Research Findings

Coffee plantation at Cajibio, Colombia. Photo by A. Salamanca-Jiménez. 2017.

Coffee Crop Fertilization in Colombia: A Mini-Review

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Abstract

Colombian coffee crops are mostly grown in mountainous areas that are susceptible to soil moisture fluctuations and soil acidity, and are subjected to the effects of climate change. The interactions between nutrients and water availability are complicated and critical determinants of coffee productivity, and hence, designing and implementing appropriate crop nutrition management represents significant challenges. The coffee crop cycle at Colombian plantations is very short; an early and full realization of the yield potential is essential and may be accomplished through suitable nutrition approaches. In terms of fertilization, research has mainly focused on nitrogen, and current recommendations indicate that nutrients should be applied differently during each developmental stage. Compared to the reproductive stage, fewer studies have addressed the nutrition requirements during the seedling and vegetative stages of Colombian coffee.

The present review aims to describe the special case of coffee nutrient requirements in Colombia, and to suggest principles and alternative respective practices of appropriate fertilization management.

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In coffee, both vegetative and reproductive growth takes about 18 months. Fertilization effects may only be fully manifested towards the end of the reproductive stage - at harvest, since nutrient remobilization is involved. For these reasons, nutrient application must never be skipped, particularly during the vegetative phase. Fertilization should be applied when soil water content is near field capacity to guarantee efficient nutrient uptake and to reduce urea volatilization. However, high precipitation in the tropics and the application of very soluble fertilizers lead to environmental risks. Multiple approaches, such as gradual or slow-release fertilizers, including the consideration of shading levels and orchard density, are recommended. A better understanding of how nutrient utilization and water availability affect coffee productivity is also required to achieve efficient nutrient use, enhance crop yields, and to better contribute to farmers' livelihoods.

Keywords: Coffea arabica; liming; magnesium; potassium; soil acidity; tropic crops.

Introduction

The genus *Coffea* is comprised of more than 70 perennial species but is usually represented by the two most grown species - *Coffea arabica* L. and *C. canephora* L. Both cultivars constitute one of the major crops cultivated in more than 70 countries, and represent an important traded commodity in the modern world, generating significant income as well as millions of direct and indirect jobs in many developing countries (DaMatta, 2004; DaMatta *et al*. 2008). In Colombia, coffee crops are grown by about 563,000 families, of which, 96% are smallholders who plant coffee in areas of less than 5 ha (Federacafe, 2017).

Successful cultivation of coffee and high cup quality in Colombia are related to a unique set of environmental conditions; the coffee region is located at altitudes ranging from 1,000 to 2,000 m above sea level, where mean annual temperatures range from between 15 and 23°C, annual precipitation fluctuates between 1,000 and 4,000 mm (Jaramillo, 2005) and almost 50% of soils are originated from or have been altered by volcanic ashes. Under these conditions, coffee crop phenology encompasses four growth stages (Arcila, 2008): germination, from sowing into a sand seedbed up to seedling transplanting into plastic bags (2 months); nursery, from transplanting into plastic bags up to development of at least one pair of branches (6 months); vegetative, from plant transplantation in the field up to first bloom (about 18 months); and, reproductive, comprising 4 or 5 years of harvest (Arcila, 2008). When productivity declines, it is recommended to initiate another crop cycle either by stem trimming or total renewal. A complete crop renovation is only used when the farmer wants to establish a new variety or change crop densities. Thus, depending on the environmental conditions, a whole production life cycle lasts 6-8 years, requiring intensive management and inputs respective to each stage in order to sustain productivity.

In terms of fertilization, recommendations indicate that nutrients must be applied differently during each stage. Compared to the reproductive stage, fewer studies have addressed the nutrition requirements during the seedling and vegetative stages of Colombian coffee. The present review aims to describe the special case of coffee nutrient requirements in Colombia, and to suggest principles and alternative respective practices of appropriate fertilization management.

Germination stage

Upon germination and at the earliest stage of seedling development, all nutrient requirements are supplied by the seed. Initial seedbed disinfection, periodic watering, and maintenance of a dark and warm bed, are the only practices needed. After about 2 months, the seedlings develop the first pair of leaves, reaching the ideal size for transplantation into plastic bags.

Photo 1. Coffee germination in Colombia.
Source: www.yoamoelcafedecolombia.com. 2017

Seedling stage

According to Salazar (1996), the early growth stages are very critical. In consequence to sub-optimal vigor, seedlings develop weak and small canopies that might fail under stresses associated with transplantation into the field 6 months later. As a result, the potential productivity of such trees might decline significantly. Plant growth and development during this stage is largely dependent on adequate and proper mineral nutrition.

At the nursery, nutrient requirements are usually supplied by the substrate in the plastic bag, consisting a mixture of soil and organic manure. Coffee seedlings are sensitive mainly to nitrogen (N), phosphorus (P), and soil pH, but potassium (K), calcium (Ca) and magnesium (Mg) are also significant. There is wide agreement that, depending on its availability at farms, different manure types such as from earthworm-processed cattle or chicken manure, or

Photo 2. Young coffee seedlings at the nursery.
Photo by A. Salamanca-Jiménez. 2017.

Photo 3. A young coffee plantation at the vegetative phase.
Source: www.yoamoelcafedecolombia.com. 2017.

organic residues (decomposed pulp or sugarcane sludge and ash) may be used in a 3:1 proportion of soil and manure, respectively (Salamanca-Jiménez and Sadeghian, 2008). However, the organic manure must be completely decomposed; in-pot decomposition of unripe manure might increase the growth-medium temperature and burn roots with a subsequent loss of plants. Promising new techniques that claim to reduce composting time while improving manure quality require further evaluation prior to their dissemination as a means of obtaining more vigorous seedlings.

Numerous studies have reported that reaching maximum growth rates during the nursery stage, particularly when no organic material is added, requires 0.4-0.5 g N per plant (Arizaleta *et al.*, 2002; Sadeghian and Gonzalez, 2014; Salamanca-Jiménez *et al.*, 2016; 2017b). Doses above that optimum N amount, such as 0.8 or 1.2 g plant^{-1}, gave rise to N luxury consumption causing adverse effects on coffee seedling growth (Salamanca-Jiménez *et al.* 2017b).

Even if organic material is properly used or totally absent in the substrate, P requirements must be satisfied by the addition of 2 g P_2O_5 per plant at 2 and 4 months after planting (Avila-Reyes *et al.*, 2010).

Potassium application should not be avoided during the nursery stage as this nutrient is required to facilitate photosynthesis and carbohydrate translocation, and to support the maintenance of the plant's water status (Zörb *et al.*, 2014). In coffee, a high K:N ratio (at least 1:1) during the early vegetative stage guarantees the desirable seedling growth and development (Wilson, 1985; Jessy, 2011; Gonçalves *et al.*, 2013; Melke and Ittana, 2015). Recently, Frois de Andrade *et al.* (2015) demonstrated the significance of adequately applied K to overcome periods of water shortage and to improve size and quality of coffee seedlings. In that study, K dose ranged from 0.625 to 2.5 kg K_2O m^{-3} substrate, divided into 4 applications, once a month.

Similarly, lime application to the growth substrate was reported to have positive effects on coffee seedling development (Diaz *et al.*, 2008). The suggested dose is around 5 g dolomite lime kg^{-1} substrate, depending on the initial and the target soil pH. According to Cenicafe (2016), 1 gram of lime per kg of soil is required to increase pH by about 0.2-0.3 units, depending on the soil buffer capacity. Seedling growth was significantly limited under no Ca application. In addition, seedling dry biomass was very sensitive to the Ca:Mg ratio, with higher dry biomass values obtained at ratios ranging from 1:1 to 4:1, respectively (Cenicafe, 2016).

Vegetative stage

Following seedling transfer from the nursery to the field soil, coffee response to fertilization is strongly associated to environmental conditions, particularly to soil fertility. Appropriate soil sampling and analyses prior to planting at least once every 2 years are therefore crucial to the successful management of the young plantation.

Coffee fertilization during the vegetative phase has been quite neglected so far, probably due to the fact that the economic significance of fertilizer application at that stage is difficult to measure. Therefore, criteria for nutrient application at the vegetative phase need to be defined further.

Current research of the vegetative stage shows that during the first 2 years, coffee crops respond positively to lime, manure, and N, P, and K applications directly to the planting spot. Thus, nutrient recommendations at this stage should relate to individual trees.

Liming recommendations, to overcome soil acidity, are based on the soil pH and Ca content. The liming doses applied during orchard establishment and 1 year later are presented in Table 1 (Sadeghian, 2013). Different Ca sources, such as calcite, dolomite limes or phosphate rock, can be used instead of lime.

Nitrogen is perceived as the dominant nutrient during the vegetative phase of coffee. Therefore, most recommended fertilizer practices suggest surface applications of increasing N doses from 2 to 18 months after planting, once every 4 months. The organic matter (OM) content of a soil and the precipitation regime must be carefully considered when determining the N dose. A threshold of soil OM content of 8% was defined (Sadeghian, 2013), below which the recommended N doses are higher, and vice versa (Table 2). In general, the common N source is urea due to its high N concentration (46%), however, under low soil P content, di-ammonium phosphate (18% N) may be preferred.

During the first 15 months (650 days after planting), N uptake by coffee trees may fluctuate from 8.6 to 19.4 g plant^{-1}, representing an accumulated extraction ranging from 33.4 to 75.6 kg N ha^{-1} at a density of 3,906 plants ha^{-1}, respectively. Such variation may be associated with the interaction between the plant's environment and genotype. In a comparison of three locations, plants accumulated 1,362 g dry biomass at Paraguaicito - the warmer location, 576 g at Santa Helena - the wet and colder place, and 812 g at Naranjal - where intermediate temperatures prevail. The ratio of N uptake to biomass accumulation was similar among the three locations - 0.0145 g N g^{-1} dry matter, which indicates a strict genetic regulation of N uptake. Environmental differences, therefore, seem to play an important role in the rate of biomass accumulation and in the way it is distributed among plant organs (Riano *et al.*, 2004).

Ramalho *et al.* (1997) stated that N fertilization causes changes in photosynthesis and in the composition of foliar pigments, thus preventing damage in the leaves of young plants (1.5-2 years) when they were exposed to successive days of high light intensity. The same authors found that a photon flux density of 1,500 µmol m^{-2} s^{-1} for a maximum period of 8 hours increased protein content after 1.5 h, a process that must have required N. Also, N application to young plants increased anti-oxidative activity, promoted the development of photo protective pigments (e.g. lutein, neoxanthin) (DaMatta, 2004), and also changed the fatty acid composition of chloroplast membranes (Ramalho *et al.*, 2000). Consequently, N availability might be considered a key factor for plant acclimation to full sunlight exposure.

These are the main reasons why currently, total N application during the vegetative stage ranges from 100 to 125 g urea plant^{-1}, and reaches rates of up to 1,250 kg urea ha^{-1} at a density of 10,000 plants ha^{-1}. However, as fertilizer is usually applied to the soil surface due to steep slopes, at least 30% N from urea may be lost by volatilization (Leal *et al.* 2010), causing adverse environmental and economic impacts. Research aimed at increasing N use efficiency as well as reducing the costs and the negative risks evolving from the current N fertilization practices in young coffee plantations is, therefore, a must. Alternative new practices should synchronize N application with plant demand and reduce N losses without compromising crop productivity (Salamanca-Jiménez *et al.*, 2016).

According to current recommendations in Colombia (Sadeghian, 2013), P, K, and Mg should be applied during the vegetative phase when soil analyses indicate contents

Table 1. Lime dose recommendation for coffee crop establishment based on soil analyses.

pH	Doses of liming material (g plant^{-1})		
	Ca ≤ 1.5	1.5 < Ca ≤ 3.0	Ca > 3.0
	-----cmol$_c$ kg^{-1}-----		
pH ≤ 4.0	120	100	80
4.0 ≤ pH < 5.0	100	80	60
5.0 ≤ pH < 5.5	40	0	0

Table 2. N, P, K and Mg recommendations for coffee at the vegetative stage based on soil analyses. Adapted from Sadeghian, 2013.

Application time (months after planting)	Nutrient doses (g plant^{-1})						
	N		P_2O_5	K_2O		MgO	
	OM ≤ 8%	OM > 8%	P ≤ 30	K ≤0.2	0.2 < K ≤ 0.4	Mg ≤ 0.3	0.3 < Mg ≤ 0.9
2	7	5	4	-	-	-	-
6	9	7	-	-	-	-	-
10	12	9	5	5	-	2	-
14	14	12	-	-	-	-	-
18	16	14	6	10	10	3	3

Note: OM, organic matter; soil P, mg kg^{-1}; and, K and Mg, cmol$_c$ kg^{-1}.

are below the critical values (as shown in Table 2). An N:K ratio of 1:1 during the vegetative phase has also been mentioned by several authors (Khan *et al*., 2001; Jessy, 2011; Gonçalves *et al*., 2013; Melke and Ittana, 2015). Other principles and aspects of coffee fertilization with K are broadly presented in the section related to the reproductive phase.

Reproductive stage

Data reported by Riano *et al.* (2004) for the vegetative stage show that a 5.5 year-old coffee crop may extract 547, 51, 508, 234 and 59 kg ha^{-1} of N, P, K, Ca and Mg, respectively, supporting the notion that coffee production is very sensitive to N and K inputs. These values also indicate the importance of Ca, which sometimes is not returned to the soil since farmers rarely re-apply lime every 2 years.

However, N is the primary nutrient applied in coffee ecosystems, with doses of N fertilizers usually ranging between 100 and 300 kg N ha^{-1} yr^{-1} (Bornemiza, 1982; Sadeghian, 2013). According to Sadeghian (2013), when N fertilizers are not applied, adverse effects start to emerge after 2 years, reducing crop yield by 49% in plantations under full sunlight, and by 40% under partial shade. Nevertheless, due to the frequent applications, and when previous applications and possible residual effects are considered, most coffee cropping systems are N saturated (Cannavo *et al*., 2013). This may provide a partial explanation for the poor N use efficiency - below 25% - during the reproductive phase.

These values are also supported by different studies about the N cycle processes, which show that when urea is applied to the soil surface, at least 30% is lost by volatilization (Leal *et al*., 2010) and from 30 to 55% is leached as NO_3^- (Cannavo *et al*., 2013). Other authors such as Fenilli *et al.* (2007) and Silva *et al.* (2015) report that coffee plants may absorb up to 43% N from the volatilized ammonia (NH_3), whereas Salamanca-Jiménez *et al.* (2017a), found that N recovery rates from urea applied either to the soil surface or incorporated close to the tree, were only 5%. When put into an N balance, these findings indicate that most of the fertilizer applied is wasted, resulting in environmental and economic impacts that have not accurately been determined yet, threatening sustainability of coffee production and coffee farmers' livelihoods.

Current recommendations to reduce volatilization, to improve N plant uptake, and to maximize nutrient efficiency, advise that fertilizer be applied to wet soil during predictably rainy periods (Sadeghian *et al*., 2014). However, rain distribution patterns have undergone significant changes in recent decades due to the global warming. DaMatta and Ramalho (2006) evaluated the strong impacts of climate change - both water deficit and excess precipitation - on coffee cultivating regions worldwide. In Colombia, more intense heavy rains coupled with longer droughts have damaged crops and farmers across the country (Salamanca-Jiménez *et al*., 2016). This climate instability confounds farmers regarding the best timing for agricultural activities, including fertilization (Lobell and Gourdji, 2012).

Recent studies reviewed by Sadeghian (2013) focused mostly on dose response curves and nutrient soil contents, and may suggest that coffee crop fertilization in Colombia - during the reproductive stage - must follow four important criteria: soil analysis, plant demands, plant density, and shade level. This approach enables a broader perspective to all macronutrients in addition to just N.

Soil analyses, when carried out frequently enough, provide significant information about the nature of the local soil, its fertility, and moreover, on the dynamics of soil macronutrients during and after the cropping season. Coffee is grown mainly in tropical climates, where soil acidity tends to increase rapidly. Under these conditions, soluble nutrients such as N and K become extremely mobile in the soil, providing only a brief opportunity for plant uptake. Therefore, critical macronutrient thresholds in the soil should be determined and should be strictly followed to prevent soil fertility collapse with consequent yield decline (Havlin *et al*., 2015).

Plant demand for N rises during the vegetative growth period that takes place towards bloom, while K demands climb during bloom and fruit development to reach a climax at fruit maturity (Jessy, 2011). However, K is stored in the foliage and is easily remobilized to reproductive organs (Sadeghian *et al*., 2014). Therefore, the annual K dose should be wisely distributed during the year with careful considerations of soil moisture content, as was concluded also in Vietnam, under unstable tropic conditions and high soil acidity (Tien *et al*., 2015). Under continuous drought periods, K application should be delayed since the nutrient is unavailable to plants in dry soil. During the wet season, however, K application should be applied at the end of a rain event, when the soil is wet but runoff has finished. Where irrigation is employed, K should be applied with the water toward the end of the irrigation session.

High plant densities respond better to fertilization, whereas low densities exhibit a poor response, even under higher fertilizer doses (Sadeghian, 2013). The difference may be attributed to soil surface application of a fertilizer, the effectivity of which depends on root distribution in the orchard. Under high planting densities, the chances of a fertilizer encountering roots are much higher than under low tree densities, where large proportions of fertilizer are wasted due to root scarcity. On the other hand, when exposed to full sunlight or under shading levels lower than 35%, coffee trees positively respond to maximum fertilizer doses (Farfan and Mestre, 2004). Nevertheless, trees under significant shade levels - above 55% - display a negligible response to fertilizer application suggesting that the latter is not the limiting factor and hence, should be avoided.

Due to such factors, coffee fertilization should follow Sadeghian's (2013) recommendations for each nutrient (Fig. 1).

Excluding N, soil analyses are key when determining recommended macronutrient doses (Fig. 1). Recommended K, P, and Mg doses decline steeply as soil content of these nutrients rises. Unfortunately, this important tool of soil testing is ignored by most coffee growers. In such cases, the maximum dose is recommended for each nutrient (Sadeghian, 2013), in spite of the vast economic and environmental consequences.

Shading level is another important parameter to consider (Fig. 1); below 35% shade, the recommended nutrient doses are at maximum, but as the shading levels increase above 45%, doses are cut down by half, significantly reducing fertilization costs. However, pruning must be considered here also, as productivity is expected to decline as well under increasing shading levels. Plant density on the other hand, seems to play a relatively minor role in the formula determining nutrient recommendations during the reproductive phase (Sadeghian, 2013).

Beyond these sophisticated considerations, most Colombian farmers need simple and clear-cut recommendations to follow. Therefore, founded on the environmental and economic impacts and concepts described above, and considering the economic and biological optimums calculated from the dose response curves (Havlin *et al.*, 2015), it is estimated that farmers applying 250, 30, 220, 100 and 35 kg ha^{-1} of N, P_2O_5, K_2O, CaO, and MgO, respectively, split into two or three applications, are likely to obtain profitable and environmentally-friendly yields.

These nutrient requirements can be supplied by a complex fertilizer with a grade of 18(N)-3(P_2O_5)-17(K_2O)-7(CaO)-3(MgO)-5(S)-0.3(B)-0.2(Zn), prepared using slow-release urea, triple-

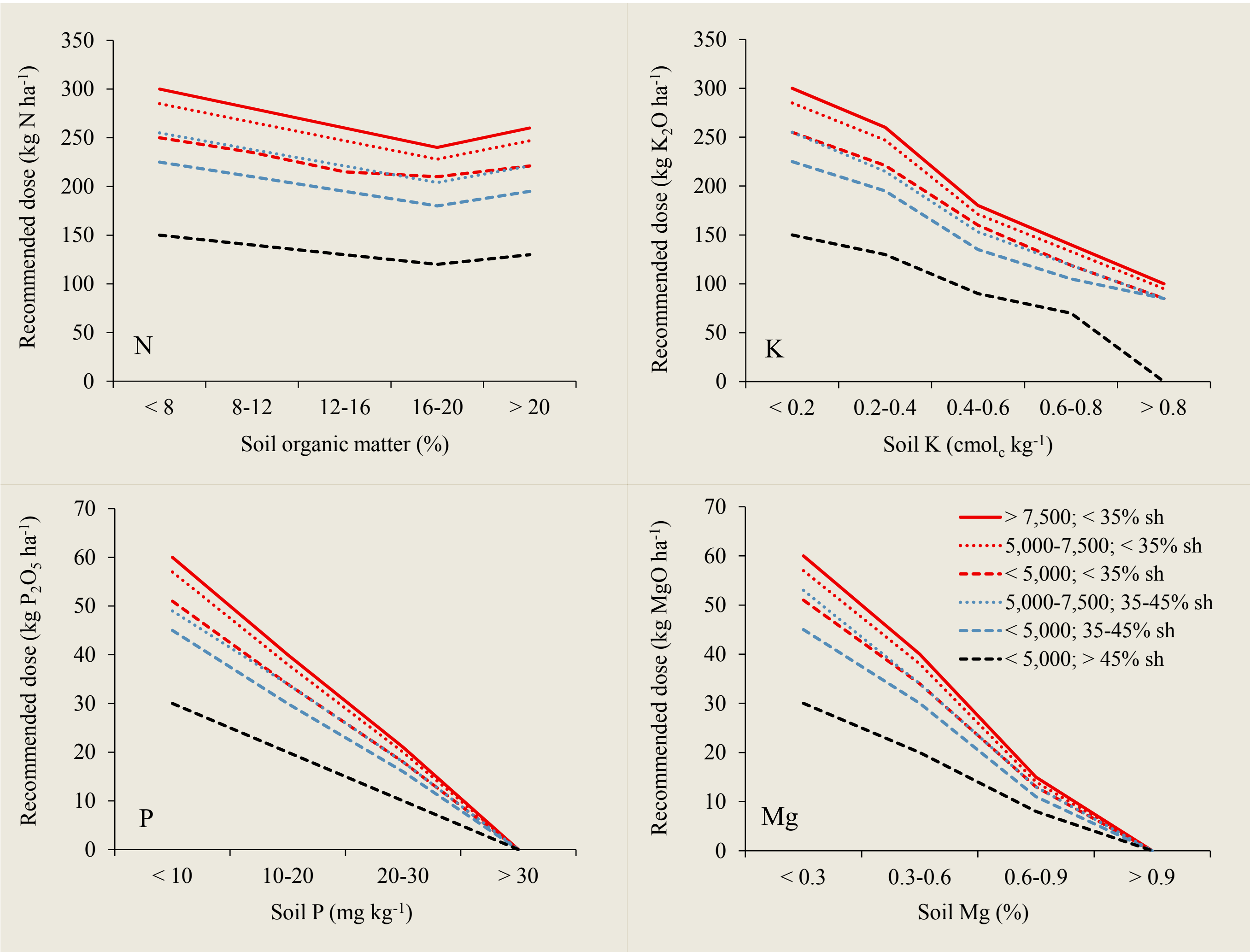

Fig. 1. Recommended doses of macronutrients for coffee fertilizers in Colombia during the reproductive phase, as affected by soil nutrient content, plant density (> 5,000; 5,000-7,500; and < 7,500 trees ha^{-1}), and level of shade (sh).

Photo 4. A young coffee tree at the reproductive stage. *Source:* www.yoamoelcafedecolombia.com. 2017.

superphosphate, potassium chloride, micronutrients, and about 20% polyhalite in the mixture. Thus, an approximate dose of 90 g plant^{-1} twice a year, or 60 g plant^{-1} up to three times a year, may satisfy the requirements of plantations at a density of 7,500 plants ha^{-1}. It may be argued, however, whether or not maintaining a balanced ratio between nutrient supply and demand, as proposed here, would be sufficient for enhanced crop performance in the absence of soil nutrient status monitoring.

While efficient N fertilization of coffee crops under humid tropical conditions still represents a significant challenge, the application of K, Ca, Mg, and S may be enhanced using polyhalite. According to Imas (2017), polyhalite is a completely soluble, natural, multi-nutrient mineral, which is low in chlorides, salinity index, and carbon footprint. Moreover, it is accepted in organic agriculture, exhibits prolonged availability (thus reduces leaching) and performs well either through direct application, physical blends or chemical mixtures. Due to its balanced formula and gradual nutrient release, polyhalite provides crops with a more balanced nutrition and high availability throughout the growing season, including during stages of high nutrient demand (Vale and Serio, 2017). In a recent experiment in Vietnam, also under humid tropical conditions and high soil acidity, polyhalite application increased yield and enhanced quality traits of the coffee (PVFCCo, 2016). Under such balanced slowly-released nutrition, a healthier crop should be better able to tolerate abiotic stresses and pathogen impacts, and to maintain or enhance yield and harvest quality.

Concluding remarks

In coffee, both vegetative and reproductive growth take about 18 months. Fertilization effects may only be fully manifested towards the end of the reproductive stage at harvest, since nutrient remobilization is involved. This explains why yields decrease only after 2 years of no fertilization (Sadeghian, 2013). For these reasons, nutrient application must never be skipped, particularly during the vegetative phase.

Fertilization should be applied when soil water content is near field capacity to guarantee efficient nutrient uptake and to reduce urea volatilization. However, high precipitation in the tropics and the application of very soluble fertilizers may lead to environmental risks of leaching, and therefore fertilization requires careful management. Multiple approaches, such as gradual or slow-release fertilizers, that consider shading level and orchard density among other factors (Cannavo, 2013), should be examined.

Photo 5. Polyhalite application. Photo by A. Salamanca-Jiménez. 2017.

Photo 6. Dense coffee plantation without shade. Photo by A. Salamanca-Jiménez. 2017.

Colombian coffee crops are mostly grown in mountainous areas that may be more susceptible to soil moisture fluctuations, and are subjected to the effects of climate change. The interactions between nutrient and water availability are critical determinants of coffee productivity that future crop management practices should address (Salamanca-Jiménez *et al*., 2016). Finally, a better understanding of how nutrient utilization and water availability affect coffee productivity is required to achieve efficient nutrient use, enhance crop yields, and to better contribute to farmers' livelihoods.

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