño in 2018 in the cultivars 'Diacol Capiro' and 'Superior' is 45 and 43%, respectively

(*Federación Colombiana de Productores de Papa* [Colombia Fedepapa], 2021). Specifically, for amendments, manures, and fertilizers, the Colombia MADR (2021) calculated 25% for the same year, underlining that this item represents an important factor in the investment made by the farmer to produce the crop.

Unlike other crops of economic and food importance such as cereals, there is little information about the potato on nutrition and fertilization, and the existing information is based on data elaborated in past decades (Koch *et al.*, 2020). This situation is not limited to the department of Nariño, because the recommendations based on critical levels and responses to fertilization are found in technical manuals, such as that of the *Instituto Colombiano Agropecuario* (Colombia ICA, 1992), or response trials (García and Obando, 1993; García and Pantoja, 1998).

The present research aimed to contribute to the fertilization management of potato crops, analyzing the agronomic responses and economic implications of six potato cultivars *Solanum tuberosum* subsp. *andigena*, subjected to three levels of fertilization in four potato producing environments of Nariño, Colombia.

MATERIALS AND METHODS

Location

The present study was carried out in southwestern Colombia, Department of Nariño, in four representative zones for the environments characterized for potato production in this region. These were chosen by edaphoclimatic characteristics, such as altitude, precipitation, temperature, and prevalent slope (Benavides *et al*, 2021). The evaluations were carried out in farms located in the municipalities of Guaitarilla (HE1), Providencia (HE2), Pupiales (HE3), and Guachucal (HE4) located in each environment (Tab. 1). The chemical properties of the soils of the site where the evaluation was developed are described in table 2.

Plant material

The potato cultivars used were the ones with the highest planting frequency for this group in the producing area of Nariño (Benavides *et al.*, 2021): 'Diacol Capiro', 'Pastusa Suprema', 'ICA Única', 'Superior', 'Roja Huila', and 'Parda Bilingüe' that have been described by Ñústez (2011) and Moreno (2000).

Experimental design

In each environment, experimental plots were established in a randomized complete block design with three replications. The treatments corresponded to three levels of fertilization (Tab. 3). The first was based on the interpretation of the nutrient contents in the soils and the needs of the potato crop (Colombia ICA, 1992); the second and third levels corresponded to 50 and 75% of the requirements of a crop to produce 40 t ha^{-1} (García and Pantoja, 1998). Along with the evaluated levels, secondary and micronutrients were applied in doses per hectare of MgO 30 kg, S 15 kg, B 2.25 kg, Cu 0.6 kg, Mn 3 kg and Zn 4.8 kg. We established a sowing density for the experiment of 33,333 plants/ha. Each experimental plot occupied an area of 45 m^2 of which 27.6 m^2 were used for recording yield variables.

Table 3. Fertilizer levels applied to six potato (*Solanum tuberosum* subsp. *andigena*) cultivars evaluated in four homogeneous production environments.

Level	Contribution (kg ha^{-1})		
	N	P_2O_5	K_2O
L1	150	200	100
L2	180	400	358
L3	262	600	538

Variables evaluated

Each 15-d destructive sampling was carried out to record the dry matter during the productive cycle. The leaf area index (LAI) was estimated from the total leaf area and the area of soil covered by it. With this information, the growth indices were calculated as follow: net assimilation rate (NAR), crop growth rate (CGR), and relative growth rate (RGR) (Mohamed *et al*., 2017; Hunt, 1978; Pandey *et al*., 2017). At the end of the cycle, the harvest index (HI) was calculated for each cultivar. In addition, we evaluated the yield per experimental unit, number and weight of tubers by size at harvest, according to the Colombian technical standard for potato classification NTC – 341 (Colombia ICONTEC, 1996), where large and very large sizes are those of commercial interest.

Statistical analysis

We used the multivariate method of principal component discriminant analysis (DAPC) for the

identification and evaluation of groups by cultivars and environments, using physiological indices and yield variables together. We performed an analysis of variance according to the experimental design and Tukey's test ($P<0.05$) for each cultivar, for comparison of averages of the yield of each component. The statistical program R version 4.0.4 was used (R Core Team, 2021) and the packages Adegenet (Jombart, 2008) for DAPC and ExpDes (Ferreira *et al*., 2013) for analysis of variance.

Economic analysis

For economic determination of the effects of nutrition levels, the methodology of partial budget net benefit and marginal analysis was used (CIMMYT *et al*., 1988; Reyes, 2001). An adjustment rate was applied to the experimental yields to represent the yield under commercial production conditions. The selling price used was the historical departmental average for each cultivar from 2018 to 2020 (Colombia Fedepapa, 2021). The price of production before harvest was estimated from the difference of the unit costs of marketing and harvesting. The marginal rate of return (MARR) was determined as the ratio of gross field profit to net field profit. The minimum rate of return (MIRR) was established as the sum of the 2020 average of the fixed term deposit rate (FTD) (BANREP, 2020), the expected inflation for Colombia in 2021 (BANREP, 2021), and the expected return on equity reported in 2020 that considers a 3-year average (Corficolombiana, 2020). For the selection of the best treatments, the MARR and MIRR rates were contrasted.

RESULTS AND DISCUSSION

Cultivar responses to productive environments in Nariño

The physiological and yield responses of the cultivars generated groupings showing differences among the environments (Fig. 1A). This suggested that there were different growth, development, and production responses due to the particularities of each environment (Tab. 2). These results underline the differentiation of homogeneous production environments carried out for the department of Nariño (Benavides *et al*., 2021). The variables that most contributed to the grouping in the DAPC for environments were mainly physiological and secondly productive.

The physiological indices that provided a greater contribution to the differentiation of behavior in environments and between cultivars were CRT and NAR. CRT is an index of dry matter production efficiency that allows quantifying the growth rate. Its contribution to the discrimination of environments is influenced by the environment where the crop

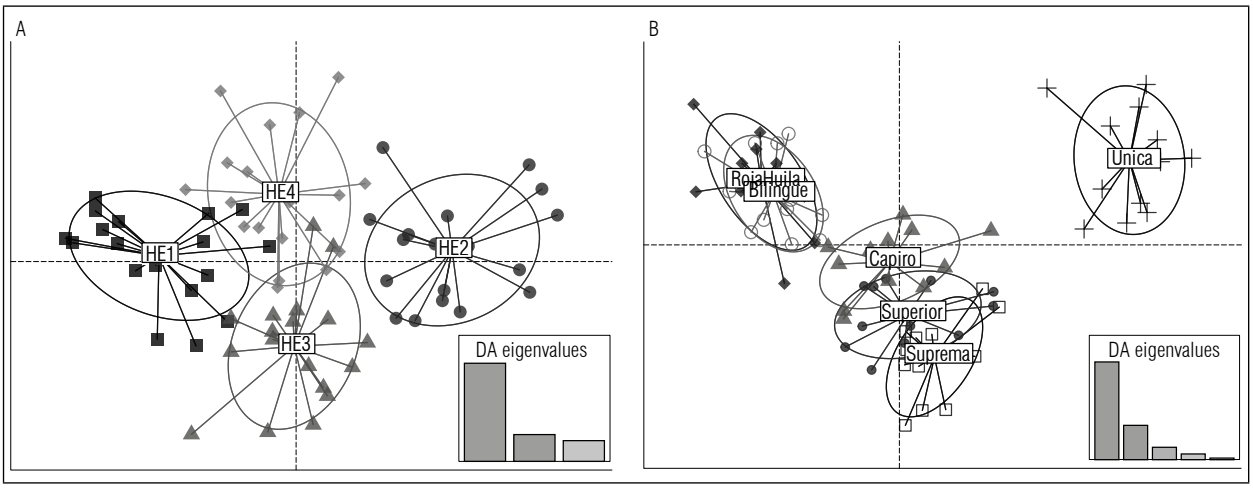

Figure 1. DAPC biplot with groupings of six potato (*Solanum tuberosum* subsp. *andigena*) cultivars in four homogeneous production environments. The dispersion in the first two principal components is plotted, using in (A) the homogeneous environments (HE) as a priori groups and in (B) the cultivars. The biplot synthesizes information on physiological variables and yields components. Inertia ellipses of each homogeneous environment or cultivar are presented around the experimental units.

develops (Mora-Aguilar *et al*., 2006). Although, the CRT also allows the separation of behaviors between genotypes since it is a measure that integrates the physiological behavior of plants (Mora-Aguilar *et al*., 2006; Santos *et al*., 2010), it was also important in the grouping of cultivars. On the other hand, NAR is an indicator of average photosynthetic efficiency, and depends on genetic factors, so it is useful for estimating the efficiency and physiological differences between potato cultivars (Borrego *et al*., 2000; Jerez *et al*., 2016; Santos *et al*., 2010).

For 'Roja Huila' and 'Parda Bilingüe' cultivars, statistical differences were found between environments (Tab. 4), showing higher yields in environments HE2 and HE4, exceeding 31 and 37 t ha^{-1} and with a better proportion of tubers of higher commercial value with respect to the other environments. In the DAPC these two cultivars formed the first separate group (Fig. 1B), given that the NAR and CRT indices were the highest (NAR between 0.194 and 0.249 g dm^{-2} d^{-1} and CRT between 0.141 and 0.148 g g^{-1} d^{-1}) in the phase of highest growth and their lower yields compared to those evaluated. These cultivars are planted by producers in the department of Nariño (Benavides *et al*., 2021) and are marketed in low volumes, mainly for regional fresh consumption. 'Parda Bilingüe' can be used for frying (Tinjacá and Rodríguez, 2015). According to the results, these cultivars are an option for producers in the HE2 environment.

'Diacol Capiro', 'Pastusa Suprema' and 'Superior' in the DACP formed the second group of cultivars, according to the physiological responses in the environments (between 0.144 - 0.194 g dm^{-2} d^{-1} for NAR and between 0.103 - 0.116 g g^{-1} day^{-1} for CRT), in the phase of highest growth; and the yields achieved were higher than those of 'Roja Huila' and 'Parda Bilingüe' and lower than those of 'ICA Única' (Fig. 1B; Tab. 4). However, the yields of these three cultivars responded differently within the productive evaluated environments. 'Diacol Capiro' reached yields between 28 and 32 t ha^{-1} in environments HE1, HE2 and HE3, like commercial yields ranging between 25 and 30 t ha^{-1} (Moreno, 2000). In HE4 it exceeded the potential yield reported by Ñústez (2011) of 40 t ha^{-1}. 'Pastusa Suprema', in the environments HE3 and HE4 exceeded 54 t ha^{-1} and was statistically superior to the yields in the environments HE1 and HE2 that did not reach 46 t ha^{-1}. However, the results exceeded the yields under optimal production conditions that for Ñústez (2011) are around 45 t ha^{-1}. In the 'Superior' cultivar no statistical differences were observed in the four environments. Its yield was between 35 t ha^{-1} and 44 t ha^{-1}, higher than the 32 t ha^{-1} produced in Nariño in 2018 (Colombia Fedepapa, 2021).

The responses of these cultivars could be attributed to the optimal ranges of adaptation of each cultivar. Thus, for 'Diacol Capiro' adequate production is reported at altitudes between 2,000 and 3,200 m a.s.l. (Moreno, 2000; Ñústez, 2011). For 'Pastusa Suprema' adequate production is seen from 2,500 to 3,200 m a.s.l. (Ñústez, 2011). For the 'Superior' cultivar a defined range is not reported in the literature; however, in this research its yields were adequate for the four environments. In addition to altitude, the observed differences may be due to the interaction of cultivars with the different edaphoclimatic factors of the environments in the producing area; these are temperature, precipitation, soil pH, and slopes. In the HE1 environment, temperatures range from 14°C to 17°C, precipitation up to 3,000 mm $year^{-1}$, moderately acid pH and slightly steep slopes (5-12%). In the HE4 environment the temperature range is 9 - 12°C, precipitation up to 2,800 mm $year^{-1}$, neutral or nearly neutral soils, and steep slopes (50-75%) (Benavides *et al*., 2021).

The cultivar 'ICA Única' differed in the DACP (Fig. 1B), since it reached growth rates of 0.149 g dm^{-2} d^{-1} of NAR and 0.118 g g^{-1} d^{-1} of CRT and attained yields superior to other cultivars. This produced more than 49 t ha^{-1} in the four environments evaluated, highlighting its behavior in HE3 and HE4 for exceeding 60 t ha^{-1} (Tab. 4). One of the characteristics of this variety is the production of large tubers, mainly observed in the environments HE2, HE3 and HE4 that produced yields of large and very large tubers greater than 47.5 t ha^{-1}. The variation in yield between environments may be due to the adaptation of the variety to the environments HE3 and HE4, where yields were higher (from 30 to 45 t ha^{-1}) than the commercial ones reached at altitudes between 2,600 to 3,200 m a.s.l. (Moreno, 2000). A commercial limitation of the cultivar is the tendency to greening of the skin (Ñústez, 2011), so the light conditions for transport or storage must be considered. This is one of the reasons why this variety is less sown in Nariño compared with the cultivars of the second group.

Table 4. Analysis of variance in six potato (*Solanum tuberosum* subsp. *andigena*) cultivars for the evaluation of three fertilization levels in four homogeneous production environments in Nariño, Colombia.

Cultivar	Factor	DF	Yield (t ha^{-1})	Yield of tubers of highest commercial value (t ha^{-1})	Number of tubers with highest commercial value per plant
Diacol Capiro	Level	2	0.479^{NS}	0.335^{NS}	0.016*
	L1		30.7 a	20.6 a	3.4 b
	L2		35.4 a	26.0 a	5.0 a
	L3		34.6 a	24.4 a	3.9 ab
	Environment	3	<0.001***	<0.001***	0.044*
	HE1		28.0 b	19.9 b	3.7 b
	HE2		27.7 b	18.0 b	3.6 a
	HE3		31.9 b	21.0 b	4.0 ab
	HE4		46.7 a	35.7 a	5.1 a
	Level*Environment	6	0.443^{NS}	0.375^{NS}	0.270^{NS}
	CV(%)		29.6	37.4	29.3
Pastusa Suprema	Level	2	0.007**	0.027*	0.977^{NS}
	L1		46.5 b	29.6 b	5.7 a
	L2		53.2 ab	34.4 ab	5.6 a
	L3		55.7 a	37.0 a	5.8 a
	Environment	3	<0.001***	<0.001 ***	0.014*
	HE1		45.5 bc	25.2 c	5.0 b
	HE2		45.3 c	29.6 bc	5.3 b
	HE3		54.1 ab	37.7 ab	5.4 ab
	HE4		62.2 a	42.2 a	7.1 a
	Level*Environment	6	0.064^{NS}	0.245^{NS}	0.815^{NS}
	CV(%)		12.8	18.9	23.3
ICA Única	Level	2	0.035*	0.002**	0.054^{NS}
	L1		56.2b	42.9 b	5.4 a
	L2		62.4 ab	52.8 a	6.3 a
	L3		63.0 a	49.3 a	5.8 a
	Environment	3	<0.001***	<0.001***	0.660^{NS}
	HE1		49.9 c	40.1 b	5.6 a
	HE2		58.0 bc	47.5 ab	5.9 a
	HE3		67.8 a	52.8 a	5.8 a
	HE4		66.3 ab	52.8 a	6.0 a
	Level*Environment	6	0.550^{NS}	0.537^{NS}	<0.001***
	CV(%)		10.9	12.3	13.9

to be continued

Table 4. Analysis of variance in six potato (*Solanum tuberosum* subsp. *andigena*) cultivars for the evaluation of three fertilization levels in four homogeneous production environments in Nariño, Colombia.

Cultivar	Factor	DF	Yield (t ha^{-1})	Yield of tubers of highest commercial value (t ha^{-1})	Number of tubers with highest commercial value per plant
Superior	Level	2	0.153^{NS}	0.096^{NS}	0.170^{NS}
	L1		34.2 a	20.0 a	4.2 a
	L2		42.1 a	27.2 a	5.4 a
	L3		42.6 a	27.5 a	5.1 a
	Environment	3	0.276^{NS}	0.173^{NS}	0.337^{NS}
	HE1		35.2 a	19.2 a	4.2 a
	HE2		36.5 a	24.7 a	4.6 a
	HE3		42.9 a	27.9 a	5.1 a
	HE4		44.0 a	27.8 a	5.6 a
	Level*Environment	6	0.319^{NS}	0.304^{NS}	0.295^{NS}
	CV(%)		28.7	36.5	33.5
Parda Bilingüe	Level	2	0.041*	0.028*	0.044*
	L1		27.3 b	16.9 b	4.2 b
	L2		30.2 ab	19.6 ab	4.7 ab
	L3		35.3 a	23.7 a	5.8 a
	Environment	3	<0.001***	<0.001***	<0.001***
	HE1		30.4 b	20.1 b	6.1 a
	HE2		42.9 a	29.3 a	6.1 a
	HE3		13.2 c	8.7 c	3.5 b
	HE4		37.2 ab	22.3 ab	4.0 b
	Level*Environment	6	0.204^{NS}	0.206^{NS}	0.431^{NS}
	CV(%)		23.4	28.6	29.3
Roja Huila	Level	2	0.041*	0.072^{NS}	0.087^{NS}
	L1		19.4 b	10.0 a	2.5 a
	L2		24.5 ab	14.5 a	3.4 a
	L3		28.6 a	16.3 a	3.8 a
	Environment	3	<0.001***	<0.001***	0.060^{NS}
	HE1		20.0 b	11.5 bc	3.6 a
	HE2		33.7 a	17.3 ab	3.7 a
	HE3		11.0 b	5.4 c	2.1 a
	HE4		31.9 a	20.3 a	3.6 a
	Level*Environment	6	0.182^{NS}	0.289^{NS}	0.553^{NS}
	CV(%)		34.0	47.6	41.1

* significance level $P<0.05$, **: significance level $P<0.01$, ***: significance level $P<0.001$; ^{NS}: not significant. Means with different letters within each factor of variation indicate statistical differences according to the Tukey test ($P<0.05$).

Cultivar response to fertilization

The evalutated genotypes did not show an interaction between fertilization levels and environment, apart from 'ICA Única' in the number of tubers (Tab. 4) that allow a general discussion of the levels evaluated in all environments. The L3 level significantly increased the total yield in the cultivars 'Pastusa Suprema', 'ICA Única', 'Roja Huila', and 'Parda Bilingüe' with experimental values of 56, 63, 29 and 35 t ha^{-1}.

Levels L2 and L3, with respect to L1, increased the number or yield of tubers of higher commercial value in all cultivars, except for 'Superior' that did not respond to the increase in fertilization, although its yield was higher than that reported for Nariño in 2018 of 32.1 t ha^{-1} (Colombia Fedepapa, 2021). In 'Diacol Capiro', the levels increased the number of tubers of higher commercial value from 4 to 6 tubers/plant. In 'Pastusa Suprema' the yield of this type of tubers reached 37 t ha^{-1} and in 'Parda Bilingüe' 24 t ha^{-1} with approximately 5 tubers/plant. Finally, 'ICA Única' had interaction between environments and levels with higher values in HE1 with level L2 (7.5 tubers/plant) and in environment HE3 with level L1 (7 tubers/plant).

Yield components in 'Diacol Capiro', 'Pastusa Suprema', 'ICA Única', 'Roja Huila' and 'Parda Bilingüe' indicate that L2 and L3 levels outperformed L1. This response suggested that the L1 level did not supply enough nutrients for the cultivars to increase their yield. Meanwhile, L2 and L3 efficiently provided nitrogen (N), phosphorus (P_2O_5) and potassium (K_2O). The highest yields are found when applying the highest dose, 3,000 kg ha^{-1} of 10-20-20 fertilizer to 'Diacol Capiro' when compared to doses of 500, 1500, and 3000 (Rios *et al*., 2010).

In general terms, soils in the production zone of Nariño belong to the order of Andisols (low availability of phosphorus, generated by the presence of allophane, as well as by the formation of insoluble compounds with iron and aluminum) (Bravo *et al*., 2016; García and Pantoja, 1998). There is also reduced mineralization of organic matter (Sánchez and Rubiano, 2015) and limited availability of potassium, due to fixation processes that can immobilize between 20 and 40% of the nutrient (Henriquez *et al*., 1994). These soils have low pH that can be lower than 5.5 in some productive areas (Marcillo *et al*., 2021) and can limit the availability of nutrients for the crop. Considering these characteristics in the soils of the producing area, the contributions provided by the L2 and L3 levels decreased the restrictions for a good supply of nutrients to the crop. This generated a positive effect on the production of most of the cultivars evaluated. In addition, the fractionation of nutrients and time of application must be considered according to the phenological state.

Individual application of each element generates yield increases with the highest doses, with up to 228 kg ha^{-1} of nitrogen (Pinochet *et al*., 2018), with 500 kg ha^{-1} of P_2O_5 (Fernandes and Soratto, 2016) or with doses up to 300 kg ha^{-1} of K_2O (Zelelew *et al*., 2016). Evaluations of compound applications also indicate that high doses improve potato yields (Rios *et al*., 2010), however, this is true up to a certain limit, as too high amounts could have a negative effect on commercial tuber yields (Pinochet *et al*., 2018).

Additionally, the proportion of each nutrient applied with reference to total fertilization should be considered, because it can generate a negative nutritional effect on the crop. The proportion of nitrogen supplied by L3 was less than 20% of the total fertilization, while for Pinochet *et al*. (2018) it was higher than 43% in the presence of 200 kg ha^{-1} of P_2O_5 and 100 kg ha^{-1} of K_2O, reporting yield decreases with doses higher than 228 kg ha^{-1} of N. With L3 no such effects were observed when applying 262 kg ha^{-1} of N, possibly due to the balance of proportions of this formulation.

Economic analysis

In the dominance analysis, the L1 level was used as a basis for the identification of fertilization alternatives. In the cultivars 'Diacol Capiro', 'ICA Única', 'Pastusa Suprema' and 'Superior' higher economic benefits and lower variable costs could be achieved with L2 for 'Parda Bilingüe' with L3 and for 'Roja Huila' with L1 (Tab. 5). From this information, in the partial budget analysis, favorable changes were found, with a MARR higher than MIRR (22.3%) in the fertilization level for 'Diacol Capiro', 'ICA Única' and 'Superior', while 'Pastusa Suprema' had a positive response, but it was not higher than MIRR. or 'Parda Bilingüe' a negative MARR was shown.

The L3 fertilization level had the highest yields in the cultivars 'ICA Única', 'Pastusa Suprema', 'Parda Bilingüe' and 'Roja Huila' while in 'Superior' no agronomic differences were found. In the case of 'Diacol Capiro', only the effect on the number of tubers of

Table 5. Dominance and partial budget analysis for the evaluation of three fertilization levels in six potatoes (*Solanum tuberosum* subsp. *andigena*) cultivars in Nariño, Colombia.

Cultivar	Alternative nutrition level	Net benefit COP	Variable cost COP	Marginal return rate MARR (%)	Economic decision (MARR > MIRR*)
Diacol Capiro	L1	13.764.080	2.335.000	-	L2
	L2	14.243.760	4.320.000	24.2	
ICA Única	L1	21.406.690	2.335.000	-	L2
	L2	22.040.880	4.320.000	31.9	
Pastusa Suprema	L1	13.992.080	2.335.000	-	L1
	L2	14.359.584	4.320.000	18.5	
Superior	L1	10.961.960	2.335.000	-	L2
	L2	12.048.480	4.320.000	54.7	
Parda Bilingüe	L1	10.402.361	2.335.000	-	L1
	L3	10.029.921	6.440.000	-9.1	
Roja Huila	L1	4.665.296	2.335.000	-	L1

* Minimum rate of return (MIRR) = 22.3%.

higher commercial value was seen. This contrasts with the results of the economic analysis, where L2 is indicated as the alternative that would generate higher income to the producers in 'Diacol Capiro', 'Superior' and 'ICA Única', while for the cultivars 'Roja Huila' and 'Parda Bilingüe' the level L1 is indicated since their income would be higher and their costs lower than the proposed alternatives. This depends on the relationship between the additional yields and the production costs to generate those yields, therefore, producing higher tuber yields does not imply higher economic gains for the farmer (Morales-Hernández *et al*., 2015). The selling price is a highly influential variable in the analysis and decision making, hence the difference in economic results is also related to the price contrast between cultivars. In the period 2018-2020, 'Diacol Capiro' had average selling prices of COP $663/kg, while 'Roja Huila' had COP $455/kg (Colombia Fedepapa, 2021).

The failure to find economic response in 'Roja Huila' and 'Parda Bilingüe' could also be related to other technical factors not considered, such as the availability of good quality seed, linked to the presence of negative phytosanitary factors that affect crop yield and prevent the expression of its productive potential (Wassihun *et al*., 2019; Avendaño and González, 2015; Esprella *et al*., 2012).

In the case of 'Pastusa Suprema', the MARR was not higher than the MIRR, that is, the remuneration that the farmer would receive for the investment when using the L2 level would not be higher than the options of the fixed income financial market. However, with L2 there was an increase in profit of 18.5% with the MARR. This rate may be acceptable for producers with marginal technological levels, whose income is below that rate, placing the L2 level as a fertilization alternative for that specific case.

Finally, it should be noted that the amounts of commercial fertilizer (packages per hectare) applied by farmers are like those used in L2; however, the contribution of nutrients is different. L2 provides 180 - 400 - 358 kg ha^{-1} of N, P_2O_5 and K_2O, while the producer's fertilization provides 292 - 297 - 354 kg ha^{-1} (Monsalve *et al*., 2020).

CONCLUSIONS

The present study found different responses of the genotypes evaluated at both agronomic and economic levels. From the agronomic component, yield varied with respect to the nutritional levels evaluated without interacting with the homogeneous production environments. The cultivars 'ICA Única', 'Pastusa Suprema', 'Parda Bilingüe' and 'Roja Huila' were favored by the high level L3 (262, 600 and 538 kg ha^{-1} of N, P_2O_5 and K_2O), that resulted in higher yields. On the other hand, the cultivars, 'Superior' and 'Diacol Capiro', did not show yield different responses with respect to nutrition levels. The latter, however, increased the number of tubers of higher commercial

value under the medium level L2 (N 180, P_2O_5 400 and K_2O 358 kg ha^{-1}). Economically, the level L2 is the alternative that would generate higher returns on investment in the cultivars 'Diacol Capiro', 'Superior' and 'ICA Única', since in these, the MARR higher than the MIRR level L1 (N 150, P_2O_5 200 and K_2O 100 kg ha^{-1}). 'Pastusa Suprema' presented an MARR of 18.5% with L2.

Acknowledgements

The authors express their gratitude for allowing the development of the present research in the project "Mejoramiento Tecnológico y Productivo del Sistema Papa en el Departamento de Nariño" financed by the *General Royalties System* (SGR by its Spanish acronym) with code BPIN N°2014000100022, executed by the Gobernación de Nariño and operated by the Corporación Colombiana de Investigación Agropecuaria – AGROSAVIA and the Universidad de Nariño - UDENAR.

Conflict of interests. The manuscript was prepared and reviewed with the participation of the authors, who declare that there exists no conflict of interest that puts the validity of the presented results at risk.

BIBLIOGRAPHIC REFERENCES

Avendaño Gómez, E. and W. González Santos. 2015. Evaluación financiera del sistema de producción de papa (*Solanum tuberosum* L.) en Oicatá, Boyacá. Cienc. Agric. 12(2), 31-41. Doi: https://doi.org/10.19053/01228420.4351

BANREP, Banco de la República - Colombia. 2020. Tasa de captación semanal y mensual. https://www.banrep.gov.co/es/estadisticas/tasas-captacion-semanales-y-mensuales; consulted: October, 2021.

BANREP, Banco de la República - Colombia. 2021. Informe de política monetaria. Issue 01. Bogota.

Benavides Cardona, C.A., C.A. Marcillo Paguay, E. Martínez Pachón, D.A. Calvache Muñoz, S.N. Yandar Erazo, L.F. Gómez Gil, and S.C. Insuasty Córdoba. 2021. Caracterización geográfica y tecnologías locales de producción asociadas al sistema productivo papa en el departamento de Nariño. pp. 53-91. In: Martínez Pachón, E., S.C. Insuasty Córdoba, C.A. Benavides Cardona, L.F. Gómez Gil, and P. Uribe Mejía (Comp.). Caracterización de los sistemas productivos de papa en Nariño 2015-2020: conocimiento para la toma de decisiones. Corporación Colombiana de Investigación Agropecuaria (Agrosavia), Mosquera, Colombia.

Borrego, F., J.M. Fernández, A. López, V.M. Parga, M. Murillo, and A. Carvajal. 2000. Análisis de crecimiento en siete variedades de papa (*Solanum tuberosum* L.). Agron. Mesoam. 11(1), 145-149. Doi: https://doi.org/10.15517/AM.V11I1.17364

Bravo Realpe, I., E. Campo, and C.A. Arboleda. 2016. Alófanos causa de indisponibilidad de aniones en suelos del departamento del Cauca – Colombia. Suelos Ecuat. 46(1/2), 13-30.

CIMMYT, Centro Internacional de Mejoramiento de Maiz y Trigo. 1988. Formulación de recomendaciones a partir de datos agronómicos: Un manual metodológico de evaluación económica. CIMMYT, Mexico, DF.

Colombia Fedepapa, Federación Colombiana de Productores de Papa. 2021. Boletín Regional Nariño. Vol. 5. Bogota.

Colombia ICA, Instituto Colombiano Agropecuario. 1992. Fertilización en diversos cultivos: quinta aproximación. Bogota.

Colombia ICONTEC, Instituto Colombiano de Normas Técnicas y Certificación. 1996. NTC 341: industria alimentaria, papa para el consumo, clasificación. Bogota.

Colombia Gobernación de Nariño. 2020. Plan departamental de extensión agropecuaria del departamento de Nariño 2020-2023. San Juan de Pasto, Colombia.

Colombia MADR, Ministerio de Agricultura y Desarrollo Rural. 2021. Cadena de la papa. Indicadores e instrumentos. Junio 2021. In: https://sioc.minagricultura.gov.co/Papa/Documentos/2021-06-30%20Cifras%20Sectoriales.pdf; consulted: October, 2021.

Corficolombiana. 2020. Rentabilidad esperada del capital propio (*Ke*). Cómo evaluar la eficiencia del mercadeo con el costo de capital. https://investigaciones.corficolombiana.com/documents/38211/0/20201123b%20-%20Rentabilidad%20del%20capital%20propio.pdf/e4211ef8-b113-9634-6870-e426a081be1b; consulted: October, 2021.

Esprella, R., P. Flores, and J. García. 2012. Guía práctica para producir nuestra semilla de papa de calidad: Guía para agricultores/ agricultoras y técnicos. Centro Internacional de la Papa, La Paz.

Fernandes, A.M. and R.P. Soratto. 2016. Phosphorus fertilizer rate for fresh market potato cultivars grown in tropical soil with low phosphorus availability. Am. J. Potato Res. 93, 404-414. Doi: https://doi.org/10.1007/s12230-016-9515-7

Ferreira, E.B., P.P. Cavalcanti, and D.A. Nogueira. 2013. ExpDes: Experimental designs package. R package v 1.1.2. In: https://cran.r-project.org/web/packages/ExpDes/index.html; consulted: October, 2021.

García Realpe, B. and L. Obando Guerrero. 1993. Fertilización del cultivo de papa en sistemas de producción en finca, departamento de Nariño. Rev. Cienc. Agric. 12(1), 21-31.

García, B. and C. Pantoja. 1998. Fertilización del cultivo de la papa en el departamento de Nariño. pp. 7-27. In: Guerrero, R. (ed.). Fertilización de cultivos en clima frío. 2nd ed. Monómeros Colombo Venezolanos, Bogota.

Henriquez, C., E. Bornemisza, and F. Bertsch. 1994. Fijación de potasio en vertisoles, inceptisoles, andisoles y ultisoles de Costa Rica. Agron. Costarr. 18(2), 133-140.

Hunt, R. 1978. Plant growth analysis. Edward Arnold Publishers, London.

Jerez Mompie, E.I., R. Martín Martín, D. Morales Guevara, and Y. Díaz Hernández. 2016. Análisis clásico del crecimiento en tres variedades de papa (*Solanum tuberosum* L.). Cult. Trop. 37(2), 79-87. Doi: https://doi.org/10.13140/RG.2.1.4860.0568

Jombart, T. 2008. Adegenet: a R package for the multivariate analysis of genetic markers. Bioinformatics 24(11), 1403-1405. Doi: https://doi.org/10.1093/bioinformatics/btn129

Koch, M., M. Naumann, E. Pawelzik, A. Gransee, and H. Thiel. 2020. The importance of nutrient management for potato production Part I: Plant nutrition and yield. Potato Res. 63, 97-119. Doi: https://doi.org/10.1007/s11540-019-09431-2

Marcillo Paguay, C.A., C.A. Benavides Cardona, C. Guatusmal Gelpud, S.N. Yandar Erazo, and J.V. Romero. 2021. Zona papera nariñense: una mirada a los ambientes productivos. Corporación Colombiana de Investigación Agropecuaria (Agrosavia), Mosquera, Colombia. Doi: https://doi.org/10.21930/agrosavia.nbook.7404777

Mohamed, E.M.E., M. Watthier, J.C. Zanuncio, and R.H.S. Santos. 2017. Dry matter accumulation and potato productivity with green manure. IDESIA 35(1), 79-86. Doi: https://doi.org/10.4067/S0718-34292017005000016

Monsalve, O.I., E.M. Espitia, and M.M Bolaños-Benavides. 2020. Split fertilization as a strategy to reduce the amount of fertilizer applied in potato crops form Colombia. Case of study. Rev. Colomb. Cienc. Hortic. 14(2), 240-248. Doi: https://doi.org/10.17584/rcch.2020v14i2.10523

Mora-Aguilar, R., J. Ortiz-Cereceres, A. Rivera-Peña, M.C. Mendoza-Castillo, M.T. Colinas-León, and H. Lozoya-Saldaña. 2006. Índices de eficiencia de genotipos de papa establecidos en condiciones de secano. Rev. Chapingo Ser. Hortic. 12(1), 85-94. Doi: https://doi.org/10.5154/r.rchsh.2004.09.049

Morales-Hernández, J.L., S. Rebollar-Rebollar, J. Hernández-Martínez, and F.J. González-Raz. 2015. Determinación del óptimo técnico y económico en el cultivo de papa de temporal. Paradigma económico. Revista de Economía Regional y Sectorial 7(1), 87-106.

Moreno, J. 2000. Variedades de papa cultivadas en Colombia. pp. 51-70. In: Herrera Heredia, C.A., L.H. Fierro Guzmán, and J.D. Moreno Mendoza (Comps.). Manejo integrado del cultivo de la papa. Colombiana de Investigación Agropecuaria (Agrosavia), Mosquera, Colombia.

Ñústez, C. 2011. Variedades colombianas de papa. Facultad de Agronomía, Universidad Nacional de Colombia, Bogota.

Pandey, R., V. Paul, M. Das, M. Meena, and R. Meena. 2017. Plant growth analysis. pp. 103-107. In: Paul, V., R. Pandey, and M. Pal (eds.). Manual of ICAR sponsored training programme on "Physiological Techniques to Analyze the Impact of Climate Change on Crop Plants". IARI, New Delhi. Doi: https://doi.org/10.13140/RG.2.2.21657.72808

Pinochet, D., J. Clunes, C. Gauna, and A. Contreras. 2018. Reasoned fertilization of potato in response to nitrogen supply in Andisols. J. Soil Sci. Plant Nutr. 18(3), 790-803. Doi: https://doi.org/10.4067/S0718-95162018005002301

R Core Team. 2021. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna.

Reyes Hernández, M. 2001. Análisis económico de experimentos agrícolas con presupuestos parciales: Re-enseñando el uso de este enfoque. Boletín 1. Universidad de San Carlos de Guatemala – Centro de Información Agrosocioeconómica, Guatemala.

Rios Quinchoa, J.Y., S.C. Jaramillo Villegas, L.H. González Santamaría, and J.M. Cotes Torres. 2010. Determinación del efecto de diferentes niveles de fertilización en papa (*Solanum tuberosum* ssp. Andigena) DIACOL Capiro en un suelo con propiedades Ándicas de Santa Rosa de Osos, Colombia. Rev. Fac. Nac. Agron. Medellin 63(1), 5225-5237.

Sánchez Espinosa, J.A. and Y. Rubiano Sanabria. 2015. Procesos específicos de formación en Andisoles, Alfisoles y Ultisoles en Colombia. Revista EIA Esc. Ing. Antioq. 12(2), 85-97.

Santos Castellanos, C., M. Segura Abril, and C.E. Ñústez López. 2010. Relación fuente – demanda de cuatro variedades de papa (*Solanum tuberosum* L.) en el municipio de Zipaquirá (Cundinamarca, Colombia). Rev. Fac. Nac. Agron. Medellin 63(1), 5253-5266.

Tinjacá Ruiz, S. and L.E. Rodríguez Molano. 2015. Catálogo de papas nativas de Nariño, Colombia. Facultad de Ciencias Agrarias, Universidad Nacional de Colombia, Bogota.

Wassihun, A.N., T.D. Koye, and A.D. Koye. 2019. Analysis of technical efficiency of potato (*Solanum tuberosum* L.) production in Chilga District, Amhara National Regional State, Ethiopia. J. Econ. Struct. 8(1), 34. Doi: https://doi.org/10.1186/s40008-019-0166-y

Zelelew, D.Z., S. Lal, T.T. Kidane, and B.M. Ghebreslassie. 2016. Effect of potassium levels on growth and productivity of potato varieties. Am. J. Plant Sci. 7(12), 1629-1638. Doi: https://doi.org/10.4236/ajps.2016.712154