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Fertilizer recommendations for optimal soybean production in North and Center Benin

Faki O. Chabi[1]*, Gustave D. Dagbenonbakin[2], Emile C. Agbangba[3], Brice T. Oussou[4], Bérékia K. Agban[1], Mireille Dakpo[1], Léonard E. Ahoton[1], Guillaume L. Amadji[5] and Saïdou Aliou[1]

[1]Integrated Soil and Crop Management Research Unit, Laboratory of Soil Sciences, Crop Sciences School, Faculty of Agronomic Sciences, University of Abomey-Calavi, 01 BP 526 RP, Cotonou, Benin.
[2]Institut National des Recherches Agricoles du Benin, 01 BP 988 RP, Cotonou 01, Benin.
[3]Laboratory of Research in Applied Biology, Department of Environmental Engineering, Polytechnic School of Abomey-Calavi, University of Abomey-Calavi, Abomey-Calavi, 01 BP 526 RP, Cotonou, Benin.
[4]Laboratoire des Sciences du Sol, Eau et Environnement (LSSEE), Centre de Recherche d'Agonkanmey, Institut National des Recherches Agricoles du Benin (INRAB), 01 BP 988 RP, Cotonou 01, Benin.
[5]Laboratory of Soil Science, Faculty of Agronomic Sciences, University of Abomey-Calavi, Abomey-Calavi, Benin.

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In the traditional cropping systems of Benin Republic, soybean is mostly cultivated with no mineral fertilizer supply, despite the decrease of soil fertility. Furthermore, there is no specific fertilizer available for the crop, in spite of its cash crop character. This leads to weak crop yield in the farmers' fields. The present study aims to determine the optimal doses of each N, P, K, Mg and Zn nutrient to improve soybean production in the Sudano-Guinean and Sudanian zones of Benin Republic. Two years (2018 and 2019) experiment has been carried out in Ouessè district (Sudano-Guinean zone) and Bembèrèkè district (Sudanian zone). Box and Behnken rotating design was used to define N, P, K, Mg and Zn dose combinations leading to 46 combinations. A completely randomized block design was set up considering farmers as replication. In total four farmers' fields are selected. A one-way analysis of variance is made on the yield data, using the linear mixed-effect model. Response surface analyses are used to determine the optimal dose for each N, P, K, Mg and Zn. The supply of macronutrients combined with Zn, significantly ($p = 0.001$) improved the soybean grain and above biomass yields as well as the harvest index. The quadratic models were efficient ($R^2 > 0.7$) to estimate soybean grain yields considering the nutrient dose variation. The optimal N, P, K, Mg and Zn doses of 15.46, 23.20, 28.6, 16.8 and 6.9 kg.ha^{-1}, respectively (for the Sudano-Guinean zone) and 14.02, 23.89, 17.82, 11.45 and 4.26 kg.ha^{-1}, respectively (for the Sudanian zone) lead to an optimal seed yield of 2 t.ha^{-1} (that is, almost 2.2 times the yield in the farmers' field). The development of fertilizer formulas using these determined optimal doses would constitute a suitable technology helping to increase soybean production in both areas.

Key words: Soil fertility, biofortication, Box and Behnken design, linear mixed-effect model, leguminous, response surface, micronutrient.

INTRODUCTION

Grain legumes are a key source of nitrogen-rich edible seeds, providing a wide variety of high-protein products (Vanlauwe et al., 2019). These legumes constitute the major source of dietary protein in the diets of the poor in most parts of Sub Sahara Africa (SSA) (Bationo et al., 2011; Bado, 2018; Semba et al., 2021). Soybean is one of the important legumes in SSA cropping systems (FAO, 2014). Soybean was identified as an alternative source of less expensive high quality protein in improving nutrition, health and livelihoods of Africa's rural communities (IITA, 2002). In the SSA, grain legumes are traditionally grown in rotation or in intercrop with cereals to secure food production (Temba et al., 2016). Despite their importance, the grain legumes' yields are far below their potential. According to Karikari et al. (2015), soybean yields in West Africa are estimated at 0.95 t ha^{-1}. This situation could be explained by the use of low yield varieties and no fertilizer (Kamara et al., 2007; Kolawole, 2012). The specific problems African farmers encounter in grain legume production includes yield instability, drought susceptibility, and low soil fertility (Bationo et al., 2011; Reynolds et al., 2015).

Legumes are often considered second to cereal crops. These crops are thus commonly promoted as not requiring any fertilizer application because of the N_2 fixation (Ndakidemi et al., 2006). In fact, grain legumes can access atmospheric N through symbiosis with rhizobia. This is why they require some minimal N fertilizer input. Legumes have the ability to fix the atmospheric N_2. This turns them into excellent components within the farming systems. The main reason for this is that they provide residual nitrogen and minimize the mineral nitrogen fertilizer needed by the plant. However, this process can be limited by the low availability of other nutrients in the soil, and the water and mineral nutrient supply (Kamanga et al., 2010; Ronner et al., 2016; Ohyama et al., 2017).

In most parts of the SSA where grain legumes are cultivated, soils are less fertile (Saïdou et al., 2012). This challenge is intensified by nutrient depletion through continuous cultivation with inadequate replenishment (Adjei-Nsiah et al., 2018; Chabi et al., 2019). The deficiencies of macronutrients (N, P and K) are widespread (Saïdou et al., 2017), limiting legume growth and input of N from N_2-fixing, which will also be restricted (Bationo et al., 2011). The nitrogen deficiency in the SSA region soils cause the minimum values to be trapped right after plant germination and establishment. This crop growth is delayed and characterized by a low yield (Salvagiotti et al., 2008).

Today, the assertion which holds that the ability to fix N_2 is a major reason for the evolutionary success of legumes is strongly contested (Vanlauwe and Giller, 2006). First, not all legumes can nodulate and fix N_2. Second, many legumes do not substantially contribute to soil fertility improvement (Vanlauwe et al., 2019). Even when legumes grow well, the contribution to soil fertility depends on the amount of N_2-fixed in relation to the amount removed from the system in the crop harvest, reflected in the N-harvest index (Giller and Cadisch, 1995). For instance, high yield varieties of soybean usually have high N-harvest indices and often are net removers of soil N (Toomsan et al., 1995). According to Chianu et al. (2011) and Odendo et al. (2011), the amounts of nitrogen fixed by soybean varieties (almost 200 kg ha^{-1}), is largely exported through the seeds and not renewed in the soil. Similarly, in many cropping systems, the aboveground biomass is used to feed animal. It contributes to the negative nutrient balance in the soils of these cropping systems (Vanlauwe and Giller, 2006). According to Kovacevic et al. (2011), nutrient removal of one ton of soybean grain and the corresponding biomass are estimated to 100 kg N, 23-27 kg P_2O_5, 50 to 60 kg K_2O, 13 to 15 kg CaO and 13 to 16 kg MgO which should normally be returned to the soil in order to maintain a sustainable production.

In fact, legumes represent an important part of the daily protein for human beings and animals. Strategies are then urgently required for the development of improved production practices. In the past, soybean was cultivated for subsistence as food crops (Adjei-Nsiah et al., 2008). However, over the past decade, soybean cultivation has assumed a commercial importance because of its demand by the agro-processing industries and for human consumption (Khojely et al., 2018). In this context, an increase in soybean production is necessary and it requires the development of a fertilizer formula. Supplementing legumes with soil nutrients has proved to double yields (da Silva et al., 1993; Nandwa et al., 2011; Dhakal et al., 2016), and increase plant growth and N_2-fixation compared with the unfertilized control (Ndakidemi et al., 2006). High soil fertility usually leads to high yield of soybeans (Rana and Badiyala, 2014; Bonde and Gawande, 2017). By supplying a constant but low concentration of N and a good concentration of P and K and micronutrients either from mineral fertilizers or organic manure, good soybean growth will occur without depressing nodulation and N_2 fixing activity (Ohyama et al., 2017).

In Benin Republic, soybean yield is low (<1 t.ha^{-1}) and below the potential yield mainly due to low soil fertility level and poor agronomic practices (Chabi et al., 2019) leading to imbalanced use of nutrients. Considering the importance of soybean in maintaining food security in the country, it would be essential to biofortify this crop in order to get quantity and quality products. Zinc and Sulphur were experimentally proved to be micronutrients which are very much conducive to increasing soybean production. The main objective of the present study is to assess soybean response to different doses of N, P, K, Mg and Zn in combination in two agroecologicals zones and the optimal doses of each nutrient as a strategy for

*Corresponding author. E-mail: chabifaki@gmail.com.

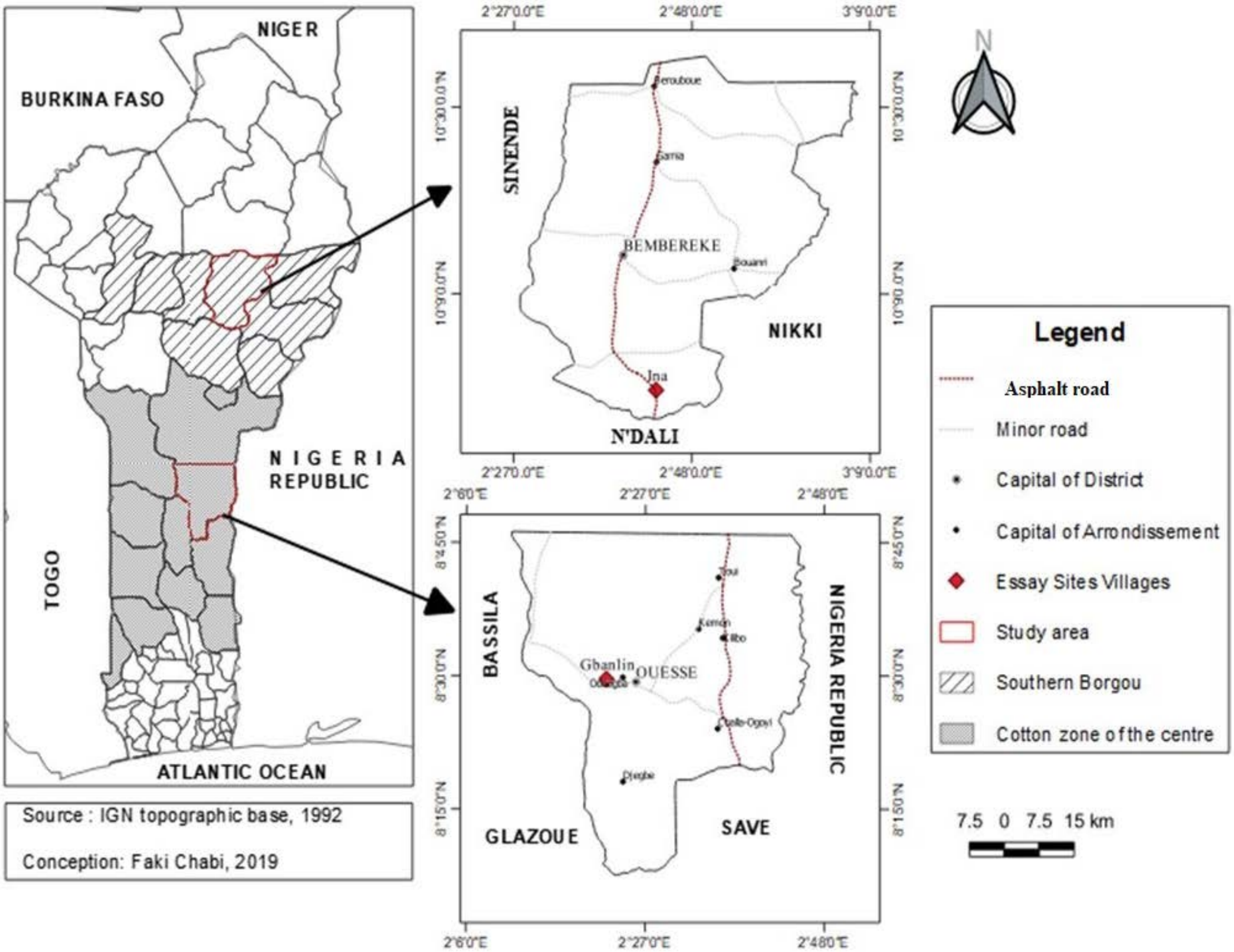

Figure 1. Location of the experiment sites in Benin Republic.

biofortication of soybean products.

MATERIALS AND METHODS

Study area

This study is carried out in the municipality of Bembèrèkè in the southern Borgou agroecological zone (AEZ 3) and the municipality of Ouessè in the cotton agroecological zone in the centre of Benin (AEZ 5) (Figure 1).

The AEZ 3 is located between 1°10'- 3°45' E and 9°45'- 12°25' N. This zone is characterized by an unimodal rainfall distribution, with an average annual rainfall less than 1,000 mm and located in the Sudanian zone. The relative moisture varies from 18 to 99% while temperature varies between 24 and 31°C. Ferric and Plintic Luvisols (FAO, 2015) are the dominant soil types in the area. Maize, sorghum, millet, yam, and groundnut are the annual crops, while cotton and soybean are the main cash crops.

The AEZ 5 is located between 1°45'- 2°24' E and 6°25'- 7°30' N. The area is under the Sudano-Guinean zone also called transitional zone. The annual mean temperature varies between 26 and 29°C whereas the average annual rainfall varies between 1,000 and 1,400 mm. The relative moisture varies from 69 to 97%. The Ferric and Plintic Luvisols are also the dominant soil types in the area. Black and hydromorphic soils are found in the river valleys as well. Maize, yam, cassava and groundnut are the annual crops, but cotton and soybean represent the main cash crops.

Experimental design and field trial

Two years (2018 and 2019) on-farm experiments were carried out during the growing season. The experimental design was a full factorial design consisting of 46 treatments (representing combinations of N, P, K, Mg and Zn doses) and a control plot all replicated at four farmers' fields. The Box and Behnken design was used to determine the different treatments tested. Three doses of each nutrient (0-20-40 kg.ha^{-1} for N; 0-30-60 kg.ha^{-1} for P; 0-20-40 kg.ha^{-1} for K; 0-20-40 kg.ha^{-1} for Mg and 0-5-10 kg.ha^{-1} for Zn) are tested. Each factor was set at its mean coded level 0 and a factorial plan of 2k (k-1) + C_0 (with k the number of factors and C_0 the number of central points) is constructed with the other factors using the minimum code -1 and maximum code +1 level of each of these factors. The different combinations of the 5 nutrient levels in each treatment are generated for the response surface plan with

MINITAB 18 software.

The experimental unit was 5 m × 4 m (20 m²). Plots with previous maize crops are selected for the trial and managed by each farmer. TGX 1448-2D (105 days of growth cycle with achievable yield of 1.8 t ha^{-1}) was soybean variety sown. Ridge ploughing is carried out with a 50 cm row spacing at the centre and flat ploughing by animal traction with a depth of 15 cm in the South Borgou zone. Sowing is carried out at a depth of 5 cm at a rate of two seeds per hole and 50 cm between rows and the sowing space was 20 cm between plants. Nutrients are applied in the form of urea (46% N), TSP (46% P_2O_5), KCl (60% K_2O), kieserite (23.5% MgO) and zinc sulphate (35% Zn^{2+}). Fertilizer application is carried out 15 days after sowing under the supervision of research team closed to each hole considering the calculated doses.

Composite soil samples are taken before the fertilizer application from nine sampling points in the experimental plots at 0 to 20 cm depth. Soil chemical analyses are carried out at the Laboratory of Soil Science, Water and Environment (LSSEE) of the National Agricultural Research Institute of Benin (LSSEE/INRAB). Analyses included particle size distribution (by sieve and Robison pipette method after removal of organic matter, carbonates and iron oxides), pH (water) using a glass electrode in 1:2.5 v/v soil solution, organic carbon according to Walkley and Black method, total nitrogen according to Kjeldahl digestion method in a mixture of H_2SO_4 and selenium followed by distillation and titration, phosphorus according to Bray 1 method, exchangeable cations and exchange cations capacity (ECC) in 1 N ammonium acetate at pH 7 method after which K^+ was determined with a flame photometer.

The soybean plants were harvested at maturity when the plants lose biomass. Seed and aboveground biomass samples were collected and sent to the laboratory for drying in an electric oven at 65°C for 72 h for dry matter determination. The harvest index was determined on the basis of the grain and the aboveground biomass yields.

Statistical analyses

The statistical analyses are performed using SAS v. 9.4 packages. Grain and aboveground biomass yields and harvest index of each zone were subject to a one-way analysis of variance considering the treatments; a general linear mixed-effect model, considering farmers as a random factor and nutrient combinations as a fixed factor. Student Newman-Keuls test is carried out for mean separation at significance levels of $p < 0.05$. The optimal nutrient doses of each nutrient are determined based on response surface analyses using MINITAB 18 software.

RESULTS

Soil physico-chemical parameters

Soil particle sizes range between sandy to sandy loamy textures. The pH (water) is 6.25 and 6.6 for the sites of Ouessè and Bembèrèkè, respectively; soil organic C is 6.42 and 5.35 g kg^{-1} for Ouessè and Bembèrèkè, respectively; total N is 0.73 and 0.5 g kg^{-1} for Ouessè and Bembèrèkè, respectively; the available P is 47.25 and 15.25 mg kg^{-1} for Ouessè and Bembèrèkè, respectively and the exchangeable K^+ is 0.28 and 0.15 $cmol.kg^{-1}$ for Ouessè and Bembèrèkè, respectively. The ECC of both soils are low (< 15 $cmol.kg^{-1}$). In general, the soils of the study area are slightly acid with low organic matter content (with C/N ratios varying between 10 and 14). The consequence of this low C/N ratio is a low level of total N which seems to be with P the most limiting nutrients for both soils.

Effect of the different treatments on soybean grain yield and the aboveground biomass production

Tables 1 and 2 show the mean values of soybean seed grain yields, the aboveground biomass production and the harvest index, considering the different treatments at the sites of Ouessè and Bembèrèkè. The analysis of variance shows that the treatments have significantly ($p < 0.001$) improved the soybean grain yields, the aboveground biomass ($p = 0.0001$) and the harvest index ($p = 0.0126$). Both yields and the harvest index variation ($p < 0.001$) are equally observed according to the research sites.

The lowest (<1 t ha^{-1}) seed grain yield is induced by the control plot (T_0) on both research sites. Considering both growing seasons (2018 and 2019) nutrient application induced high seed grain yields (up to 4.7 and 3.2 times) compared to the control plot. Treatments with high N and P doses (for instance $N_{40}P_{30}K_0Mg_{20}Zn_5$ and $N_{20}P_{60}K_{20}Mg_{20}Zn_0$) induced high aboveground biomass yields and low seed grain yields. The treatments with intermediate N and P doses combined with the intermediate Zn dose increased the seed grain yields and the aboveground biomass yields. On both sites, the overall harvest indices varied from 0.18 to 0.65.

At Ouessè, the lowest harvest index (0.13 and 0.15, respectively in 2018 and 2019) was obtained with the treatment with minimum N dose and high P level, due to the high aboveground biomass produced at the expense of the seed grain. The harvest index of treatments that induce a balance between the aboveground biomass and the seed grain yields vary between 0.4 and 0.45. This seems to be acceptable for good soybean production, depending on the cultivars used. Treatments with Zn have a harvest index in this range.

At Bembèrèkè, the lowest harvest index in 2018 was 0.18 obtained with treatment $N_{20}P_0K_{20}Mg_{20}Zn_0$. For this first growing season, the harvest indices range between 0.18 and 0.39. However, in 2019 the harvest indices vary between 0.4 and 0.6.

Nutrient optimal doses

Figure 2 shows the contour plots of the seed grain yields regarding the different treatments. Doses of Mg (30 kg ha^{-1}) and N (20 kg ha^{-1}) enhanced the seed grain yield. There is a gradual decrease when the rates of these nutrients are high in the treatment. However, with an increase rate of N and Zn in the treatment, the seed grain yields increase and a decrease is observed when the N rate exceeds 20 kg ha^{-1} threshold regarding Zn rate in the treatment. Thus, application of an intermediate dose of N interacts effectively with Zn in the treatment. An increase rate of K and a low rate of Zn induced a rise in the seed

Table 1. Average (± Standard Errors) values of the seed grain yields, aboveground biomass and harvest index of soybean crop regarding the treatments during the growing season of 2018 and 2019 at the site of Ouessè.

Treatment	Aboveground biomass yield (t MS ha^{-1})		Seed grain yield (t MS ha^{-1})		Harvest index	
	2018	2019	2018	2019	2018	2019
$N_0 P_0 K_0 Mg_0 Zn_0$	0.79 ± 0.02^{g}	0.76 ± 0.05^{e}	0.66 ± 0.04^{o}	0.75 ± 0.05^{q}	0.45 ± 0.008^{a}	0.42 ± 0.05^{cd}
$N_{20} P_{30} K_0 Mg_{20} Zn_0$	3.44 ± 0.18^{ab}	2.65 ± 0.35^{abc}	2.83 ± 0.06^{a}	2.4 ± 0.01^{bcd}	0.39 ± 0.01^{abcde}	0.4 ± 0.02^{abc}
$N_{40} P_{30} K_0 Mg_{20} Zn_5$	3.37 ± 0.53^{abcde}	3.45 ± 0.15^{abc}	2.15 ± 0.04^{b}	2.55 ± 0.15^{bcd}	0.39 ± 0.03^{abcde}	0.4 ± 0.001^{abcd}
$N_{20} P_{30} K_{20} Mg_{40} Zn_{10}$	2.27 ± 0.14^{bcdef}	2.65 ± 0.15^{abcd}	1.56 ± 0.03^{fhg}	1.65 ± 0.05^{ijklmno}	0.41 ± 0.01^{abcde}	0.4 ± 0.0001^{abcd}
$N_{20} P_{30} K_{20} Mg_{40} Zn_0$	2.04 ± 0.07^{def}	2.25 ± 0.05^{abc}	1.46 ± 0.05^{ihg}	1.65 ± 0.05^{ijklmno}	0.32 ± 0.01^{abcde}	0.3 ± 0.0001^{bcd}
$N_{20} P_0 K_0 Mg_{20} Zn_5$	3.65 ± 0.22^{ab}	3 ± 0.5^{abc}	0.99 ± 0.03^{lm}	1.10 ± 0.1^{pq}	0.21 ± 0.01^{gh}	$0.250.05^{cd}$
$N_{40} P_{30} K_{40} Mg_{20} Zn_5$	2.86 ± 0.28^{f}	3.4 ± 0.1^{abc}	1.37 ± 0.04^{ihj}	1.7 ± 0.001^{hijklmno}	0.43 ± 0.04^{abc}	0.4 ± 0.001^{bcd}
$N_{20} P_{60} K_{40} Mg_{20} Zn_5$	2.24 ± 0.27^{bcdef}	3.05 ± 0.05^{abc}	2.08 ± 0.005^{cb}	2.3 ± 0.1^{bcdefg}	0.48 ± 0.03^{a}	0.4 ± 0.001^{abcd}
$N_{20} P_{30} K_{20} Mg_{20} Zn_5$	2.34 ± 0.11^{bcdef}	2.15 ± 0.35^{abc}	2.03 ± 0.06^{ab}	2.05 ± 0.05^{opq}	0.45 ± 0.02^{ab}	0.43 ± 0.001^{bcd}
$N_{40} P_{30} K_{20} Mg_{40} Zn_5$	2.66 ± 0.31^{bcdef}	2.85 ± 0.85^{abc}	2.13 ± 0.02^{cb}	2.15 ± 0.05^{defghi}	0.45 ± 0.02^{abc}	0.45 ± 0.05^{abcd}
$N_{20} P_{30} K_0 Mg_0 Zn_5$	2.7 ± 0.1^{bcdef}	2.45 ± 0.35^{abc}	2.02 ± 0.02^{cbd}	2.7 ± 0.2^{bc}	0.42 ± 0.01^{abc}	0.45 ± 0.05^{ab}
$N_{20} P_{30} K_{20} Mg_{20} Zn_5$	2.29 ± 0.14^{bcdef}	2.6 ± 0.3^{abc}	2.02 ± 0.06^{efg}	2.1 ± 0.1^{defghi}	0.48 ± 0.02^{a}	0.45 ± 0.05^{abcd}
$N_{20} P_{30} K_{20} Mg_{20} Zn_5$	2.20 ± 0.14^{cdef}	2.25 ± 0.55^{abc}	2.04 ± 0.06^{cbd}	2.35 ± 0.05^{bcefd}	0.48 ± 0.02^{a}	0.45 ± 0.05^{abcd}
$N_{20} P_{60} K_{20} Mg_{20} Zn_{10}$	1.68 ± 0.15^{f}	1.65 ± 0.35^{ef}	0.75 ± 0.08^{on}	1.15 ± 0.05^{opq}	0.35 ± 0.012^{bacdef}	0.2 ± 0.0001^{d}
$N_{20} P_0 K_{20} Mg_0 Zn_5$	1.65 ± 0.21^{f}	1.85 ± 0.55^{ef}	0.88 ± 0.04^{nm}	1.6 ± 0.1^{jklmnop}	0.43 ± 0.03^{abc}	0.35 ± 0.05^{abcd}
$N_{20} P_0 K_{40} Mg_{20} Zn_5$	1.83 ± 0.15^{f}	2.7 ± 0.2^{abc}	1.4 ± 0.01^{hi}	1.35 ± 0.05^{mnop}	0.43 ± 0.02^{abc}	0.3 ± 0^{cbd}
$N_{20} P_{60} K_{20} Mg_{20} Zn_0$	2.22 ± 0.34^{cdef}	3 ± 0.1^{abc}	1.3 ± 0.011^{ij}	1.55 ± 0.05^{jklmnop}	0.37 ± 0.03^{abcde}	0.3 ± 0.0001^{bcd}
$N_{20} P_{60} K_{20} Mg_0 Zn_5$	2.83 ± 0.22^{bcdef}	3.2 ± 0.2^{abc}	1.3 ± 0.081^{ij}	1.75 ± 0.05^{jklm}	0.42 ± 0.02^{abc}	0.5 ± 0^{abc}
$N_0 P_{30} K_{20} Mg_0 Zn_5$	3.41 ± 0.18^{abcd}	2.1 ± 0.2^{abc}	2.12 ± 0.04^{cb}	2.05 ± 0.05^{defghikj}	0.38 ± 0.02^{abcde}	0.5 ± 0.001^{abc}
$N_{40} P_{30} K_{20} Mg_{20} Zn_{10}$	2.32 ± 0.18^{bcdef}	2.7 ± 0.1^{abc}	0.89 ± 0.03^{nm}	1.50 ± 0.2^{eghijklmn}	0.28 ± 0.02^{defgh}	0.35 ± 0.05^{abcd}
$N_{40} P_0 K_{20} Mg_{20} Zn_5$	2.84 ± 0.44^{bcdef}	2.55 ± 0.75^{abc}	0.57 ± 0.05^{o}	1.25 ± 0.1^{nop}	0.38 ± 0.04^{abcde}	0.4 ± 0.1^{abcd}
$N_0 P_{30} K_{40} Mg_{20} Zn_5$	2.58 ± 0.16^{bcdef}	2.3 ± 0.7^{abc}	1.81 ± 0.04^{ef}	1.25 ± 0.05^{nop}	0.31 ± 0.02^{bcdefg}	0.35 ± 0.05^{abcd}
$N_{20} P_{30} K_{20} Mg_0 Zn_0$	2.58 ± 0.34^{bcdef}	2.55 ± 0.35^{abc}	1.39 ± 0.04^{hij}	1.75 ± 0.05^{ghijklmn}	0.35 ± 0.03^{abcde}	0.4 ± 0.001^{abcd}
$N_{20} P_{30} K_{40} Mg_{20} Zn_{10}$	2.82 ± 0.29^{bcdef}	2.60 ± 0.3^{abc}	1.63 ± 0.03^{ef}	1.9 ± 0.1^{efghijklm}	0.40 ± 0.02^{abcde}	0.45 ± 0.05^{abcd}
$N_{20} P_{30} K_{20} Mg_0 Zn_{10}$	2.30 ± 0.29^{bcdef}	2.25 ± 0.45^{abc}	1.7 ± 0.031^{ef}	1.8 ± 0.1^{fghijklmn}	0.42 ± 0.02^{abc}	0.45 ± 0.05^{abcd}
$N_0 P_{30} K_0 Mg_{20} Zn_5$	2.3 ± 0.17^{bcdef}	2.25 ± 0.35^{abc}	1.71 ± 0.02^{hij}	1.65 ± 0.05^{ijklmno}	0.32 ± 0.02^{bcd}	0.45 ± 0.05^{abcd}
$N_{20} P_{30} K_0 Mg_{20} Zn_{10}$	2.28 ± 0.16^{bcdef}	2.95 ± 0.05^{ab}	1.43 ± 0.04^{lkm}	1.6 ± 0.05^{lmn}	0.32 ± 0.01^{bcefg}	0.35 ± 0.05^{ab}
$N_0 P_{30} K_{20} Mg_{20} Zn_0$	2.75 ± 0.09^{bcdef}	3.2 ± 0.6^{abc}	1.93 ± 0.04^{efg}	2 ± 0.1^{efghijk}	0.41 ± 0.01^{abcde}	0.4 ± 0.1^{abcd}
$N_{20} P_{30} K_{20} Mg_{20} Zn_5$	2.83 ± 0.35^{bcdef}	3.05 ± 0.85^{abc}	2.06 ± 0.02^{bcd}	1.80 ± 0.01^{fghijklmn}	0.37 ± 0.03^{abcde}	0.35 ± 0.05^{abcd}
$N_{40} P_{60} K_{20} Mg_{20} Zn_5$	3.47 ± 0.24^{abcd}	2.85 ± 0.05^{abc}	1.14 ± 0.02^{lm}	1.25 ± 0.05^{cdefgh}	0.37 ± 0.01^{abcde}	0.45 ± 0.05^{abcd}
$N_{40} P_{30} K_{20} Mg_{20} Zn_0$	2.77 ± 0.29^{bcdef}	3.25 ± 0.15^{abc}	1.33 ± 0.02^{mo}	1.40 ± 0.1^{lmno}	0.32 ± 0.02^{bcdefg}	0.3 ± 0.001^{bcd}
$N_0 P_{60} K_{20} Mg_{20} Zn_5$	2.37 ± 0.3^{cdef}	2.6 ± 0.2^{abc}	0.34 ± 0.02^{o}	0.50 ± 0.01^{bcdefg}	0.13 ± 0.02^{abcde}	0.15 ± 0.001^{abc}
$N_{20} P_{30} K_{40} Mg_0 Zn_5$	2.26 ± 0.12^{bcdef}	2.75 ± 0.15^{ab}	2.01 ± 0.01^{bc}	1.25 ± 0.05^{nop}	0.27 ± 0.01^{efgh}	0.25 ± 0.05^{cd}
$N_{20} P_{60} K_{20} Mg_{40} Zn_5$	2.57 ± 0.3^{bcdef}	2.85 ± 0.45^{abc}	1.3 ± 0.13^{lm}	1.45 ± 0.05^{efghij}	0.33 ± 0.006^{bcdef}	0.34 ± 0.05^{abcd}

Table 1. Contd.

$N_{20} P_{30} K_{40} Mg_{40} Zn_5$	2.28 ± 0.45^{bcdef}	3.5 ± 0.1^{abc}	1.98 ± 0.05^{bc}	1.95 ± 0.05^{efghijkl}	0.31 ± 0.03^{bcdefg}	0.35 ± 0.05^{abcd}
$N_{20} P_0 K_{20} Mg_{20} Zn_{10}$	2.89 ± 0.37^{bcdef}	3.35 ± 0.55^{abc}	1.38 ± 0.02^{hi}	1.75 ± 0.05^{ghijklmn}	0.39 ± 0.02^{abcde}	0.35 ± 0.05^{abcd}
$N_{20} P_0 K_{20} Mg_{40} Zn_5$	2.5 ± 0.09^{bcdef}	2.45 ± 0.5^{abc}	1.42 ± 0.12^{hi}	1.85 ± 0.05^{efghijklm}	0.39 ± 0.01^{abcde}	0.4 ± 0.05^{abcd}
$N_{20} P_{30} K_{40} Mg_{20} Zn_0$	1.95 ± 0.16^{def}	2.05 ± 0.45^{abc}	1.84 ± 0.08^{ef}	1.95 ± 0.05^{efghijkl}	0.42 ± 0.03^{abc}	0.48 ± 0.05^{abc}
$N_0 P_0 K_{20} Mg_{20} Zn_5$	0.91 ± 0.22^{gh}	0.9 ± 0.7^{gh}	0.49 ± 0.02^{o}	1.15 ± 0.15^{opq}	0.35 ± 0.03^{abcd}	0.3 ± 0.001^{bcd}
$N_{40} P_{30} K_{20} Mg_0 Zn_5$	2.17 ± 0.02^{cdef}	2.65 ± 0.15^{abc}	1.56 ± 0.01^{fgh}	1.25 ± 0.05^{nop}	0.18 ± 0.001^{h}	0.3 ± 0.001^{bc}
$N_{20} P_0 K_{20} Mg_{20} Zn_0$	2.04 ± 0.16^{def}	1.8 ± 0.1^{bc}	0.98 ± 0.08^{lm}	0.84 ± 0.1^{q}	0.44 ± 0.02^{abc}	0.3 ± 0.03^{a}
$N_0 P_{30} K_{20} Mg_{20} Zn_{10}$	2.5 ± 0.2^{bcdef}	2.6 ± 0.1^{abc}	1.66 ± 0.08^{efg}	2.05 ± 0.05^{defghijk}	0.40 ± 0.02^{abcd}	0.45 ± 0.05^{abcd}
$N_0 P_{30} K_{20} Mg_{40} Zn_5$	2.52 ± 0.35^{bcdef}	1.85 ± 0.35^{abc}	$1.83\pm0.0.05^{ef}$	2 ± 0.2^{efghij}	0.39 ± 0.02^{abcde}	0.55 ± 0.05^{ab}
$N_{20} P_{30} K_0 Mg_{40} Zn_5$	2.26 ± 0.36^{bcdef}	2.25 ± 0.45^{abc}	1.06 ± 0.05^{lkm}	1.85 ± 0.05^{efghijklm}	0.36 ± 0.02^{abcde}	0.45 ± 0.05^{abcd}
$N_{20} P_{30} K_{20} Mg_{20} Zn_5$	2.58 ± 0.12^{abc}	2.2 ± 0.3^{c}	1.91 ± 0.01^{bc}	1.82 ± 0.02^{op}	0.42 ± 0.006^{fgh}	0.4 ± 0.1^{abc}
$N_{20} P_{30} K_{20} Mg_{20} Zn_5$	2.28 ± 0.33^{abc}	2.65 ± 0.05^{ab}	1.82 ± 0.05^{bc}	1.96 ± 0.1^{cd}	0.44 ± 0.05^{abcde}	0.43 ± 0.01^{bcd}
$N_{20} P_{60} K_0 Mg_{20} Zn_5$	2.51 ± 0.01^{bcdef}	2.3 ± 0.8^{abc}	0.46 ± 0.01^{mo}	0.85 ± 0.05^{efghijklm}	0.15 ± 0.003^{efgh}	0.26 ± 0.1^{abc}

In a column mean followed by the same alphabetic letters are not significantly different (P>0.05) according to Student Newman-Keuls test.

Table 2. Average (± Standard Errors) values of the seed grain yields, aboveground biomass and harvest index of soybean crop regarding the treatments during the growing season of 2018 and 2019 at the site of Bembèrèkè.

Treatment	**Aboveground biomass yield (t MS ha^{-1})**		**Seed grain yield (t MS ha^{-1})**		**Harvest index**	
	2018	**2019**	**2018**	**2019**	**2018**	**2019**
$N_0 P_0 K_0 Mg_0 Zn_0$	0.62 ± 0.04^{i}	0.7 ± 0.42^{p}	0.25 ± 0.01^{t}	0.72 ± 0.06^{r}	0.29 ± 0.02^{bcdefghi}	0.4 ± 0.09^{ab}
$N_{20} P_{30} K_0 Mg_{20} Zn_0$	2.14 ± 0.31^{cdefg}	2.25 ± 0.09^{bc}	0.97 ± 0.08^{jklmno}	1 ± 0.001^{q}	0.25 ± 0.009^{efghij}	0.47 ± 0.02^{ab}
$N_{40} P_{30} K_0 Mg_{20} Zn_5$	2.51 ± 0.22^{cdefgh}	2.12 ± 0.37^{bc}	1.12 ± 0.09^{ijklm}	2.25 ± 0.03^{a}	0.31 ± 0.02^{ab}	0.6 ± 0.06^{ab}
$N_{20} P_{30} K_{20} Mg_{40} Zn_{10}$	2.7 ± 0.17^{cdefgh}	1.90 ± 0.27^{bcde}	1.06 ± 0.008^{jklmn}	1.32 ± 0.04^{jklmno}	0.29 ± 0.014^{bcdefghi}	0.42 ± 0.02^{ab}
$N_{20} P_{30} K_{20} Mg_{40} Zn_0$	2.22 ± 0.21^{cdef}	2.72 ± 0.27^{b}	1.19 ± 0.09^{ghijk}	1.62 ± 0.05^{fghi}	0.27 ± 0.01^{efghij}	0.48 ± 0.04^{ab}
$N_{20} P_0 K_0 Mg_{20} Zn_5$	1.77 ± 0.13^{gh}	1.67 ± 0.19^{efg}	0.71 ± 0.06^{opqr}	1.45 ± 0.06^{hijkl}	0.29 ± 0.01^{bcdefghi}	0.62 ± 0.06^{ab}
$N_{40} P_{30} K_{40} Mg_{20} Zn_5$	2.54 ± 0.13^{bcde}	1.95 ± 0.54^{cdef}	1.71 ± 0.1^{opqr}	2 ± 0.04^{bc}	0.32 ± 0.01^{abcdef}	0.52 ± 0.09^{ab}
$N_{20} P_{60} K_{40} Mg_{20} Zn_5$	2.62 ± 0.61^{bcd}	1.95 ± 0.53^{cdef}	1.43 ± 0.004^{efg}	1.97 ± 0.08^{bc}	0.3 ± 0.04^{abcdefghi}	0.55 ± 0.06^{ab}
$N_{20} P_{30} K_{20} Mg_{20} Zn_5$	2.52 ± 0.28^{bcdef}	2.15 ± 0.12^{bc}	2.15 ± 0.01^{a}	2.25 ± 0.02^{a}	0.2 ± 0.01^{ijk}	0.4 ± 0.001^{ab}
$N_{40} P_{30} K_{20} Mg_{40} Zn_5$	3.6 ± 0.34^{bcd}	2.87 ± 0.12^{b}	1.56 ± 0.09^{efd}	2 ± 0.04^{bc}	0.3 ± 0.02^{abcdefgh}	0.52 ± 0.02^{ab}
$N_{20} P_{30} K_0 Mg_0 Zn_5$	2.63 ± 0.3^{cdefgh}	2.05 ± 0.41^{bc}	1.63 ± 0.09^{cde}	1.80 ± 0.04^{cd}	0.38 ± 0.02^{ab}	0.47 ± 0.06^{ab}
$N_{20} P_{30} K_{20} Mg_{20} Zn_5$	2.32 ± 0.37^{cdef}	2 ± 0.32^{cd}	1.56 ± 0.07^{def}	1.75 ± 0.05^{de}	0.32 ± 0.03^{abcdefg}	0.5 ± 0.04^{ab}
$N_{20} P_{30} K_{20} Mg_{20} Zn_5$	2.04 ± 0.38^{cdefg}	2.15 ± 0.46^{bcd}	1.24 ± 0.06^{ghij}	1.42 ± 0.06^{hijklmn}	0.3 ± 0.03^{abcdefghi}	0.42 ± 0.07^{ab}
$N_{20} P_{60} K_{20} Mg_{20} Zn_{10}$	1.62 ± 0.29^{bcd}	1.77 ± 0.23^{cd}	1.39 ± 0.05^{fgh}	1.45 ± 0.08^{hijklm}	0.28 ± 0.02^{cdefghi}	0.47 ± 0.02^{ab}
$N_{20} P_0 K_{20} Mg_0 Zn_5$	1.53 ± 0.13^{cdefgh}	0.9 ± 0.11	1.54 ± 0.11^{def}	1.8 ± 0.04^{cd}	0.37 ± 0.02^{abcd}	0.65 ± 0.03^{a}
$N_{20} P_0 K_{40} Mg_{20} Zn_5$	2.67 ± 0.18^{cdefgh}	2.22 ± 0.13^{cd}	1.31 ± 0.04^{fghi}	1.32 ± 0.04^{jklmno}	0.33 ± 0.01^{abcdef}	0.52 ± 0.04^{ab}

Table 2. Contd.

$N_{20} P_{60} K_{20} Mg_{20} Zn_{0}$	1.76±0.28^{fgh}	1.95±0.41^{bcde}	0.72±0.03^{opqr}	1.55±0.08^{efghijk}	0.13±0.005^{k}	0.45±0.06^{ab}
$N_{20} P_{60} K_{20} Mg_{0} Zn_{5}$	1.88±0.23^{cdefg}	1.85±0.44^{bcd}	1.53±0.02^{def}	1.62±0.06^{defghi}	0.35±0.02^{abcde}	0.52±0.07^{ab}
$N_{0} P_{30} K_{20} Mg_{0} Zn_{5}$	1.97±0.3^{cdefg}	1.75±0.25^{cd}	1.32±0.02^{fghi}	1.40±0.04^{jklmno}	0.31±0.02^{abcdefg}	0.45±0.02^{ab}
$N_{40} P_{30} K_{20} Mg_{20} Zn_{10}$	3.68±0.45^{bc}	1.62±0.37^{fgh}	1.31±0.04^{ghi}	1.20±0.04^{jklm}	0.39±0.03^{a}	0.6±0.05^{ab}
$N_{40} P_{0} K_{20} Mg_{20} Zn_{5}$	1.51±0.19^{h}	1.62±0.26^{ghi}	0.54±0.020.54^{rs}	1.05±0.06^{lmnop}	0.27±0.02^{efghij}	0.45±0.05^{ab}
$N_{0} P_{30} K_{40} Mg_{20} Zn_{5}$	1.94±0.15^{cdefg}	1.85±0.27^{cdef}	1.03±0.03^{jklmn}	1.35±0.06^{jklmno}	0.26±0.01^{efghij}	0.42±0.04^{ab}
$N_{20} P_{30} K_{20} Mg_{0} Zn_{0}$	2.7±0.22^{cdefgh}	2.27±0.31^{ab}	1.58±0.08^{hijkl}	1.5±0.07^{fghijkl}	0.3±0.02^{abcdefghi}	0.45±0.02^{ab}
$N_{20} P_{30} K_{40} Mg_{20} Zn_{10}$	2.28±0.33^{cdef}	2.22±0.25^{ab}	1.03±0.09^{jklmn}	1.32±0.02^{jklmno}	0.24±0.005^{fghij}	0.37±0.04^{ab}
$N_{20} P_{30} K_{20} Mg_{0} Zn_{10}$	2.87±0.07^{cdefg}	1.27±0.26^{hijk}	1.83±0.04^{c}	1.77±0.02^{de}	0.39±0.008^{a}	0.57±0.04^{ab}
$N_{0} P_{30} K_{0} Mg_{20} Zn_{5}$	2.18±0.12^{efgh}	1.35±0.17^{hijklm}	0.88±0.05^{lmnop}	1.67±0.04^{defgh}	0.29±0.02^{bcdefghi}	0.55±0.03^{ab}
$N_{20} P_{30} K_{0} Mg_{20} Zn_{10}$	2.82±0.23^{cdefg}	1.97±0.34^{bcd}	0.98±0.02^{jklmno}	1.3±0.05^{klmno}	0.26±0.01^{efghij}	0.4±0.04^{ab}
$N_{0} P_{30} K_{20} Mg_{20} Zn_{0}$	2.36±0.08^{cdefgh}	1.82±0.36^{bcd}	1.10±0.03^{ijklmn}	1.45±0.06^{hijklm}	0.31±0.01^{abcdefg}	0.47±0.04^{ab}
$N_{20} P_{30} K_{20} Mg_{20} Zn_{5}$	2.24±0.16^{defgh}	1.82±0.32^{bcd}	1.47±0.01^{jklmno}	1.42±0.04^{ijklmn}	0.30±0.01^{abcdefgh}	0.45±0.05^{ab}
$N_{40} P_{60} K_{20} Mg_{20} Zn_{5}$	2.92±0.3^{cdefg}	2.57±0.49^{bc}	0.98±0.05^{lmnop}	1.05±0.03^{pq}	0.24±0.16^{fghi}	0.3±0.04^{b}
$N_{40} P_{30} K_{20} Mg_{20} Zn_{0}$	3.55±0.39^{bcde}	3.15±0.53^{a}	1.1±0.02^{ijklmn}	1.18±0.04^{op}	0.38±0.03^{abc}	0.5±0.07^{ab}
$N_{0} P_{60} K_{20} Mg_{20} Zn_{5}$	2.25±0.04^{defgh}	1.57±0.32^{ghi}	0.5±0.04^{rs}	1.45±0.02^{hijklm}	0.18±0.01^{jk}	0.47±0.04^{ab}
$N_{20} P_{30} K_{40} Mg_{0} Zn_{5}$	2.48±0.15^{cdefgh}	1.30±0.24^{ijklmn}	0.7±0.06^{pqr}	1.15±0.03^{opq}	0.22±0.01^{ghij}	0.5±0.04^{ab}
$N_{20} P_{60} K_{20} Mg_{40} Zn_{5}$	3.15±0.22^{cdef}	1.8±0.26^{cd}	1.23±0.01^{ghij}	1.7±0.04^{defg}	0.28±0.01^{defghi}	0.5±0.04^{ab}
$N_{20} P_{30} K_{40} Mg_{40} Zn_{5}$	3.17±0.3^{cdef}	1.32±0.13^{ijklm}	0.94±0.03^{klmnop}	1.4±0.01^{ijklmno}	0.23±0.01^{fghi}	0.55±0.02^{ba}
$N_{20} P_{0} K_{20} Mg_{20} Zn_{10}$	2.42±0.16^{cdefgh}	2.27±0.36^{bc}	0.93±0.05^{klmnop}	1.30±0.04^{klmno}	0.28±0.008^{defghij}	0.65±0.15^{a}
$N_{20} P_{0} K_{20} Mg_{40} Zn_{5}$	2.4±0.24^{cdefgh}	1.9±0.07^{bc}	0.86±0.03^{mnop}	1.47±0.04^{ghijk}	0.27±0.015^{efghi}	0.62±0.02^{ab}
$N_{20} P_{30} K_{40} Mg_{20} Zn_{0}$	2.91±0.14^{cdefg}	1.7±0.4^{bc}	1.01±0.01^{jklmn}	1.55±0.06^{efghijk}	0.26±0.007^{efghi}	0.5±0.07^{ab}
$N_{0} P_{0} K_{20} Mg_{20} Zn_{5}$	1.44±0.24^{i}	1.27±0.33^{klmno}	0.61±0.05^{qrs}	1.05±0.02^{pq}	0.21±0.01^{hij}	0.47±0.06^{ab}
$N_{40} P_{30} K_{20} Mg_{0} Zn_{5}$	3.48±0.15^{a}	3.72±0.27^{a}	1.08±0.05^{jklm}	1.05±0.05^{pq}	0.29±0.004^{bcdefghi}	0.5±0.04^{ab}
$N_{20} P_{0} K_{20} Mg_{20} Zn_{0}$	2.18±0.13^{efgh}	1.4±0.22^{jkl}	0.46±0.01^{s}	1.27±0.02^{lmnop}	0.18±0.015^{jk}	0.47±0.04^{ab}
$N_{0} P_{30} K_{20} Mg_{20} Zn_{10}$	2.15±0.24^{fgh}	1.57±0.34^{ghi}	0.81±0.05^{nopq}	1.57±0.02^{efghi}	0.28±0.03^{cdefghi}	0.5±0.05^{ab}
$N_{0} P_{30} K_{20} Mg_{40} Zn_{5}$	2.08±0.13^{cdefg}	1.7±0.1^{cde}	1.02±0.01^{jklmn}	1.2±0.04^{nopq}	0.26±0.008^{efghij}	0.4±0.1^{ba}
$N_{20} P_{30} K_{0} Mg_{40} Zn_{5}$	2.55±0.12^{cdefgh}	1.45±0.27^{hijk}	0.91±0.08^{klmnop}	1.17±0.04^{nopq}	0.26±0.01^{efghij}	0.45±0.06^{ab}
$N_{20} P_{30} K_{20} Mg_{20} Zn_{5}$	2.34±0.2^{cdef}	2.1±0.8^{cd}	2.33±0.08^{a}	2.05±0.06^{a}	0.28±0.008^{bcefghi}	0.5±0.1^{ab}
$N_{20} P_{30} K_{20} Mg_{20} Zn_{5}$	3.09±0.22^{cdefg}	1.82±0.3^{cdef}	1.05±0.07^{jklmn}	1.27±0.2^{lmnop}	0.25±0.01^{efghij}	0.42±0.04^{ab}
$N_{20} P_{60} K_{0} Mg_{20} Zn_{5}$	2.77±0.12^{cdefgh}	1.57±0.38^{ijklm}	1.33±0.03^{fghi}	1.45±0.06^{hijklm}	0.32±0.01^{abcdefgh}	0.5±0.07^{ab}

In a column mean followed by the same alphabetic letters are not significantly different (P>0.05) according to Student Newman-Keuls test.

grain yields. With an increase rate of Mg and a low rate of Zn, there is an increase of the seed grain yield. In general, the application of Zn at a low rate in the treatments improved the efficiency of the macronutrients which induced high seed grain yields.

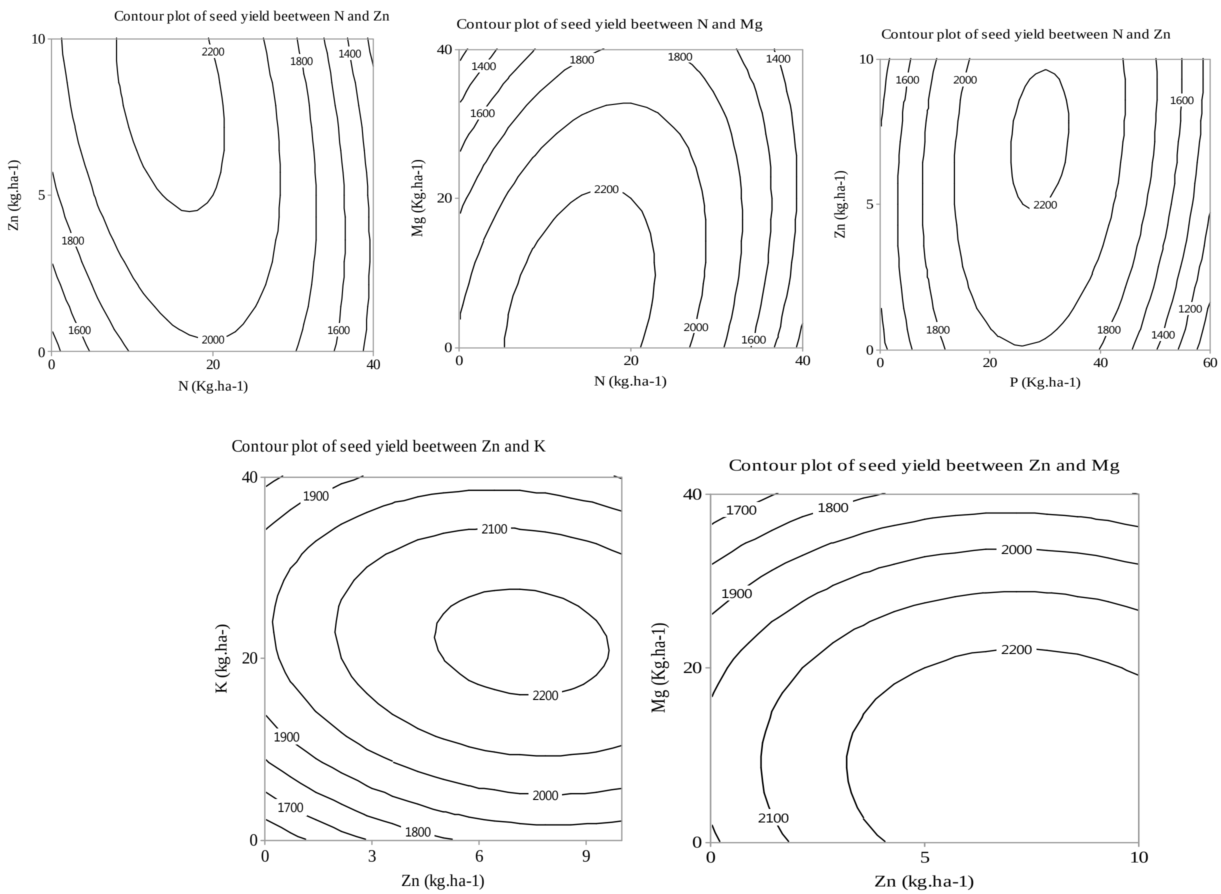

Figure 2. Contours plots of the seed grain yields between pair nutrients.

Figure 3 shows soybean response curves to the different nutrients applied. Soybean seed grain yields increase with an increasing rate of N and P, and gradually decreased above 20 kg N ha^{-1} and above 30 kg ha^{-1} of P. At a rate of 0 kg ha^{-1} of N and P low soybean seed grain yields were induced. An increasing rate of K and Mg leads to an increase of seed grain yield. This decreases beyond the intermediate rate of the nutrients, but the minimum rates induced seed grain yields varying between 0.8 and 1.1 t ha^{-1}. High doses of Zn induced low seed grain yields. In summary, there is a stronger response to Zn followed by P then N after Mg and K.

Table 3 presents the regression equations determining the optimal nutrient doses for optimal yield. The full quadratic models (with interaction) are efficient ($R^2 > 0.5$) in estimating soybean seed grain yields at Bembèrèkè, whereas simple quadratic models are efficient and highly significant ($p = 0.001$) in estimating soybean seed grain yields at the site of Ouessè. The determination coefficients of the model vary between 0.83 and 0.98 while the adjusted determination coefficients vary between 0.75 and 0.89. Thus, the quadric models were the most effective models in estimating soybean grain yields.

The optimal doses of N, P, K, Mg and Zn are the solutions of the system of equation formed using the first derivative of the regression equations presented in Table 3. To do this, it is necessary to consider the partial derivatives of the functions with respect to N, P, K, Mg and Zn^{2+}, that is, the marginal product which is the ratio of the variation in the yield to the variation in the applied fertilizer. The maximum profit is obtained by equating the marginal product to the factor/product price ratio according to the system of equation. The optimum doses obtained (Table 4) vary between 13.95 and 15.46 $kgha^{-1}$ for N; 23.20 and 23.96 $kgha^{-1}$ for P; 17.82 and 29 $kgha^{-1}$ for K; 11.45 and 16.8 $kgha^{-1}$ for Mg and 4.02 and 6.9 $kgha^{-1}$ for Zn. The highest optimal doses are obtained for P in both sites while the optimal doses of K are low at Bembèrèkè compared with Ouessè. The same observation is made for Zn.

DISCUSSION

Soil fertility status in the soybean cropping system

Soils of the study area were slightly acid with pH values

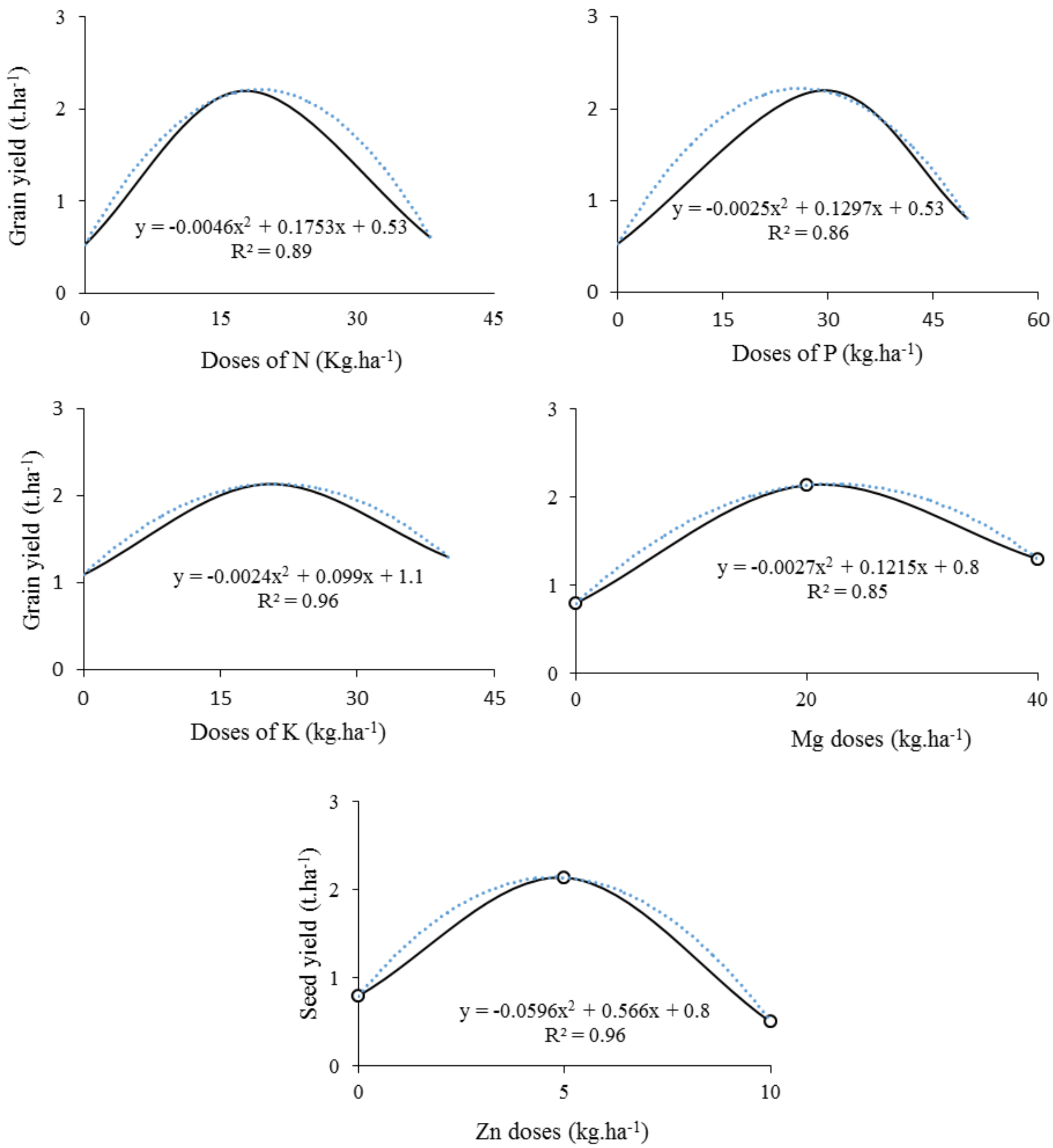

Figure 3. Response curves of soybean seed grain yields to the different nutrients applied

between 6.25 and 6.6 suitable for soybean cultivation. Saïdou et al. (2017) also reported the same pH values in this agroecological zones. This confirms Ramarson (2002) findings which revealed that optimum conditions for growing soybean are deep and light soils with slightly acid characteristic. In general, soybean production requires an optimum pH of 6.0 to 6.8, since soils with a pH below 4.0 limit its growth (Walangululu et al., 2014). The low ECC level (< 15 cmol kg^{-1}) indicated a low soil organic matter content which is a limiting factor because soybean cultivation requires high level of organic matter as mentioned by Rienke and Joke (2005). Moreover, Owusu and Sadick (2016) showed that a so-called productive soil requires at least 2.3% organic carbon. However, a low level of N, P and K is found in the study area. This would probably be the source of the low yield levels observed when compared with the control treatment with no fertilizer. The same findings are reported by Saïdou et al. (2017) on maize cultivation. This would also be explained by an N and P deficiency as reported in several studies (Koné et al., 2009, 2010; Saïdou et al., 2017). Indeed, a soil P deficiency would be a source of major abiotic stress that would limit plant growth and productivity (Miao et al., 2007). This shows

Table 3. Regression equation between nutrients N, P, K, Mg and Zn and the seed grain yields of soybean in the studied sites in 2018 and 2019.

Site		Regression equations	R^2	R^2_{adj}
Bembèrèkè	2018	Seed grain yield ($t.\ ha^{-1}$) = -0.081+ 0.0806 N + 0.0439 P +0.0107 K +0.0324 Mg + 0.120 Zn -0.00182 N^2 - 0.000947 P^2 - 0.000764 K^2 - 0.000905 Mg^2 -0.0152 Zn^2 - 0.000139 N*P + 0.000288 N*K -0.000089 N*Mg + 0.00136 N*Zn +0.000284 P*K – 0.000258 P*Mg -0.000051 P*Zn + 0.000464 K*Mg – 0.00176 K*Zn – 0.00211 Mg*Zn	0.98***	0.89***
	2019	Seed grain yield ($t.\ ha^{-1}$) = -0.083 + 0.0393 N + 0.0540 P + 0.0273 K + 0.0514 Mg + 0.1358 Zn - 0.001290 N^2 - 0.000743 P^2- 0.000847 K^2 - 0.000949 Mg^2 - 0.01030 Zn^2 - 0.000297 N*P + 0.000132 N*K - 0.000097 N*Mg + 0.00153 N*Zn + 0.000157 P*K - 0.000366 P*Mg - 0.000037 P*Zn + 0.000368 K*Mg - 0.00187 K*Zn - 0.00125 Mg*Zn	0.97***	0.86***
Ouessè	2018	Seed grain yield ($t.ha^{-1}$) = 0.626 + 0.0496 N + 0.05453 P + 0.0168 K – 0.0159 Mg + 0.0319 Zn – 0.001395N^2- 0.000960 P^2 - 0.000260 K^2 + 0.000459 Mg^2 - 0.00187 Zn^2	0.87***	0.78***
	2019	Seed grain yield ($t.ha^{-1}$) = 0.726 + 0.0492 N +0.05077 P + 0.0317 K -0.0163 Mg + 0.0483 Zn – 0.001503 N^2 – 0.000920 P^2- 0.000274 K^2 + 0.000463 Mg^2- 0.003 Zn^2	0.83***	0.75***

***$p<0.001$.

Table 4. Optimal nutrient doses and optimal seed grain yields of soybean on the sites of Ouessè and Bembèrèkè during the cropping season of 2018 and 2019.

Site		Optimal doses of N-P-K-Mg and Zn ($kg\ ha^{-1}$)	Optimal seed grain yields ($t\ ha^{-1}$)
Bembèrèkè	2018	14.02-23.89-17.82-11.45-4.26	2.02
	2019	13.95-23.96-18.54-11.52-4.02	1.99
Ouessè	2018	16.6-23.5-29-15.2-7.7	2.08
	2019	15.46-23.20-28.6-16.8-6.9	1.89

the importance of these two nutrients in the improvement of soybean productivity. The findings in this research work show a P deficiency in a large portion of the soybean cropping system as also suggested by Bamisa (2016), as well as nitrogen (Saïdou et al., 2017). This late nutrient is an important component of the grain protein (Mehmet, 2008; Kindomihou et al., 2014). This finding could explain the fact that high seed grain yields were obtained with treatments containing middle doses of N and P as observed in the context of the present study.

Soybean responses to N, P, K, Mg and Zn fertilization

The results of the present study show a response of the soybean plants to the N supply. High yields (2 $t\ ha^{-1}$) were obtained with the application of N doses below 20 $kg\ ha^{-1}$ because above this value, a decrease was noticed in the seed grain yields. These results indicate that soybean fertilization with N is compulsory to guarantee good production (Vanlauwe et al., 2019). Similarly, the interaction of N with other nutrients showed that N application rates of less than 20 $kg\ ha^{-1}$ are appropriate practice in improving the efficiency of the N use with other nutrients, as evidenced by the contours plots seed grain yields of N with other nutrients. Some related observations were reported by Barker and Swayer (2005) and Hungria et al. (2006), who contend that the N application, especially in agroecologicals areas potentially favorable to soybean cultivation, improves the efficiency of nutrient use by the plant. In these environments, N application probably contributes to overcome environmental constraints that may limit the supply of N or its uptake by the crop (Gan et al., 2003; Barker and Sawyer, 2005). Soybean yield is more likely to respond to N fertilization in high-yield environment (Salvagiotti et al., 2008).

Likewise, the response curves to nutrients show a strong response to Zn, P and N. This may be due to the soil low fertility in the area for these nutrients, as evidenced by the values determined in the soil samples. Similarly, P is a very important nutrient for soybeans to enable the plant to cover its energy needs. According to Muhammad (2010) and Ballo (2018), P also improves the symbiotic nitrogen fixation process, by increasing soybean rooting system, nodules, therefore, good nitrogen nutrition and seed grain yield. This result corroborates those of Kindomihou et al. (2014) and Ballo et al. (2018). According to Giller and Dashiell (2007), P supply is often necessary to improve the symbiotic fixing of atmospheric N_2 and for a good soybean production. Weak responses are observed with Mg at both sites and K at Bembèrèkè. This may be due to the fact that in both agro-ecological zones, the soils in the soybean cropping systems own some adequate values for K and Mg.

The findings show also that the N, P, K, Mg and Zn supply mostly improve soybean aboveground biomass and the soybean seed grain yields. This could be explained by the primary role of macronutrients in soybean mineral nutrition. Also, mineral fertilization including Mg and Zn induced significantly high values of seed grain yield at moderate application rates. Yield plots contours show the improvement of macronutrient efficiency with the addition of Zn and Mg (Vanlauwe et al., 2015; da Silva et al., 2019). Indeed, high seed grain yields are achieved with quantities below intermediate doses of macronutrients (Bandyopadhyay et al., 2010). As mentioned by Zahoor et al. (2013), soybean generally responds to micronutrients by enhancing nodulation and the grain yield. Similarly, other findings revealed the beneficial effects of supplying Zn with macronutrients on the photosynthetic activity of soybeans, which contributes to significant dry matter production (Bender et al., 2015; Goli et al., 2015; Dimkpa and Bindraban, 2016).

Furthermore, the present study findings also show that without nutrient interactions, yield improvement cannot be achieved. However, it is also observed that interaction of N, P, Mg and K with Zn is a prerequisite to improve soybean productivity. But the low responses observed for Mg may not allow the recommendation of the application of this nutrient when it is not available. But to avoid long-term agriculture mining, it would be wise to find alternative sources (incorporation of residues into the soil) to compensate export.

Efficiency of the response surface method in determining the optimal nutrient doses

Within the scope of the current work, the quadratic models were efficient based on the coefficient of determination (R^2) for the soybean seed grain yields determination regarding the applied N, P, K, Mg and Zn doses. Quadratic regression models were the best predictors of crop responses to nutrient application (Spironello et al., 2004; Agbangba et al., 2016; Myers et al., 2016). Many related results are also part of Alam et al. (2020) findings, who used the quadratic models to determine the optimal levels of the biochar, compost and nitrogen rate for optimizing soybean production in an intercropping soybean cropping system. In the same ways, these quadratic models have also been used effectively by Beanland et al. (2003) and da Silva Gomes et al. (2020) to determine optimal micronutrient (B, Fe and Zn) doses for soybean production under hydroponic and field conditions. Many other studies (Chiezey and Odunze, 2009; Poruţiu et al., 2013; Antonangelo et al., 2019) have determined optimal nutrient doses for soybean production under different environmental conditions with the quadratic regression model. This shows that recommendations for optimal fertilizer doses in other Benin agroecological zones based on the use of the models will be efficient.

The R^2 values found are greater than 0.7 with variations from year to year and from site to site. The coefficient of determination (R^2) is used to evaluate the general predictive capability of the fitted model. This variation is not likely to affect the reliability of the model, especially since these coefficients are really great (Azaïs and Bardet, 2006; Myers et al., 2016). However, R^2 is not a sufficient index for this evaluation and other criteria should be investigated. But, most of the studies (Myers et al., 2016; Yolmeh and Jafari, 2017) revealed that RSM is successfully applied to optimize many factors in different domains, because of good R^2-adj and R^2-pred values, insignificant p values for lack-of-fit value, and good compatibility of the predicted and experimental values. This applies in the current scrutiny with high values of R^2-adj. However, high values of the R^2 (predictive) allow a great predictive capacity (Azaïs and Bardet, 2006; Agbangba et al., 2016). The high values of R^2-adj obtained in this study show a good adequacy between soybean seed grain yields and the doses of N, P, K, Mg and Zn applied, which showed a minimization of model errors (Azaïs and Bardet, 2006).

Agronomic implications of the determined nutrient optimal doses

N, P, K, Mg and Zn doses of 15.46, 23.20, 28.6, 16.8 and 6.9 kg ha^{-1} (for the centre) and 14.02, 23.89, 17.82, 11.45 and 4.26 kg ha^{-1} (for the south Borgou), respectively were the optimal doses for soybean production. The optimal doses of P obtained in this study are within the range recommended (20-25 kg ha^{-1}) by other authors (Afolabi et al., 2014; Tekle and Walelign, 2014; Zoundji et al., 2015;

Amapu et al., 2018). Nevertheless, one can notice that these authors' recommendations are accompanied by the use of inoculum or organic fertilizers. Future investigations can be made with our optimal doses to see the contribution of organic fertilizers or inoculum to decrease doses for yield improvement. The optimal doses determined allow an average seed grain yield of 2.035 t ha^{-1}, that is, 2.5 times the yield in farmers' field and these doses can ensure a best return on investment for producers. The doses of N and P found in this study are different from those recommended by Yakamba et al. (2009), Yaya et al. (2011) and Zamakulu et al. (2018) who recommend 50 kg ha^{-1} N, 40 kg ha^{-1} P and 30 kg ha^{-1} P, respectively. This could be explained by differences in soil characteristics. The response of a crop to a given fertilizer depends on the stock of that nutrient in the soil. So a poor soil with deficiencies in one element will require a high supply of that element compared to a rich soil.

An appropriate mineral fertilization depends on several parameters (rainfall, mineral content of the soil). This can vary from one area to another. Thus, the doses established in this work should be validated in other soybean production areas and take into account variants of soybean cultivars (Tossou et al., 2015). Another constraint for appropriate mineral fertilization implementation is the provision of nutrients in a single formulation. In this study, nutrients are provided in the form of single fertilizers. Making such a recommendation at the production scale would be almost impossible for farmers. In this context, the development of fertilizer formulation containing the 5 nutrients should be a target. Combining these 5 nutrients in a single formula may not be possible, especially when the determined rates are high. It would therefore be wise to consider the essential nutrients (N, P, K and Zn) and to find organic sources that can provide Mg. But the doses used in this study, can be recommended in a single combination but the satisfaction of the quantities can lead to high doses for the fertilizer.

The economic profitability of fertilizer application varies according to the rates applied, and high rates are less profitable for crop (Kitabala et al., 2016). However, Nyembo et al. (2012) recommended the application of low doses of nutrients as they are no longer cost-effective at high application rates. This observation confirms the present study findings. These findings recommend moderate doses of nutrients for optimum seed grain yields. This empirical formula is part of a reasoned and balanced fertilization requiring that only the necessary nutrients should be applied in appropriate quantities. The adoption of such a formula enables production cost minimization on the one hand, and yield maximization on the other hand. It also contributes to sustainable management of soil fertility. Indeed, the capacity of soybean to fix N through symbiotic process is acknowledged (Badou et al., 2013). Study by Giller (2001) revealed that the Biological N_2-fixing can contribute as much as 300 kg N ha^{-1} in a season in grain legumes or green manure. Therefore, the N nutrient management in this cropping system must be ensured efficiently. This could explain the fact that, in most of the Benin leguminous cropping systems, farmers do not apply fertilizers to the crop to compensate the exportations of nutrients in the grain and crop residues which are then often consumed by animals.

The present study findings reveal also the necessity to apply fertilizers for soybean in these soil types as they are almost degraded and need a minimum fertilizer application, especially N for yield sustainability. Moreover, Chabi et al. (in press) show N, P and Zn deficiency in these soils using DRIS model. The doses found have improved seed grain yield twice to three times when compared with the control plots. The nutrient supply is therefore essential and necessary to ensure the quality of soybean grain, including micronutrients (Batamoussi et al., 2016; Takuji et al., 2017), especially on degraded tropical ferruginous soils (Saïdou et al., 2017). This fertilization based on Zn and macronutrient application can not only improve soil fertility by helping to limit agriculture mining, but also contribute to the adaptation of soybean production to climatic variability in both study areas (Movahhedy-Dehnavy et al., 2009; Ashraf et al., 2014).

Conclusion

The current research showed that the application of macronutrients in combination with Zn significantly improves soybean aboveground biomass and seed grain yields and the harvest index. The supply of Zn in combination with macronutrients improves the nutrient utilization efficiency as it improves the grain yields. The quadratic model derived from the response surface analysis was efficient ($R^2 > 0.7$) in estimating soybean seed grain yields regarding nutrient doses in both study zones. The doses of N, P, K, Mg and Zn of 15.46, 23.20, 28.6, 16.8 and 6.9 kg ha^{-1} (for the centre) and 14.02, 23.89, 17.82, 11.45 and 4.26 kg ha^{-1} (for the south Borgou), respectively are the optimal doses for soybean production suggested. This will boost up the seed grain yields to about 2 $t.ha^{-1}$ in both areas. These optimal doses are the most economic and efficient fertilizer rates that gave maximum return to investment for farmers. In order to ensure sustainable soybean production in both zones, it is suggested to develop fertilizer formula based on these optimal nutrient doses. Moreover, it would be advisable to assess these optimal nutrient dose efficiencies as adaptation perspective of soybean production to future climate variability.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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