Research Findings

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Polyhalite Application Improves Coffee (*Coffea robusta*) Yield and Quality in Vietnam

Article from report contributed by PVFCCo, Vietnam(1)

Abstract

Vietnam produces around 1.2 million tons of coffee per year, the second highest yield in the world after Brazil. Improving resource utilization efficiency has recently been determined as the major strategic goal of the industry. Appropriate mineral nutrition practices are pivotal to achieving these goals. The humid, tropical climate and acid soils create considerable challenges to achieving the optimum balance for crop nutrition practices. The availability of alkaline elements, particularly potassium (K), calcium (Ca), and magnesium (Mg), is steadily declining. Polyhalite, a natural marine sedimentary mineral consisting of a hydrated sulfate of K, Ca, Mg and sulfur (S, 48%) was examined as a potential additive to composite NPK fertilizers. The mineral was tested as part of an alternative fertilization program for the coffee industry in the Lam Dong province. An experiment testing three fertilization practices (CT1 - farmers' practice control; CT2 - employing composite NPKS but lacking Ca and Mg; and, CT3 - similar to CT2, with additional polyhalite applications) was carried out in Bao Lam (reddish brown soil) and Di Linh (grey soil) during 2016. In both districts, CT2 was significantly more profitable than CT1, and CT3 more so than CT2. The results suggest that the common

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coffee fertilization practice (CT1) in these regions of Vietnam may be considerably improved using additional S fertilizers. The availability of Ca and Mg appears to be significant to coffee crop production, and their increased application should be considered. Added to a systematic NPK fertilization program, polyhalite enhanced coffee yields and quality parameters, thus increasing productivity by 9-11.5% and raising profits by 10 and 14% at Di Linh and Bao Lam, respectively. Polysulphate demonstrated an ability to supply plant Ca and Mg requirements and maintain soil fertility, whilst supporting greater biomass production, compared to the alternative fertilization programs.

Keywords: calcium; *Coffea robusta*; mineral nutrition; Polysulphate; potassium; sulfur.

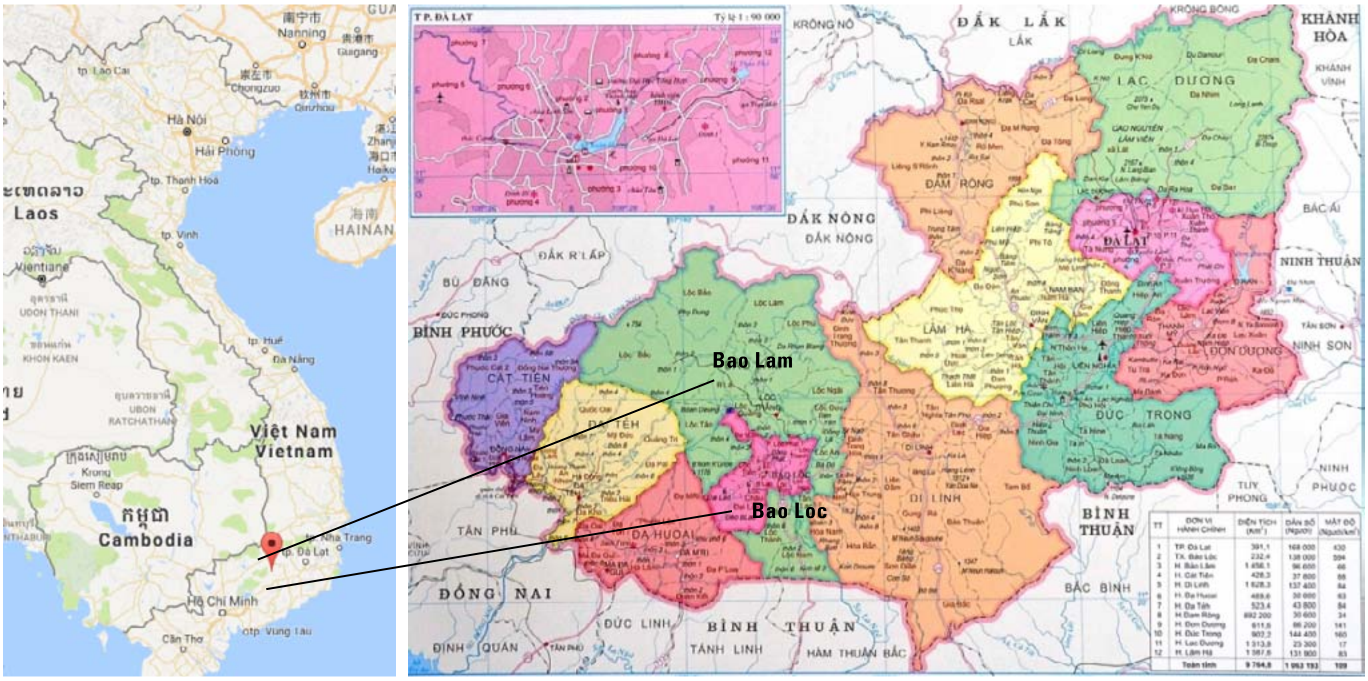
Introduction

Coffee is an important crop for Vietnam, producing around 1.2 million tons of coffee per year, the second highest yield in the world after Brazil. Exported coffee products contributed U\$3.62 billion to the Vietnamese economy in 2014 alone (FAO, 2015).

Through intensified farming methods, including irrigation during the dry season, Vietnam has been able to develop robusta coffee (*Coffea robusta* or canephora) as a high yielding cash crop (Marsh, 2007). Nevertheless, the coffee industry in Vietnam is currently experiencing significant challenges (Amarasinghe *et al.*, 2015). Improving resource utilization efficiency has recently been determined as the major strategic goal of this industry.

With over 144,000 ha of coffee under cultivation and total annual output of about 347,000 tons, Lam Dong province is the country's second largest coffee-growing area (Lam Dong Portal, 2016). However, more than 50,000 ha comprise of old plantations planted 15-35 years ago, and are suffering from a decline in productivity. According to the province's coffee development plan, 33,300 ha of coffee were re-planted during 2015. Three new varieties, TR4, TR9 and TR11 developed by the Central Highlands Institute for Agro-Forestry Science and Technology were used. The new area is expected to produce an annual coffee output of 2.8-3.0 Mg ha^{-1} instead of the current 2.5 Mg ha^{-1} (Lam Dong Portal, 2016).

In addition to the necessary renewal of plant resources, appropriate mineral nutrition practices are pivotal to the enhancement of coffee productivity in Vietnam (Tiem, 1999). The nature of the soil may be crucial to the quality and productivity. Soils in Vietnam were developed from many different parental rocks including basalt, gneiss, granite, shale, limestone, lava and volcanic ash. Soil texture may vary from heavy loam to sandy soils with no obvious effects on coffee production as long as the soil layer is deep (at least 0.7 m), easily drained (belowground water deeper than 1 m), but porous enough (64%, bulk density 0.9-1.0 g cm^{-3}, and particle density about 2.54 g cm^{-3}) to hold considerable levels of water, air, and nutrients (Tiem, 1999). Studying suitable soil properties for coffee production, Chiem and Nhan



Map 1. Vietnam map (left, Google Maps); and right the two experiment sites, Bao Lam and Bao Loc, in Lam Dong province (http://www.lamdong.gov.vn/EN-US/HOME/ABOUT/Pages/Lam-Dong-map.aspx).

(1974) showed that coffee yields are strongly affected by the content of organic matter - total nitrogen (N), potassium (K) and available phosphorus (P).

In recent years, intensive farming practices have been introduced to the Vietnamese coffee industry. The consequent rise in productivity has generated significant pressure on the mineral nutrition status of the soil (Sanh, 2009; Tien *et al*., 2015a, b). The availability of alkaline elements - in particular K, calcium (Ca), and magnesium (Mg) - is steadily declining (Nam and Hong, 1993; Hong, 1997; Tien *et al*., 2015b). The tropical climate of Lam Dong and frequent heavy precipitation accelerates soil weathering and nutrient loss through leaching from the root zone. Consequently, deficiency symptoms often occur in plantations that were previously highly productive (Sanh, 2009).

The recently introduced composite NPK fertilizers (Phu My products) are not diverse enough to meet all nutrient requirements at each stage of growth, and on differing soils. To obtain suitable fertilization formulas, Phu My NPK fertilizers are used in combination with additives, such as urea (NH_4^+), ammonium sulphate ($\{NH_4\}_2SO_4$) and potassium chloride (KCl). However, these do not always provide a sufficient solution for the declining alkaline cations (Forestier, 1969).

Sulfur (S) is recognized as the fourth major plant nutrient after N, P, and K (Khan *et al*., 2005), and has been associated with high productivity (Zhao *et al*., 1999; Saito, 2004; Kovar and Grant, 2011). Sulfur often interacts with N to significantly enhance crop productivity (Jamal *et al*., 2010). However, current information regarding S application to acidic soils under tropical climates, is scarce.

Polysulphate (produced by Cleveland Potash Ltd., UK) is the trade mark of the natural mineral 'polyhalite', which occurs in sedimentary marine evaporates and consists of a hydrated sulfate of K, Ca, and Mg, with the formula:

$$K_2Ca_2Mg(SO_4)_4{\cdot}2(H_2O).$$

The deposits found in Yorkshire, England, typically consist of 14% potassium oxide (K_2O), 48% sulfur trioxide (SO_3), 6% magnesium oxide (MgO), and 17% calcium oxide (CaO). Polyhalite has slow-release properties and due to this, it is postulated that if integrated into a fertilization program as an additive to Phu My NPK products, a more balanced and stable flow of nutrients could be achieved.

The objectives of the present study were to evaluate the agricultural efficiency of Polysulphate for coffee production in Vietnam, and to test economically, two novel alternative fertilization programs in comparison to traditional practice.

Table 1. Fertilizer compositions and programs (CT1, CT2, and CT3) used on robusta coffee plantations at Bao Lam and Di Linh districts, Vietnam.

Fertilizer	Amount of fertilizer		
	CT1 (Control; farmers' practice)	CT2 (Phu My Fertilizer)	CT3 (Phu My Fertilizer + Polysulphate)
	-----------------------------------	*kg ha^{-1}*	-----------------------------------
Polysulphate	0	0	200
NPKS (16-16-8-13)	0	400	400
NPK (15-15-15)	0	500	500
NPKS (15-8-20-10)	0	500	500
Urea	715	250	250
Fused Ca-Mg-P	1,193	0	0
KCl	545	200	153

Materials and methods

Two parallel experiments were conducted at two districts, Bao Lam and Di Linh, of the Lam Dong province in Vietnam (Map 1). Ten year old robusta coffee plantations were studied at both sites. The experiments lasted from April to December 2015.

Three fertilization programs were tested (Table 1): CT1 (control) simulated farmers' common practice through which N was applied using urea, K through KCl (60% K_2O), and P through a local blend containing fused Ca, Mg, and P; CT2 employed commercially available Phu My composite fertilizers, one of which included S but none included Ca and Mg; CT3 was similar to CT2 but was fortified with Polysulphate. Fertilizer rates were similar at Bao Lam (reddish brown soil), and at Di Linh (grey soil), and KCl administration aimed at balancing K supply between the programs.

All treatments were applied with 15-20 m^3 ha^{-1} cattle manure, which was applied at early or mid-rainy season, embedded 10-15 cm deep in the soil under the tree canopy. For the CT1 program, the entire annual fertilizer dose, including fused Ca-Mg-P, was applied at the end of the dry season. For CT2 and CT3, fertilizer applications were distributed during the season as detailed in Table 2. During the dry season, fertilizer was applied toward the irrigation cycle.

Soil samples were taken (one sample from each experimental plot, 5-30 cm deep) once before fertilizer application and then again during harvest (December) to be analyzed for fertility parameters (Table 3). At the beginning of the experiment, soil at both sites was acidic, with pH_{KCl} ranging from 4.49-4.58 at Di Linh, and from 5.03-5.07 at Bao Lam. Soil organic matter (OM) content was much higher at Bao Lam (8.7%) than at Di Linh (4.6%). Soil fertility was far better at Bao Lam than at Di Linh, as indicated by almost all levels of soil available nutrients (Table 3).

Table 2. Time of fertilizer application during the season.

Time of year		Polysulphate	Urea	NPKS 16-16-8-13	NPK 15-15-15	NPKS 15-8-20-10	KCl
April	End of dry season	100	150	-	-	-	-
May-Jun	Early rainy season	-	100	400	-	-	-
Jul-Aug	Mid rainy season	-	-	-	500	-	153
Sep-Oct	Late rainy season	100	-	-	-	500	-

Table 3. Soil properties at the two experimental sites before and after the growing season.

Location	Soil property	Treatment					
		Before			After		
		CT1	CT2	CT3	CT1	CT2	CT3
Bao Lam (reddish brown soil)	pH_{KCl}	5.07	5.03	5.06	5.04	5.01	5.02
	OM (%)	8.72	8.74	8.75	8.68	8.70	8.70
	Total soil N (%)	0.293	0.295	0.295	0.294	0.296	0.297
	Total soil P_2O_5 (%)	0.24	0.25	0.24	0.24	0.25	0.25
	Total soil K_2O (%)	0.14	0.14	0.14	0.14	0.14	0.14
	Available P_2O_5 (mg 100 g^{-1})	14.6	14.7	14.8	14.8	15.0	15.1
	Available K_2O (mg 100 g^{-1})	26.9	26.8	26.9	26.9	27.0	27.0
	Ca^{++} (meq 100 g^{-1})	3.1	3.2	3.1	3.3	2.9	3.2
	Mg^{++} (meq 100 g^{-1})	2.7	2.8	2.5	2.8	2.5	2.6
	S (%)	0.019	0.018	0.019	0.017	0.018	0.020
Di Linh (grey soil)	pH_{KCl}	4.56	4.58	4.49	4.48	4.55	4.44
	OM (%)	4.63	4.64	4.66	4.65	4.65	4.68
	Total soil N (%)	0.193	0.195	0.195	0.195	0.197	0.196
	Total soil P_2O_5 (%)	0.12	0.12	0.12	0.12	0.12	0.12
	Total soil K_2O (%)	0.09	0.09	0.09	0.09	0.09	0.10
	Available P_2O_5 (mg 100 g^{-1})	7.6	7.7	7.8	7.8	7.8	8.0
	Available K_2O (mg 100 g^{-1})	13.3	13.5	13.5	13.5	13.6	13.7
	Ca^{++} (meq 100 g^{-1})	2.5	2.6	2.5	2.7	2.4	2.5
	Mg^{++} (meq 100 g^{-1})	2.2	2.2	2.1	2.3	2.0	2.2
	S (%)	0.015	0.016	0.016	0.014	0.017	0.017

However, no significant differences were observed regarding soil S contents.

Coffee plant leaf samples were taken 30 days before and after fertilizer application. In each experimental plot, 10 leaves per tree were sampled from five trees. Indicative leaves were defined as the fourth couple, counting down from the top of the branch. In the laboratory, samples were dried at 70ºC, ground to fine powder and analyzed for mineral content. Samples were digested with sulfuric acid (H_2SO_4) and hydrochloric acid (HCl), then N content was determined by Kjeldahl, K by flame photometer and P by spectrophotometer; Ca and Mg contents were determined by digesting samples with nitrous acid (HNO_2) and HCl, then determined by atomic absorption spectroscopy. Tree growth rate was evaluated through monthly measurements of the elongation and branching of four pre-designated branches per tree.

The infection rates of rust disease and green scale-bugs were determined monthly by a visual inspection of 50 trees per plot. After fruit set, a 1 m branch per tree was tagged and the fruitlets were counted monthly until harvest, determining fruitlet abscission rate. At harvest, fruit and core yields were determined for each plot and fruit samples were used to measure yield and quality parameters (fruit weight, volume, flesh/core ratio, core size). The economic efficiency of the fertilizer treatments was evaluated using total costs, revenue, and profit.

The experimental plan at each site comprised of nine 0.11 ha plots using a completely randomized block design with three repetitions.

Results and discussion

The impact of the different fertilization programs on soil fertility parameters was very small but complex (Table 3). Soil acidity tended to increase during the growing season at both locations, under all treatments. This trend indicates soil is undergoing active degradation processes and requires a significant supplementation of lime. Content of OM decreased slightly during the growing season at Bao Lam but increased marginally at Di Linh. Total OM as well as available NPK levels remained stable or increased very slightly (Table 3). No differences could be observed between treatments regarding the above mentioned soil parameters. Such results indicate that N, P and K were sufficiently applied in all three programs.

However, significant differences between treatments did occur with regard to Ca and Mg. While the content of these elements remained stable or even increased under the CT1 and CT3 programs, they tended to decline at CT2, suggesting a fragile balance between soil availability and coffee crop Ca and Mg requirements. At both sites, soil S content slightly decreased using the CT1 fertilizers, remained stable using CT2, and increased a little with CT3 (Table 3).

Nitrogen content ranges from 2.8-3.5% in the leaves of normally yielding *Coffea robusta* trees (Chiem and Nhan, 1974). Suitable P content range is between 0.11-0.13% (Nhan, 1988), and required K content is 2-2.20% (Forestier, 1969). These NPK values are in line with those mentioned by Wairegi and Asten (2012). According to Bragança and Venègas (1990), the contents of secondary elements should range from 0.6-0.9% Ca, 0.20-0.26% Mg and 0.12-0.17% S, twofold less than those found by Wairegi and Asten (2012) under East African conditions. Thus, leaf NPK contents before fertilizer application were at the lower, but acceptable levels at both sites. However, the contents of the secondary elements were at the lower range, indicating deficiency (Table 4), depending which reference values are used.

Table 4. Effect of fertilizer treatments on leaf N, P, K, Ca, Mg, and S contents (%) in *Coffea robusta* at Bao Lam and Die Linh in Vietnam.

Site	Element	Before fertilization			After fertilization		
		CT1	CT2	CT3	CT1	CT2	CT3
		%					
Bao Lam	N	2.88	2.83	2.85	3.25	3.28	3.27
	P	0.116	0.113	0.115	0.126	0.124	0.127
	K	2.05	2.07	2.06	2.16	2.13	2.15
	Ca	0.66	0.64	0.65	0.84	0.52	0.81
	Mg	0.24	0.23	0.22	0.24	0.18	0.24
	S	0.126	0.127	0.124	0.112	0.155	0.156
Di Linh	N	2.80	2.79	2.82	3.11	3.14	3.13
	P	0.112	0.112	0.110	0.121	0.123	0.122
	K	2.01	2.01	1.99	2.09	2.11	2.09
	Ca	0.61	0.63	0.59	0.74	0.50	0.72
	Mg	0.19	0.21	0.20	0.22	0.17	0.22
	S	0.122	0.120	0.121	0.108	0.147	0.149

Thirty days after fertilizer applications, leaf N contents significantly increased by 13%, while increases in leaf P and K contents were moderate or low - 8.5 or 5%, respectively (Table 4). Fertilization effects on leaf Ca and Mg differed significantly among treatments. CT1 and CT3 brought about a significant increase in leaf Ca content and maintained Mg levels. CT2, which did not provide Ca and Mg, resulted in a considerable drop in these nutrients at both sites. No advantage was observed for any of the fertilizers, fused Ca-Mg-P or Polysulphate, as a source of Ca or Mg. However, it is questionable whether the additional Ca/Mg from fertilizer applications were sufficient to support maximum yield production. It is possible that fertilizer doses should be increased further.

Leaf S content following CT1 treatment, where fertilizers lacked S, declined significantly during the season. The CT2 and CT3 treatments contained an amount of 102 kg S ha^{-1} applied through NPKS fertilizers (Tables 1 and 2), which may explain why leaf S content rose markedly (Table 4). The additional dose of 28 kg S ha^{-1} provided by Polysulphate in CT3 did not bring about any further rise in leaf S content. It appears then, that for the reddish brown soil in Bao Lam and the grey soil in Di Linh, an S rate of 100 kg ha^{-1} would be appropriate.

Tree growth, exhibited by branch elongation, was significantly affected by the fertilization treatments (Fig. 1). The CT3 fertilization program led to a significantly higher growth rate than CT1, while CT2 showed intermediate values. Trees grew faster at Bao Lam than at Di Linh.

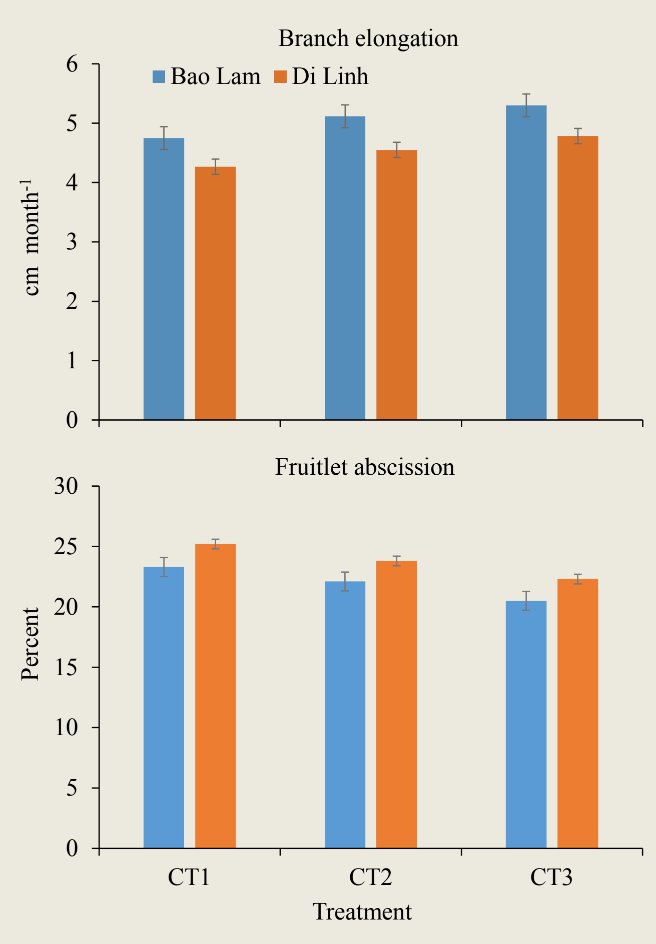


Fig. 1. Effect of fertilizer treatments on branch elongation and on fruitlet abscission in *Coffea robusta* trees grown at Bao Lam and Di Linh districts, Lam Dong province, Vietnam. Bars indicate LSD at 5%.

Photo by G. Kalyan.

Infection rates of rust disease were somewhat higher at Bao Lam (4-6%), compared to Di Linh (2-4%), but no differences occurred among treatments in this regard. The frequency of green scale-bugs was relatively high at Bao Lam (8-10%), but much lower at Di Linh (2-4%). Again, no differences occurred between treatments.

During the reproductive phase of the coffee tree, immature fruit (fruitlets) often tend to abscise. The reasons for fruitlet abscission may include physiological disorders, stormy weather, water stress as well as inadequate mineral nutrition (Mitchell, 1988; Wilson, 2004). In the present study, fruitlet abscission rates were the highest at CT1, slightly lower at CT2, and significantly less at CT3 (Fig. 1). Abscission rates were consistently higher at Di Linh than at Bao Lam.

The CT3 treatment gave rise to a 10-11.5% increase in coffee yield compared to the CT1 control treatment (Fig. 2). The CT2 program resulted in a somewhat higher yield than the control, but significantly lower than CT3. Also here, CT2 yields at Di Linh were always lower than at Bao Lam. Under the CT1 treatment, fruit weighed 92.8 g 100 fruit^{-1} and 93.8 g 100 fruit^{-1} at Di Linh and Bao Lam, respectively, 93.9/94.7 g under CT2, and 94.6/95.3 g under CT3 (Fig. 2). Nevertheless, the significantly higher yield of CT3 should be attributed to the accumulative effect of many small changes, such as the number and length of platform branches carrying the reproductive organs, and the decrease in fruitlet abscission. Both factors contribute to an elevated number of tree fruit.

Fertilizer treatments also influenced fruit quality. Flesh/core ratio decreased steadily from 4.42 and 4.45 in CT1, to 4.37 and 4.40 in CT2, and further to 4.28 and 4.31 in CT3, at Bao Lam and Di Linh, respectively. A core diameter greater than 6.3 mm is an indicator of high-quality fruit; the rate of A-size core production climbed consistently from about 19.5% in CT1 to 20-21.5% in CT2, and further to 22.2% in CT3 (Fig. 2).

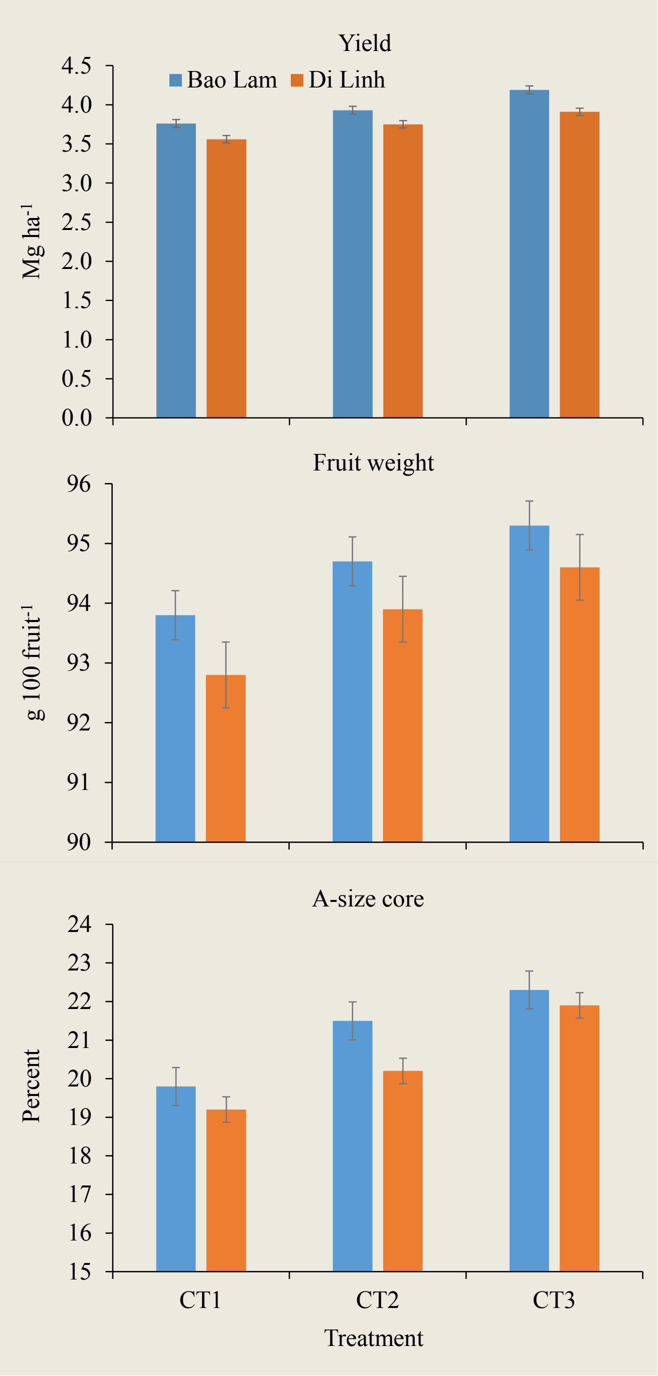


Fig. 2. Effect of fertilizer treatments on core yield, fruit weight, and fruit quality in *Coffea robusta* trees grown at Bao Lam and Di Linh districts, Lam Dong province, Vietnam. Bars indicate LSD at 5%.

Compared with CT1, the farmers' practice control, CT2 enhanced coffee crop performance (Figs 1 and 2). This is probably due to the more even distribution of fertilizer application throughout the season, and to the diverse nature of the fertilizer. The considerable

Fig. 3. Effect of fertilizer treatments on the total costs, revenue, and profit of *Coffea robusta* grown at Bao Lam and Di Linh districts, Lam Dong province, Vietnam.

disadvantage of CT2 i.e. the lack of Ca and Mg, seems to have been largely compensated for by the addition of S from composite NPKS fertilizers. Yet, the consequent rising production costs deducted from the surge in revenue, so the profits of CT1 and CT2 equalized (Fig. 3). CT3 demonstrated the advantage of combining a more even application of diverse composite NPKS fertilizers with the employment of Polysulphate, a stable, slow-release, source of Ca, Mg, S, and K. By providing sufficient nutrient uptake (Table 4), this combination can fully replace the cheaper but less efficient basal application of urea, KCl, and fused Ca-Mg-P practiced under the CT1 program. Possible advantages of splitting K fertilizer annual dose or using slow-release sources of Ca, Mg, S and K were already envisaged in previous studies carried out on similar soil types in neighboring Dak Lak district in Vietnam (Tien *et al.*, 2015a, b). Thus, in spite of a 10% increase in costs, CT3 brought about profit increases ranging from 10-14% more than CT1 (Fig. 3) and maintained profit rates of 49-56% - also slightly higher than that of CT1.

Conclusions

In both districts, CT2 was significantly more profitable than CT1, and CT3 more so than CT2. These results suggest that the common coffee fertilization practice (CT1) in the Bao Lam and Di Linh regions of Vietnam may be considerably improved using additional S fertilizers. While no direct effect of S could be observed, it may have facilitated N uptake and metabolism by coffee plants leading to yield enhancement. The availability of nutrients such as Ca and Mg, appears to be significant for coffee crop production and their increased application should be considered. Polysulphate, added to a systematic NPK fertilization program for coffee plants grown on reddish brown soil at Bao Lam or on grey soil at Di Linh, enhanced coffee yields and quality parameters, thus increasing productivity by 9-11.5%. Overall, Polysulphate application gave rise to profit increases of 10% and 14% at Di Linh and Bao Lam, respectively. Polysulphate demonstrated an ability to supply plant Ca and Mg requirements and maintain soil fertility, while supporting greater biomass production, compared to the alternative fertilization programs.

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