NJAS - Wageningen Journal of Life Sciences 88 (2019) 1–9

Contents lists available at ScienceDirect

NJAS - Wageningen Journal of Life Sciences

journal homepage: www.elsevier.com/locate/njas

Research paper

Understanding the heterogeneity of smallholder production systems in the Andean tropics – The case of Colombian tomato growers

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ARTICLE INFO

Keywords:
data collection instruments
farming systems
agronomic efficiency of fertilizers
knowledge empowerment

ABSTRACT

In developing countries, a common goal is to improve horticultural production systems as a strategy to increase food security and to improve the living conditions of these rural communities. However, smallholder-based agricultural systems are highly heterogeneous due to the wide range of biophysical conditions to which the crops are exposed, and the diversity in the management practices. In order to implement programs aimed at improving the productivity of these systems it is necessary to recognize its variability in quantitative terms. The main objective of this work was to describe the heterogeneity associated to smallholder production systems, using as a case study the Colombian tomato growers. Data were collected from two tomato production zones located in the Colombian Andes and under two cropping systems being the open field (*OF*) and the greenhouse (*GH*) production models. In both zones, the climate was described based on historical records, soil samples were taken to determine the natural fertility and the growers' management practices were inquired. We also compared two instruments for data collection, surveys and detailed follow-ups. A higher heterogeneity in environmental conditions and management practices was evidenced for the *OF* system compared to the *GH* system. The fertilization strategies used by *GH* growers caused a significant increase in soil nutrient content, electrical conductivity and acidity. We found a higher productivity per square meter in the *GH* system, however the yield per plant was higher for the *OF* system (4.88 kg plant^{-1}) in comparison with the *GH* system (2.84 kg plant^{-1}). Results also indicated that follow-ups are an appropriate instrument to obtain accurate inventories. Knowledge empowerment arises as the key point to improve the smallholder's productivities; in opposition to results elsewhere, where economic constraints are highlighted as the important sources of variability and low yields.

1. Introduction

In developing countries, smallholder-based agricultural systems have great importance from a socio-economic point of view. These low-tech systems are focused on providing commodities demanded by domestic markets, at the minimum cost without a proper business-oriented model in place. Moreover, on the technical side, these production systems are characterized by a huge gap between actual and potential yields (Ruben and Pender, 2004; Tittonell et al., 2008). This gap is due to multiple factors, some of which are difficult to control, such as climate, while others rely on decisions made by the growers related to crop management, especially factors such as nutrient supply (Tittonell et al., 2008) and pest management. In addition, many production areas have biophysical constraints such as low natural soil fertility, steep slopes, and strong climatic uncertainty, especially with regard to water availability (Ruben and Pender, 2004). As a result, these production systems are distinguished by a huge heterogeneity in relation to crop yields (Ruben and Pender, 2004), inputs employed (Bojacá et al., 2012) and the subsequent environmental impact (Bojacá et al., 2014; Gil et al., 2017). In this work, the term heterogeneity is used to refer to a high-variation in quantitative variables, while the term diversity is used to refer to the variability observed in categorical variables. Moreover, this heterogeneity increases over time due to cycle-to-cycle variability in fertilization, irrigation and mechanization practices. This situation threatens the existence of these production systems, especially when there is land use competition for crops that

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https://doi.org/10.1016/j.njas.2019.02.002
Received 4 September 2018; Received in revised form 8 January 2019; Accepted 3 February 2019
Available online 12 February 2019
1573-5214/

offer higher profit margins and less susceptibility to environmental factors, such as oil palm (Chenoune et al., 2016).

Currently, the need to increase food production to meet the demands of a growing population (Licker et al., 2010), raises the interest to improve the productivity of smallholder farming systems, as an alternative to restrict the advance of the agricultural border (Vanlauwe et al., 2010). Smallholder systems have a greater potential to increase productivity as compared to high-tech systems. In addition, improving the productivity of those systems would also generate socio-economic benefits, such as an increase in growers income, improvement of the rural infrastructure, and ultimately raising the quality of smallholders' lives (Ruben and Pender, 2004). However, improving the productivity requires quantifying and understanding the current status of the system, including its variation degrees. This heterogeneity may lead to the variable performance of the new tools and technologies introduced to improve productivity (Tittonell et al., 2010). On this basis, it has been proposed that understanding the inherent heterogeneity of smallholder systems should be the first task to properly orient agricultural innovations (Chenoune et al., 2016). Acknowledging this heterogeneity will contribute to analyse other aspects such as the environmental impact of these systems.

Nowadays, Colombia is recognized as an emerging economy with investment-grade status; however, sectors such as agriculture still running on low technology techniques, especially subsectors such as horticulture. The country seems to have followed the standard policies of developing countries; which according to Ruben and Pender (2004), has left aside investment in smallholders to focus entirely on high potential agricultural production systems, seeking to promote rapid economic growth. At present, with the recently signed peace agreement, a great deal of attention is focused on the development of rural areas, not only those directly affected by the conflict but the rural sector in general with special emphasis on smallholders (Presidency of the Republic of Colombia, 2016). This will require investment in research and development to improve these production systems. However, to allocate resources in an efficient way, one must start with an up to date characterization portraying how heterogeneous these systems are, while also explaining the causes of this high-variation (Chenoune et al., 2016; Ruben and Pender, 2004).

The present work is a response to the limited body of information regarding the diversity of smallholders' agricultural systems in Latin America and with the certainty that this type of knowledge helps to improve the overall performance of these systems. We analysed the case of the tomato (*Solanum lycopersicum* L.) production system in Colombia, which, in addition to being the main horticultural crop in the country, is mostly developed by smallholders. Moreover, tomato is one of the main cropping alternatives to promote the development of rural areas, since the country has extensive agroclimatic zones suitable for this crop. Nowadays, tomato is mainly cultivated under two production systems: open field (*OF*) and under greenhouse (*GH*), whose planted areas in 2014 were 14,768 and 2305 ha, respectively (Agronet - Colombian Ministry of Agriculture and Rural Development, 2010).

The main purpose of this work was to study the heterogeneity associated to smallholder agricultural systems, using as a case study detailed data on Colombian *OF* and *GH* tomato systems. The following three specific objectives are proposed: (I) to describe the climate of the production zones under study as well as the spatial variation of the soil properties driving its fertility; (II) to expose the variability in the management practices under which tomato production is carried out by comparing the information obtained from two sources of data: surveys and detailed follow-ups; and (III) to analyse the agronomic efficiency of fertilizers use (nitrogen, phosphorus and potassium) for each production system.

2. Materials and methods

The data used in this work came from two of the main tomato production areas in Colombia located in the provinces of Guanentá in the departments of Santander (*OF* system) and Alto Ricaurte (*GH* system) inside the Boyacá department. The distance between the two production zones is 115 km. *OF* tomato production is carried out countrywide; however, five departments concentrate almost 60% of the national production. Santander was the second largest producer of tomatoes with a cultivated area of 1958 ha during 2014. As opposed to the *OF* production, *GH* tomato production is concentrated in 31% of the country departments, and the most important five hold 87% of the national production. Boyacá is the main GH tomato producer in Colombia with an area of 990 ha reported in 2014 (Agronet - Colombian Ministry of Agriculture and Rural Development, 2010).

For the *OF* system, data was collected in seven municipalities (802 km^2), namely Curití, San Gil, Mogotes, Pinchote, Valle de San José, Páramo, and Confines. Guerrero and Torres (2016) estimated a tomato planted area of about 320 ha in these municipalities, based on secondary data about annual seedlings sold by local nurseries. In the case of *GH*, data corresponded to the municipalities of Villa de Leiva, Sutamarchán, Sáchica, Tinjacá and Santa Sofia (441 km^2); for this region, the area under *GH* systems is approximately 330 ha, estimated through visual interpretation of satellite imageries Guerrero and Torres (2016). In Alto Ricaurte, *GH* tomato is the main crop, while in Guanentá the main crops are coffee (*Coffea arabica* L.) and sugarcane (*Saccharum officinarum* L.). These two systems represent the extremes of smallholder tomato production in Colombia, from the low input and low-tech production (*OF*) to a system with higher inputs and highest technology level (*GH*).

Data related to climate, soils fertility and main characteristics of both productions systems with emphasis on fertilization efficiency were employed for systems description. Data analyses quantified the heterogeneity and compared its magnitude between and within production systems depending on the data source. Special attention was paid to the effect of the *GH* tomato production on soil fertility.

2.1. Climate

For each production zone, climate data were obtained from the Colombian meteorological services agency (IDEAM). In Alto Ricaurte, the weather station was located in the municipality of Villa de Leiva (5°39′12″ N – 73°34′39″ W; 2060 masl), while in Guanentá the station was placed in the municipality of Mogotes (6°28′34″ N – 72°58′13″ W; 1680 masl). For both regions, the climate records corresponded to daily series spanning a 50-year period for Villa de Leiva station (1964–2014) and a 57-year period for Mogotes station (1958–2015); however, it is important to highlight that these time series presented a high proportion of missing data. For climate description purposes, we excluded the information of years with strong or very strong El Niño or La Niña effects, based on the Oceanic Niño Index (ONI). The climate variables included in the analysis were the monthly average precipitation (mm), daily mean temperature (ºC), relative humidity (%) and solar radiation ($MJ\ m^{-2}\ d^{-1}$). In addition to the daily or monthly average, the standard deviation was calculated as a measure of the interannual variation.

2.2. Natural soil fertility

Soil natural fertility was described based on 75 soils samples taken within each production area between May and July 2015. The samples were collected up to a 30 cm depth over fallow plots. Sampling spots were determined by a non-aligned random sampling procedure and adjusted once on the field to sample only uncropped soils. Based on the geographic coordinates of the sampling points, we determined the altitude and slope using a digital elevation model (DEM). Soil samples were processed in the soils laboratory of the Centro de Bio-Sistemas, belonging to the Universidad Jorge Tadeo Lozano. The analysis included chemical properties such as nitrate ($N\text{-}NO_3$), ammonium ($N\text{-}NH_4$), phosphorus (P) and potassium (K) contents, pH, electrical conductivity (EC), soil organic carbon (SOC); and physical properties such as clay, silt and sand contents (%). Exchangeable $N\text{-}NH_4$ and $N\text{-}NO_3$ were determined by extraction with KCl, and the solution was analyzed

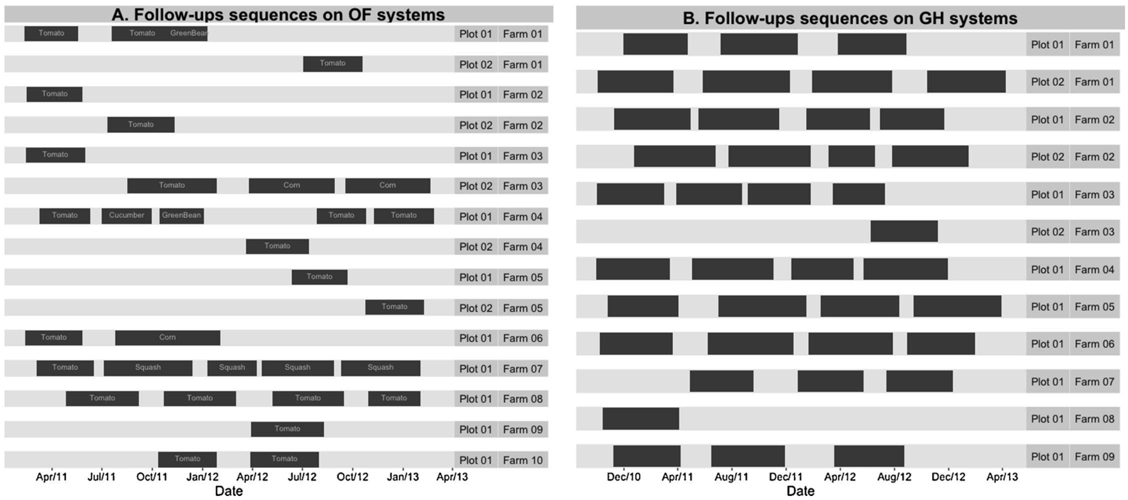

Fig. 1. Tomato crop cycles sequence observed during the follow-ups data collection period in the (A) *OF* and (B) *GH* systems. Each segment represents the cycle length from transplanting until the end of harvest.

as described by (Bremner and Keeney (1966)). Available P was determined by the Bray II method, K by flame photometry, pH and EC were determined in a 1:2 (v/v) soil:water suspension, SOC by the wet oxidation method and texture was measured through a hydrometer.

A preliminary data inspection evidenced unusually high values in some samples, which were detected based on the square Mahalanobis distance and the quantile 0.98 of a chi-square distribution, with the number of variables as degrees of freedom, to set the threshold from which a sample is considered unusual (Gnanadesikan, 1977; Filzmoser et al., 2005) Those samples probably corresponded to recently cropped areas; therefore, we excluded them from the analysis. Final datasets comprised 67 and 70 records for Guanentá and Alto Ricaurte, respectively. We used the mean ($\bar{x}$) and median (Md) to describe the centrality and data distribution, while the coefficient of variation (CV) was used to report the heterogeneity within and between zones. To compare the soil properties between the two zones, we first verified the data fit to a normal distribution (Kolmogorov–Smirnov test) and the homogeneity of variances (Levene test). For normally distributed and homoscedastic variables, the t-student test (at 95% confidence level) was used to compare the variables between production zones. For non-normal distributions and heteroscedastic variables, the Mann–Whitney non-parametric U test (at 95% confidence level) was applied.

Afterwards, a principal component analysis (PCA) was performed with the soil natural fertility dataset composed of 10 variables and 137 soil samples. We did the PCA to arrange the soil samples along an underlying natural fertility gradient, and also to establish the association among variables by means of the cosine angle between the vector variables. PCA results were represented as biplots, in which only the first two principal components were plotted.

2.3. Effect of the GH system on soil properties

As part of the characterization, we determined the effect of *GH* production on soil properties. We only considered the *GH* system since no rotations are involved, and planting can be done at any time throughout the year. Based on the above, changes in soil properties depend exclusively on the fertilization management conducted by the growers. To analyze the effect of *GH* production, we took 30 cm depth soil samples inside greenhouses with more than two years dedicated to tomato production and on adjacent non-cultivated areas (100 to 500 m away from the greenhouse edges). Samples were analyzed at the soils laboratory of the Centro de Bio-Sistemas following the methods described above for natural soils fertility dataset. We took 38 pairs of soil samples during June 2013. We used the U test or t-test to compare the soil properties differences (inside and outside the greenhouse) depending on the outcome of the normality and homoscedasticity tests, as it was described in for natural soils fertility.

2.4. Production systems characterization

Two data collection tools were used to characterize the production systems: surveys and follow-ups. The surveys consisted on face-to-face interviews of closed-ended questions applied between 2009 and 2010 to 80 and 174 randomly selected growers from the *OF* and *GH* systems, respectively. The survey instrument was designed to collect information at both farm and plot level. At farm level, data corresponded to available infrastructure (e.g. greenhouse features, water sources, infrastructure), household characteristics and marketing strategies. At plot level, we asked about technical aspects related to the last growing cycle such as cropped area, plant density, cycle length, type and amount of fertilizers, crop management practices, irrigation rate and yield.

For the follow-ups, we selected among the surveyed growers a group of farmers to carry out detailed inquiries on consecutive tomato production cycles. At the beginning of each production cycle, we measured some crop features such as planted area, plant density, and features associated to the available infrastructure. Remaining features were recorded through weekly interviews with the growers, focused on crop management practices including time and resources allocation, irrigation schedule, dosing and timing for inputs used in fertilization, as well as fruit production. The follow-ups were conducted from soil preparation to the end of harvest. In Guanentá, we collected data on 32 production cycles, from October 2011 to February 2013. Since *OF* tomato is rotated with other horticultural crops, just 22 of them corresponded to tomato cycles. For the *GH* system we recorded activities on 39 tomato cycles located in nine farms from September 2010 up to March 2013. As no crop rotation is involved under GH system, all information collected was related to tomatoes. A schematic sequence of the production cycles that composed the follow-ups dataset can be seen in Fig. 1.

Finally, an agronomic efficiency of fertilizer use (AEF), in which, tomatoes yield was divided by the amount of nitrogen, phosphorus and potassium applied by each grower. For this purpose the approach proposed by Aujla et al. (2007) for nitrogen, extended for phosphorus and potassium, was used, as shown below:

$$AEF_{i,j} = \frac{Y_i}{UF_j}$$

where, $AEF_{i,j}$ is the agronomic efficiency of fertilizer use for the jth fertilizer (j = nitrogen, phosphorus or potassium) and for the ith grower, Y_i is the yield obtained by the *i*th grower (kg ha^{-1}) and UF_j is the amount of fertilizer used by each grower (kg ha^{-1}). This *AEF* is reported as kg tomatoes yield per kg of fertilizer applied. The results were used to compare the Colombian production systems to others elsewhere.

Data analysis was carried out in the same way as for the soils fertility dataset. After outliers detection and exclusion, descriptive statistics such as the mean and median were used to describe the centrality and distribution of the considered variables, while the *CV* was included to quantify the uncertainty. As the *CV* is invariant to measurement units, it allowed comparing the variation degree between data sources and production systems. The final dataset for crop management was composed for 71 and 138 tomatoes cycles characterized by surveys for *OF* and *GH* systems, respectively; while 22 (OF) and 38 (GH) cycles were characterized by detailed follow-ups. All statistical procedures described above were implemented through the R statistical software (R Core Team, 2017).

3. Results

3.1. Climate

Fig. 2 shows the average monthly precipitation and daily temperature throughout an average year in both production zones. A bimodal rainfall pattern was observed for monthly precipitation in both zones (Fig. 2A). However, in Guanentá, average (± standard deviation) annual rainfall is higher (2457 ± 125 mm) compared to Alto Ricaurte (1112 ± 78 mm). In addition, rainfall seasons are more intense in Guanentá province occurring between the strong dry season of December and February and the mild dry season of June and August. This rainfall distribution ensures a good water supply during most of the year; although topography in this zone restricts the access to water near the mountaintops. Oppositely, the water supply is drastically reduced in Alto Ricaurte during its two dry seasons, which occur between December-February and June-August (Guerrero and Torres, 2016).

Regarding temperature, Guanentá has higher temperatures throughout the year as compared with Alto Ricaurte (Fig. 2B). In Guanentá, the average (± standard deviation) annual temperature is

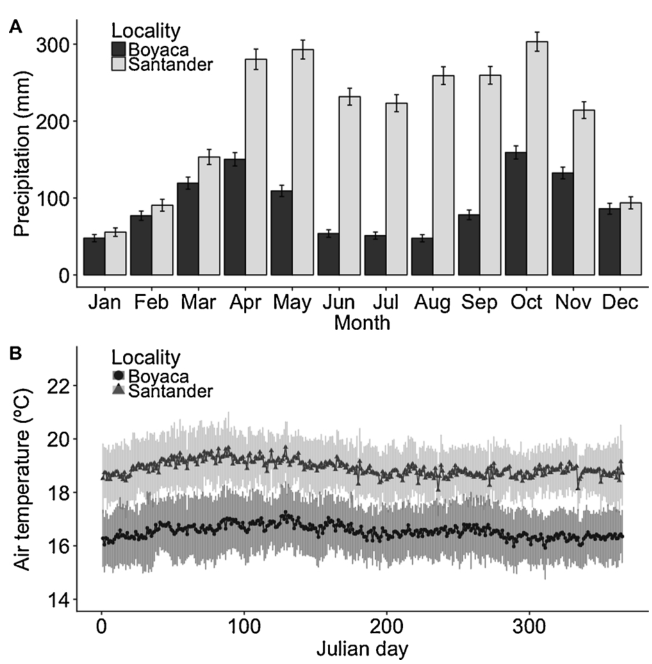

Fig. 2. Average monthly precipitation (A) and daily temperature (B) of the production regions of Boyacá and Santander. For precipitation, error bars represent the standard deviation, while for temperature the shaded area indicates the standard deviation.

18.9 ± 1.0 °C while in Alto Ricaurte is 16.5 ± 1.1 °C. However, the temperature exhibits a greater spatial variation, especially in Guanentá due to the mountainous landscape. Simultaneous climatic records on two tomato crops, one located at 1700 m (6°25′15″ N, 73°11′56″ W) and the other at 1150 m (6°28′55″N, 73°06′54″ O) and distanced by 11.5 km, presented average daily temperatures of 19.5 and 22.8 °C, respectively. The low average temperature in Alto Ricaurte production zone is the main reason why farmers use greenhouses structures for tomato production. In contrast to precipitation, the temperature does not show a strong seasonal trend, although the maximum temperatures are usually recorded between February and March (26.9 °C in Guanentá and 23.6 °C in Alto Ricaurte). Regarding the relative humidity (RH), the annual average (± standard deviation) is lower in Alto Ricaurte province (75 ± 2.5%) compared to Guanentá (81 ± 2.0%) and variations throughout the year follow the same trend of the rainfall. Finally, solar radiation exhibited a similar trend to the temperature, without showing a marked seasonality; however, the annual average (± standard deviation) is slightly higher in Guanentá (16.45 ± 1.07 MJ m^{-2} d^{-1}) than in Alto Ricaurte (15.52 ± 1.12 MJ m^{-2} d^{-1}).

3.2. Soils

The results of the mean differences test between both provinces indicated that all soil properties showed significant differences with the exception of N-NO_3 content and SOC. According to the results, the tomato production area in Guanentá province has sandier textures, steeper slopes, higher content of N-NH_4 and higher soil acidity; but lower P and K contents, as well as a lower EC, as compared with Alto Ricaurte (Table 1). Concerning data distribution, in both production areas, most of the variables had positive biases; that is, a higher data proportion with values below the mean were observed.

In Alto Ricaurte biases were more pronounced in variables such as N-NO_3, P and EC, and to a lesser extent in N-NH_4 content. In Guanentá, although the biases were less pronounced in comparison with Alto Ricaurte, the variables with the greatest asymmetry were N-NO_3, N-NH_4, P and K contents. The main difference between both production zones, with respect to data distribution, was observed for terrain slope. While in Guanentá the slope is distributed symmetrically, in Alto Ricaurte it is have a slight positive bias. The only variables that consistently showed a symmetric distribution were the content of clay and sand (soil texture).

Regarding the variation, the *CV* revealed that soil properties in both production zones exhibited a high heterogeneity. However, with exception of the P, K and clay content, other variables showed a greater variation degree in Alto Ricaurte. Although variations are function of the production area, largest ones (in order of importance) were detected for N-NO_3, P, N-NH_4 and EC, in both zones, but the latter with a particularly high *CV* in Alto Ricaurte province (115%). On the other hand, pH was the variable that showed the lowest variation in both production zones; however, it should be taken into account that pH is expressed on a logarithmic scale. The bias shown for most of the variables in both production zones, together with the high *CV* indicate a huge heterogeneity in natural soils fertility, which is particularly low in Guanentá province.

Regarding the PCA results, the total variance explained for the first two components were 51.52% with 34.45% explained in the first component and 17.07% by the second component. Fig. 3 shows the biplot for the first two components describing the soil properties variation as well as the relationship between the variables. According to the vector lengths, which represent each variable, all of them exhibit large variances with the exception of SOC and terrain slope. Largest variances correspond to sand and clay contents, which contribute in greater proportion to the first component. The first factorial axis discriminates the soils by its location and associates the characteristic properties to each one. However, data distribution on the factorial plane, moving away from the biplot center in different directions, shows the soils heterogeneity, even within the same production area. Different degrees of correlation were observed based on the cosine

Table 1
Natural fertility characterization of the soils used for tomato production in open field (Santander) and under greenhouse (Boyacá) production systems.

Variable	Unit	Open-field			Greenhouse			p-value
		Mean	Median	CV	Mean	Median	CV	
Ammonium (N-NH_4)	mg kg^{-1}	10.59	9.00	55	8.28	6.25	73	< 0.05
Nitrate (N-NO_3)	mg kg^{-1}	5.13	3.90	94	4.44	2.95	108	0.40
Phosphorus (P_2O_5)	mg kg^{-1}	15.22	6.65	144	71.27	37.81	110	< 0.05
Potassium (K_2O)	mg kg^{-1}	158.05	127.70	72	219.10	199.98	63	< 0.05
pH		5.09	4.80	15	5.93	5.65	17	< 0.05
EC	dS m^{-1}	0.15	0.11	79	0.65	0.34	115	< 0.05
SOC	%	2.10	1.98	43	1.90	1.70	48	0.19
Slope	%	11.01	11.01	51	5.87	5.17	57	< 0.05
Sand	%	44.86	43.50	29	27.53	27.70	42	< 0.05
Clay	%	17.66	16.70	49	29.56	28.75	37	< 0.05

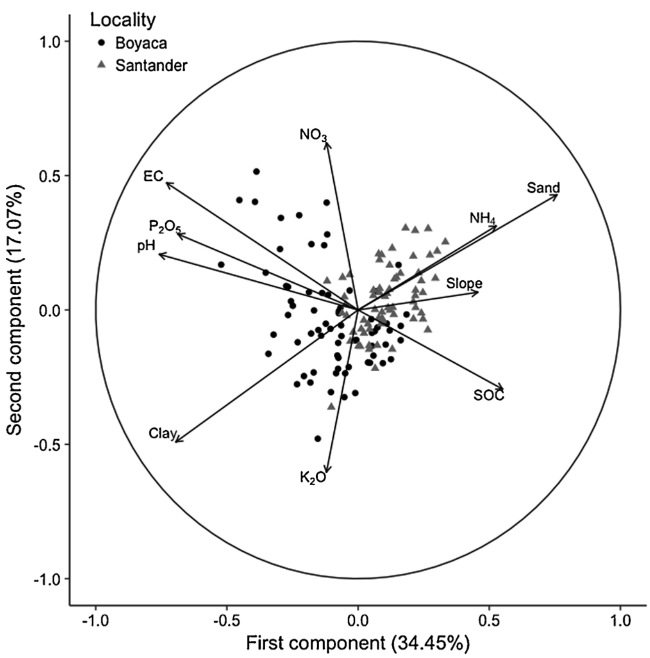

Fig. 3. PCA-biplot showing the soil variation based on measurements of physical and chemical properties.

angle formed between each pair of variables. A high positive correlation was observed between pH and P availability; since in both zones, soils are acids (Table 1). The correlation indicates that a lower soil acidity generates a greater availability of P. Also, a high positive correlation was observed between the sand content and N-NH_4; this relationship is observed because a higher proportion of sand limits the N-NH_4 nitrogen fixation by the clay fraction. Finally, negative associations were observed among some variables; the slope is negatively correlated with the pH and P content.

The comparison between soils located inside and outside greenhouses revealed the impact of tomato production on soil properties in Alto Ricaurte study area. This comparison allowed understanding the effect of continuous monocrop of tomato under *GH* conditions on the soil fertility. Table 2 shows the properties differences between both soil types. The *GH* tomato production significantly modifies some soil properties, increasing the nutrients content (NPK), and consequently the EC. Beyond the statistical significance, it is important to highlight the huge increase in some nutrient contents; on average, N-NO_3 and P_2O_5 were 6.7 and 5.2 times higher inside *GH* compared with the uncultivated soils around them. For pH, SOC, sand and clay, no significant changes were detected as a consequence of *GH* tomato growing. The results showed how the chemical properties on surface soils layers (0–30 cm) are more susceptible to being modified by agricultural practices management; which agrees with what was reported by (Yemefack et al., 2005).

3.3. General characteristics of tomato production systems

The main characteristics of tomato production systems are described below; firstly, as a general overview and afterwards the emphasis is on management practices, particularly those related to NPK fertilization.

In the *OF* system, the small processing-type *chonto* tomato is cultivated while under the *GH* system both, *chonto* and beefsteak-type, tomatoes are cropped. In both systems, production is carried out almost exclusively on soil (*OF* = 100%, *GH* = 99.28%), starting with four weeks old seedlings. In both zones, hybrid cultivars with a high genetic potential are planted; under *GH* the two main cultivars are planted by 80.1% of the growers; while in *OF* there are a greater diversity of cultivars, and this percentage drops to 38.1%. All tomato production is destined to fresh consumption in the Colombian local markets. Under both systems, plants are guided by a training system consisting of a wooden structure on which galvanized wires are laid. In the *OF* system,

Table 2
Soil properties comparison between uncultivated soils and those used for tomato production under the *GH* system.

Variable	Unit	Uncultivated soils		Soils under greenhouses		p-value
		Mean	CV	Mean	CV	
Ammonium (N-NH_4)	mg kg^{-1}	13.80	88	34.50	55	< 0.05
Nitrate (N-NO_3)	mg kg^{-1}	10.66	133	71.82	82	< 0.05
Phosphorus (P_2O_5)	mg kg^{-1}	98.74	126	510.77	132	< 0.05
Potassium (K_2O)	mg kg^{-1}	280.75	132	535.85	93	< 0.05
pH		6.13	18	6.57	16	0.08
EC	dS m^{-1}	0.58	101	2.57	52	< 0.05
SOC	%	1.73	67	1.95	64	0.42
Sand	%	30.25	39	35.24	34	0.07
Clay	%	41.76	23	41.83	22	0.97

the training system is installed and removed for each cropping cycle, while under the *GH* system is a permanent structure. Greenhouses are naturally ventilated, consisting of a wood structure covered with a single sheet of polyethylene, without active climate control systems. Most of *GH* farmers prune stems (98.6%), to have vigorous single stem plants, but also senescent leaves (99.3%) and even fruits (24.5%) are pruned; while the *OF* farmers omit all these practices. Unlike the *GH* system, which is dedicated exclusively to tomato production, many *OF* smallholders rotate tomato with other species (58.8%) such as corn (*Zea mays*), green beans (*Phaseolus vulgaris*), cucumber (*Cucumis sativus*) and squash (*Cucurbita* spp.).

Tomato growers are also characterized by a low associativity level (no growers associations or similar were found) and consequently, their trading power with suppliers and customers is also low. The farmer's educational level ranges from basic to secondary levels (84.2%), but this does not imply that they have received agricultural-oriented formation. Growers infrequently share information with each other, but access to extension services is relatively high (*OF* = 55.3%; *GH* = 78.0%); however, these services comes mostly from agrochemical dealers (*OF* = 48.7%; *GH* = 69.3%) whose impartiality is questionable due to their commercial interests. Based on the above, each producer builds his own experience that uses as the main criterion for decision-making. The growers have a relatively low experience in tomato cultivation, in the OF system 90% of the producers have an experience less than 6 years, while in GH this experience time reaches 10 years.

Tomato fertilization is carried out using both organic and synthetic sources. As indicated by the detailed follow-ups, nitrogen (N) input comes mostly from synthetic sources (*OF* = 83.1%, *GH* = 68.6%), while the remaining is applied in the form of organic sources. In the *OF* system, the most used synthetic fertilizers correspond to multi-nutrient solid fertilizers and the most frequent formula are 10-30-10 (20.6%) and 15-15-15 (11.0%). Under the *GH* system, the most used fertilizers are soluble multi-nutrient represented by a great diversity of brands, along with nitrate salts of calcium, magnesium, and potassium. In both systems, chicken manure (*OF* = 53.7%, *GH* = 45.7%) is the preferred organic fertilizer source. Growers commonly use chicken manure because Guanentá province is an important area in terms of poultry production (Guerrero and Torres, 2016); consequently, manure is an abundant and cheap organic source, which is used by both, *OF* and *GH* growers. The fertilization method is different for each production area. In Guanentá, solid fertilizers are diluted in water, sometimes mixed with organic sources or amendments such as lime, which are manually applied per plant; this procedure is repeated several times along the production cycle. In contrast, 100% of the *GH* growers apply highly soluble fertilizers through basic fertigation systems.

3.4. Tomato production systems description

Table 3 presents the main characteristics of the two tomato production systems under study. We gave emphasis on the *AEF* for NPK fertilizers. In the *OF* system, a lower planting density is used, the production cycles are shorter, larger areas are planted and the yield per hectare is lowest as compared to the *GH* system. Regarding productivity, although it is higher per square meter in the *GH* system, when standardized by the planting density, we observed that the plant average yields were higher for the *OF* system (4.88 kg $plant^{-1}$) in comparison with *GH* system (2.84 kg $plant^{-1}$). In the *OF* system, the surveyed growers reported an average yield 18.8% lower than the one calculated through the follow-ups; while for the *GH* system it was the opposite, surveyed growers reported an average yield 38.22% higher than the one determined with the follow-ups. Yield *CV* calculated from the follow-ups showed a lower dispersion (*OF* = 66%, *GH* = 54%) than the one obtained by the surveys (*OF* = 120%, *GH* = 75%). In relation to water inputs, in the *OF* system the water supply by irrigation presented the lowest *Md* (Table 3) and simultaneously the highest *CV* ; this is due to the dependence of the crop on rainfall water contributions, which are highly variable. Under the *GH* system, the water input comes entirely from the irrigation, and contrary to *OF*, it is a variable with relatively low degree of variation. Based on these results, it was established that *OF* yields have associated a greater degree of uncertainty in comparison to those of the *GH* system.

3.5. Agronomic efficiency of fertilizer use

In both systems, the yield obtained per kg of fertilizer applied changed depending of the data collection tool (survey or follow-ups). In the *OF* system, a poor *AEF* (i.e. a lower yield per kg of fertilizer applied) was determined through the follow-ups as compared with results obtained for the surveys. The appositive trend is observed for nitrogen and phosphorus in the *GH* system, where the survey´s showed a poor *AEF* in comparison with follow-ups dataset.

The *CV* calculated for both data sources also showed differences, decreasing when the follow-ups data were used. The *CV´s* estimated for the AEF based on the surveys presented average value of 198%, whereas when them were calculated based on the follow-ups this value was reduced to 78%. This confirms the reduction in the uncertainty caused by the follow-ups data collection tool.

In both production systems, the distribution of the *AEF* showed a positive asymmetry. This bias was propagated from previous estimates (e.g. yield) which also presented it. In the *OF* production system, the follow-ups dataset reduced this asymmetry, which was evidenced by a smaller difference between the median and mean. In the *GH* system, although the trend was similar and reduction in asymmetry was observed, the *AEF* showed a slight increase in its bias when estimation was derived from the follow-ups dataset.

Based on the above, detailed follow-ups provided more accurate information to describe not only the *AEF*, but also about other features related to tomato production. The weak point of follow-ups is that sample size which is lower, compared with the obtained by surveys,

Table 3
Main features of the open field and greenhouse tomato systems determined through surveys and detailed follow-ups.

Production factor	Unit	Open field						Greenhouse					
		Survey			Follow-up			Survey			Follow-up		
		Mean	Median	CV	Mean	Median	CV	Mean	Median	CV	Mean	Median	CV
Plant density	plants m^{-2}	1.3	1.2	27	1.1	1.1	28	3.0	3.1	17	3.0	3.0	15
Cycle duration	days	116.0	112.0	9	114.0	109.0	15	186.0	183.0	16	166.0	166.0	12
Cultivated area	m^2	4986.4	4000.0	78	6004	3750	103	2522.7	2425	43	3000.6	2835	46
Yield	t ha^{-1}	43.6	35.9	53	53.7	47.5	50	117.9	111.1	45	85.3	87.5	37
Irrigation	l m^{-2}	387.1	230.4	129	120.3	46.5	152	603.2	495.2	65	521.7	467.5	65
Precipitation	mm	916.4	912.0	10	220.5	231.0	36	–	–	–	–	–	–
AEF, total nitrogen	kg kg^{-1} N	645.6	254.8	215	370.1	264.5	77	241.7	183.3	82	272.6	200.2	66
AEF, phosphorus	kg kg^{-1} P_2O_5	701.6	207.5	258	278.7	183.2	79	249.8	168.9	211	435.0	213.6	123
AEF, potassium	kg kg^{-1} K_2O	803.5	233.2	305	221.8	157.5	59	190.2	136.2	121	162.9	131.5	67

affecting the results representativeness. Although it should be taken into account that the follow-ups, in the context of the present study, allowed to increase the temporal representativeness by had recorded consecutive tomato production cycles in the same lot. Finally, it should be remarked that minimum *CV* for *AEF* was 59%, even for the follow-ups dataset; this shows the high diversity in fertilization management practices.

4. Discussion

In the study zones, the contrast in climatic conditions shows the heterogeneous conditions in which horticultural production takes place in Colombia. While in Guanentá province, the climate is warm and humid, in Alto Ricaurte it is cold and dry; both zones have bimodal rainfall distributions and strong spatial variations in temperature caused by the mountainous landscape, especially in Guanentá. Although smallholders seem to be aware of constraints imposed by the climate, they adapt trying to find genotypes able to tolerate rough weather conditions; in *OF* systems, this is especially evident by the greater diversity of cultivars planted. They also appeal to planting during favorable periods, or building low-tech structures to protect plants from extreme conditions. However, the use of climate control technologies to create a comfortable environment for plants is not a priority, even for farmers that use greenhouses. As a consequence of the low-tech greenhouses used, the internal microclimate strongly depends on external conditions (Bojacá et al., 2009). This means that Colombian smallholder farmers, as well as in other parts of the world (e.g. Africa), are highly susceptible to the constraints imposed by the climate (Tittonell et al., 2007).

The results of the present work showed low fertility soils, especially in *OF* production zone; associated to a high heterogeneity, mainly observed in Alto Ricaurte where tomato is cropped under GH. In *OF* production zone, soils are representative of tropical zones, characterized by high acidity levels and low concentrations of total N and P, mainly due to the high precipitation regime during a large part of the year (Haileslassie et al., 2005). This general description for tomato production systems coincides with reports that associate smallholder agricultural production with low fertility and heterogeneous soils (Haileslassie et al., 2005; Tittonell et al., 2007; Yemefack et al., 2005). Given the scant information about the effect of low-tech greenhouse production systems handled by smallholders on soil fertility, our results are novel by showing an unbalanced nutrient enrichment of the soil top layer. This is the opposite of results reported for African agricultural soils managed by smallholders, in which a depletion of soil fertility has been documented (Haileslassie et al., 2005). But this increase in nutrients soil stock does not necessarily mean an increase of the tomato yields because other factors such as specific nutrient deficiencies or too low pH's values constrain the effects of fertilizer application.

The high concentration of some nutrients such as total N and P on the topsoil layer poses a risk to the environment (Kwong et al., 2002). While soils remain covered by greenhouses, the mobility of these nutrients will be constrained by low water inputs and is expected that losses occur toward the air by processes such as volatilization. However, if these soils return to *OF* production systems a flow of the accumulated nutrients toward water sources during the rainy seasons by runoff and leaching will be expected (Kwong et al., 2002).

Regarding the data sources employed, the results showed that the survey has a greater uncertainty ($CV > 120\%$ in *OF* and $CV > 75\%$ in *GH*) compared with the follow-ups. It is important to highlight that smallholders rely on their memory to keep record of the management practices such as fertilization. Additionally, smallholders vary their strategies from cycle to cycle making it difficult to characterize the system with a snapshot instrument such as the survey. On the other hand, follow-ups are more time-consuming, expensive and the numbers of observations generally are lower. Despite the above, the follow-ups offer a higher resolution, especially concerning input and output inventories. We suggest the follow-ups as the collection instrument in cases where, in addition to the socio-economic characterization, data will be used to estimate aspects such as system efficiency, environmental impacts or others where high accuracy is required.

The results of the present study also expose the diversity of management practices employed by growers, supporting Tittonell and Giller (2013) in the sense that local farming practices determines, together with the environment and genotype, the final yield. The results show important variations for both *AEF* (CV > 59%) and application methods, ranging from the dilution of solid fertilizers mixed with organic fertilizers and amendments in *OF*, to the use of fertigation under *GH*. This fertilization practices diversity, along with others not included in this work (e.g. pest management), caused the observed heterogeneity in yields; similar cases have been documented in other production systems managed by smallholders (Tittonell et al., 2005, 2007; Bojacá et al., 2012). In this regard, it should be noted that the lower variation found in the *GH* production system has been associated with a less dependency on environmental conditions, achieved by the plastic isolation (Gruda, 2005). Regarding to the *AEF*, in absence of a local reference that relates the potential tomato yield with the amounts of NPK-fertilizers necessary to obtain it; we use as a reference the averages calculated from Hatirli et al. (2006), Boulard et al. (2011), Torrellas et al. (2012) and Payen et al. (2015) for greenhouse tomato crops grown on soil; which were 359.5 (kg kg^{-1} N), 433.5 (kg kg^{-1} P_2O_5) and 222.7 (kg kg^{-1} K_2O), respectively. Comparing these values with our results (medians) it is clear that, despite technological levels and environmental offer differences, a wide margin to improve the *AEF* in local systems still present. It is known that small farmers' knowledge is a determining factor to decide the amount of fertilizers used, and seems that they have the pre-established idea that always a larger fertilizers application lead to a yields increase (Pishgar-Komleh et al., 2017; Tittonell et al., 2007, 2008). Therefore, results here presented generate concerns from both economic and environmental point of view. Tomato growers seem to have a high-risk aversion and decide to invest in excessive fertilization doses to be confident that no yield reduction will occur due to this production factor. In Colombia, the inadequate fertilization strategy by tomato growers not only decreases the efficiency of the system but also increase soil nutrient stocks and therefore, increase the risk of environmental pollution, as was shown for the *GH* system. On the other hand, in *OF* systems higher fertilization rates together with a high precipitation regime create the ideal conditions for nutrient (N and P) losses through leaching and runoff.

Contrary to the African scenario, where low efficiencies and heterogeneity observed in smallholder systems are associated, additionally to climate and soil natural variations, to low fertilization rates due to economic constraints (Ruben and Pender, 2004; Tittonell et al., 2005); high productive potentials seeds and high fertilization rates show that farmer's endowments are not the main cause of current low yields. In this sense, our results show a huge potential to increase productivity in tomato production in systems managed by smallholders in the Colombian Andes. However, achieving this purpose is conditioned by understanding the biophysical constraints in the production zones and diversity of management practices employed by growers. This is a well-documented prerequisite to be able to define locally adapted alternatives aimed at increasing farmer's yields (Tittonell et al., 2007, 2010; Vanlauwe et al., 2010). In the case of smallholders, is equally inconvenient to ignore the heterogeneity and diversity characteristic of these systems, as well as trying to design customized strategies based on all possible combinations between environmental conditions and farmer capacities. According to (Vanlauwe et al. (2010)), a realistic approach should be based on agroclimate zones delimitation and characterization to develop standardized practices addressed to increase productivity and this aligned with farmer's endowments; and at the same time chasing an increase in the farmer's knowledge level. In Colombia a major cause of low yields seems to be the low level of knowledge that farmers have about their production system, which is reflected in the set of management practices that contradict the technical criteria.

The low knowledge level is not only due to the educational level but is also associated with other shortcomings of smallholders such as restricted access to truthful and unbiased information sources, and the low level of associativity. Regarding the sources of information, our results showed that small producers access extension services mainly from agricultural inputs suppliers and in less proportion from universities that intermittently execute research projects; while extension services from governmental agencies are almost null. Grower's exposure to low-quality information sources creates skepticism regarding the adoption of new technologies and/or results of research processes. Recently, Weber and McCann (2015) found that knowledge transfer is less likely to be adopted by growers when coming from agrochemical dealers. On the other hand, low associativity limits the flow of information among producers, which has been recognized as an important factor to increase the level of knowledge of grower's communities (Wall, 2007). To improve the farmer's technical skills is challenge that should be focused on developing and implementing strategies that lead to a knowledge empowerment situation. Smallholder growers, beyond being able to implement a particular technology, should be formed to evaluate the recommendations from different sources and decide rightly the most convenient one with full awareness of the complexity of their production system. This kind of approaches has emerged as alternatives to improve the productivity of smallholder-base production systems in developing countries (Friis-Hansen, 2004). For that reason, a formal training program directed to producers has been proposed as a strategy to increase the *AEF* (Luo et al., 2016; Pishgar-Komleh et al., 2017). The aim is to abandon the excessive application of fertilizers as a strategy to increase yields; and on the contrary, to focus on improving management practices that increase *AEF*.

Based on our results, we propose three management practices that have already proven be effective to increase *AEF*. First, to carry out a soil test before each planting and use its results jointly with plant demands to define the fertilization strategy, with respect to fertilizers types, quantities, and timing (Pishgar-Komleh et al., 2017). This is especially important in the *OF* system, in which annual rains modify the soil nutrient contents and pH values. Second, to train the farmers to use correctly the different types of fertilizers (Wang et al., 2018), and avoiding incorrect practices such as those described for the *OF* system, in which solid soil fertilizers are applied water diluted. Third, to use amendments to correct soil limitations (e.g. pH) that allow increase nutrients the availability (e.g. P). Although apparently are simple tasks, smallholders prefer strategies directly linked to nutrient supplies, which difficult the appropriation of this kind of approaches focused in improving the soil characteristics to facilitate the plant nutrients uptake (Lopes et al., 2018). Based on the above, we propose as hypothesis for future works to assess if adjustments of the fertilization strategies carried out by farmers with a higher level of knowledge about the production system would achieve an increase in *AEF*, using as a baseline the results presented in this work.

5. Conclusions

In Colombia, smallholder tomato growers face the commercial-oriented production planting high production potential genotypes, which they grow in heterogeneous climatic conditions and on soils with low fertility levels, in some cases characterized by properties (e.g. pH) that could limit the crop response to the fertilization. Despite this, growers resort to excessive fertilization as the main strategy to increase production, which leads them to obtain highly variable yields.

With respect to data sources, surveys consistently showed greater variation in relation to the amount of inputs employed in the production cycle and yields. This is due to smallholders referred in this work do not keep formal records about production cycles, making of surveys an ineffective instrument to capture data concerning inputs inventories. As an alternative, we evaluated and propose to carry out detailed follow-ups on production cycles; although, the sample size is reduced and it is a time-consuming method compared to surveys.

Based on the low fertilizer use efficiencies but the good endowments with which growers count, there is an enormous potential to increase the yields of smallholders. However, this increase seems to be strongly conditioned by an increase in farmer's knowledge. Yield improvements demand changes in the fertilization strategy; leaving aside over-fertilization practices and instead, adopt a soil management strategy based on soil analysis, plant requirements and amend the soils factors that limit the plant nutrient uptake. Until this happens, mismanagement practices carried out by growers could be increasing the risk by creating favorable conditions for nutrients losses to the environment.

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