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Nutrient assimilation trends in basil: under different edaphoclimatic conditions in Tolima (Colombia)

Tendencias de asimilación de nutrientes en albahaca: bajo diferentes condiciones edafoclimáticas en el Tolima (Colombia)

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Basil (*Ocimum basilicum* L.) crop under tropical conditions (Tolima-Colombia).

Photo: D.A. Cruz-Lara

ABSTRACT

Basil is a promising crop in Colombia due to its high adaptability and demand in export markets. However, there are no studies focused on nutrient absorption dynamics under local conditions, which would allow for the identification of nutrient uptake dynamics throughout the production cycle. The objective of this study was to examine the dynamics of minerals uptake, distribution, and accumulation in two basil cultivation systems (conventional fertilization and alternative mineral fertilization). Two experimental trials were established in commercial plots located in the municipalities of El Espinal and Mariquita (Tolima Department, Colombia), using a randomized complete block design with three replications. Two fertilization programs designed by the producers were used: (i) conventional fertilization using highly soluble fertilizers, and (ii) an alternative mineral fertilization program based on acids, sulfates, and mineral inputs. During six harvest periods, yield, macro- and micronutrient content, and dry matter accumulation in leaves, stems, and roots were determined. In general, it was found that the order of greatest minerals accumulation was K > N > Ca > Mg > P > S > Na > Fe > Zn > Mn > B > Cu for both production schemes. Additionally, the mineral alternative fertilization production system achieved a total of 17 t ha^{-1} (El Espinal), while the conventional system recorded 11 t ha^{-1} of dry matter (Mariquita). Finally, alternative mineral production registered a 46.22% increase in the total major element's uptake and around 25.25% increase in the total minor element's uptake compared to the conventional scheme, a response that was highly influenced by nutrient management and plant density.

Additional key words: *Ocimum basilicum*; mineral nutrition; fertilization; nutrient uptake; plant density; dry matter accumulation; alternative agriculture.

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RESUMEN

La albahaca es un cultivo promisorio en Colombia debido a su alta adaptabilidad y demanda en los mercados de exportación. Sin embargo, no existen estudios enfocados en la dinámica de absorción de nutrientes bajo condiciones locales, que permitan identificar la dinámica de absorción de minerales a lo largo del ciclo de producción. El objetivo de este estudio fue examinar la dinámica de absorción, distribución y acumulación de nutrientes en dos sistemas de cultivo de albahaca (convencional y mineral alternativo). Se establecieron dos ensayos experimentales en parcelas comerciales ubicadas en los municipios de El Espinal y Mariquita (departamento de Tolima, Colombia), utilizando un diseño de bloque completos al azar con tres réplicas. Se usaron dos programas de fertiirrigación diseñados por los productores: (i) fertilizantes convencional utilizando fertilizantes altamente solubles y (ii) programa de fertilización mineral alternativa basada en ácidos, sulfatos y minerales. Durante seis períodos de cosecha, se determinó el rendimiento, el contenido de macro y micronutrientes y la acumulación de materia seca en hojas, tallos y raíces. En general, se encontró que el orden de mayor acumulación de minerales fue K > N > Ca > Mg > P > S > Na > Fe > Zn > Mn > B > Cu para ambos esquemas de producción. Adicionalmente, el sistema de producción mineral alternativo alcanzó un total de 17 t ha^{-1} (El Espinal), mientras que el sistema convencional registró 11 t ha^{-1} de materia seca (Mariquita). Finalmente, la producción mineral alternativa registró un incremento del 46,22% en la captación total de elementos mayores y alrededor del 25,25% en la captación total de elementos menores en comparación con el esquema convencional, respuesta que estuvo altamente influenciada por el manejo de nutrientes y la densidad de plantas.

Palabras clave adicionales: *Ocimum basilicum*; nutrición mineral; fertilización; absorción de nutrientes; densidad de plantas; acumulación de materia seca; agricultura alternativa.

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INTRODUCTION

Basil (*Ocimum basilicum* L.) is a tropical aromatic plant. It is consumed in fresh form and is an increasingly popular commodity (Rodeo and Mitcham, 2024). It belongs to the Lamiaceae family (Montilla-Coronado and Ramos-Gómez, 2022) and is considered an important crop because its production is highly valued in the culinary and pharmaceutical fields due to its high content of essential oils, phenolic polyphenols, flavonoids, and phenolic acids (Fattahi *et al*., 2020; Shahrajabian *et al*., 2020; Jimayu, 2021; López-Hernández *et al*., 2024).

In Colombia, basil production is concentrated in Tolima and Cundinamarca departments, covering an area of 176 and 65.5 ha, respectively, these locations have a general yield of 5.5 and 5.1 t ha^{-1}, respectively (UPRA, 2022). In this context, Tolima reports for 78% of national production, consisting of over 130 farms distributed across the municipalities of Honda, Mariquita, El Espinal, and Flandes. Basil is considered a promising aromatic plant with recent expansion in Colombia (Combatt-Caballero *et al*., 2020). It has great economic potential and is increasingly attracting producers due to its growing commercialization in international markets (Cortés and Clavijo, 2008). The principal export destination is the USA, generating a total income of USD $179 million in the first semester of 2021, representing a growth rate of 6% (Analdex, 2021). Furthermore, its rapid production cycle enhances cash flow and farm profitability (Elementi *et al*., 2006; Bączek *et al*., 2019; Corrado *et al*., 2020).

Basil is a fast-growing, versatile, and adaptable plant, suitable for both soil and hydroponic cultivation. Its ability to continuously regenerate makes it highly productive. Multiple harvests allow the strategy to be adapted according to the end use (fresh market, oils, industry), but successive cuts can slightly decrease quality and significantly alter the phytochemical and bioactive profile (Ronzón-Ortega *et al*., 2012; Vázquez-Vázquez *et al*., 2015; Naiji and Souri, 2018; Corrado *et al*., 2020). Basil cultivation allows up to three production cycles per year, allowing between 10 and 14 harvests per production cycle, which is why it is considered a nutrient-extracting plant that needs an especial mineral nutrition management (Souri *et al*., 2019). Therefore, it has been determined that fertilization practices positively impact fresh yield by stimulating growth, enhancing antioxidant capacity, and increasing the production and quality of essential oil (Singh *et al*., 2004; Alhasan *et al*., 2020; Gavrić *et al*., 2021). Despite extensive studies on basil; however, the nutritional requirements of basil have not been studied in the local conditions. Nevertheless, high application rates of chemical fertilizers may have a detrimental impact on soil health and fertility (Aghaye *et al*., 2019; Zargar *et al*., 2020).

Understanding the dynamics of essential element uptake during the production cycle allows for efficient crop fertilization management, for this reason is necessary to make with nutrient uptake studies focused on nutrition plan (Rodas-Gaitán *et al*., 2012; Souri and Neumann, 2018). These studies help the precision determination of the amount of nutrients absorbed by a crop, considering productivity in a determined time (Bertsch, 2009). An uptake curve is the graphical representation of nutrient extraction and indicates the quantities of each element accumulated by the plant's organs during its life cycle (Mércia de Sá *et al*., 2025).

Therefore, the objective of this study is to evaluate the dynamics of macronutrient (nitrogen, phosphorus, potassium, calcium, magnesium, and sulfur) and micronutrient (iron, manganese, copper, boron, zinc, and sodium) uptake in six harvest stages of 'Nufar' basil cultivated in two locations in Tolima (Colombia).

MATERIALS AND METHODS

Plant material and growth conditions

The research was made in open-field commercial basil crops located in two municipalities of El Espinal (4°11'53'' N, 74°57'54'' W, altitude: 321 m) and San Sebastian de Mariquita (5°13'07'' N, 74°48'28'' W, altitude: 378 m) (Colombia), between July and September 2023. The soil analysis of the two study locations is presented in table 1. The environmental conditions (temperature, relative humidity, and radiation) during the experiment are presented in figure 1. Seeds of the Nufar cultivar were sown in 200-cell polypropylene trays filled with peat-based substrate (Klasmann-Deilmann, Geeste, Germany).

Table 1. Soil characteristics are recorded at the experiment locations.

Parameters	Unit of measure	El Espinal	Mariquita
pH	-	6.74	6.46
Effective cation exchange capacity (ECEC)	cmol kg^{-1}	7.49	8.52
Electrical conductivity	dS m^{-1}	0.39	0.32
Total nitrogen	%	0.15	0.14
Organic carbon	%	0.54	3.52
Organic matter	%	0.93	6.09
Ca	cmol kg^{-1}	5.22	6.09
K	cmol kg^{-1}	0.26	0.53
Mg	cmol kg^{-1}	1.84	1.78
P	mg kg^{-1}	92.83	163.91
Cu	mg kg^{-1}	5.68	1.93
Fe	mg kg^{-1}	107.56	33.65
Mn	mg kg^{-1}	4.95	2.27
Zn	mg kg^{-1}	3.85	11.53
B	mg kg^{-1}	0.37	0.48
Texture		Sandy loam 9% clay 16% silt 75% sand	Sandy clay loam 19% clay 25% silt 56% sand

In each location (El Espinal and Mariquita), a commercial plot of 2,500 m^2 was selected, on which beds measuring 0.20 m high by 0.80 m wide were laid out. The plot was divided into three blocks used as replicates. In each block, six experimental units were established corresponding to the sampling dates. Each unit consisted of 12 plants, resulting in a total of 72 plants per block.

Transplanting was carried out when the seedlings four fully expanded leaves (approximately 25 d after sowing), and the seedlings were arranged in the field as follows: El Espinal, a three-row per bed system was implemented, with plants spaced 0.18×0.30 m (90,000 plants/ha); Mariquita, a single-row per bed system was used, with plants spaced 0.30×0.30 m (67,000 plants/ha).

Fertilization and crop management

Fertilization was applied using a fertigation system, utilizing nutrient solutions according to the phenological development of plants. The nutrient solutions

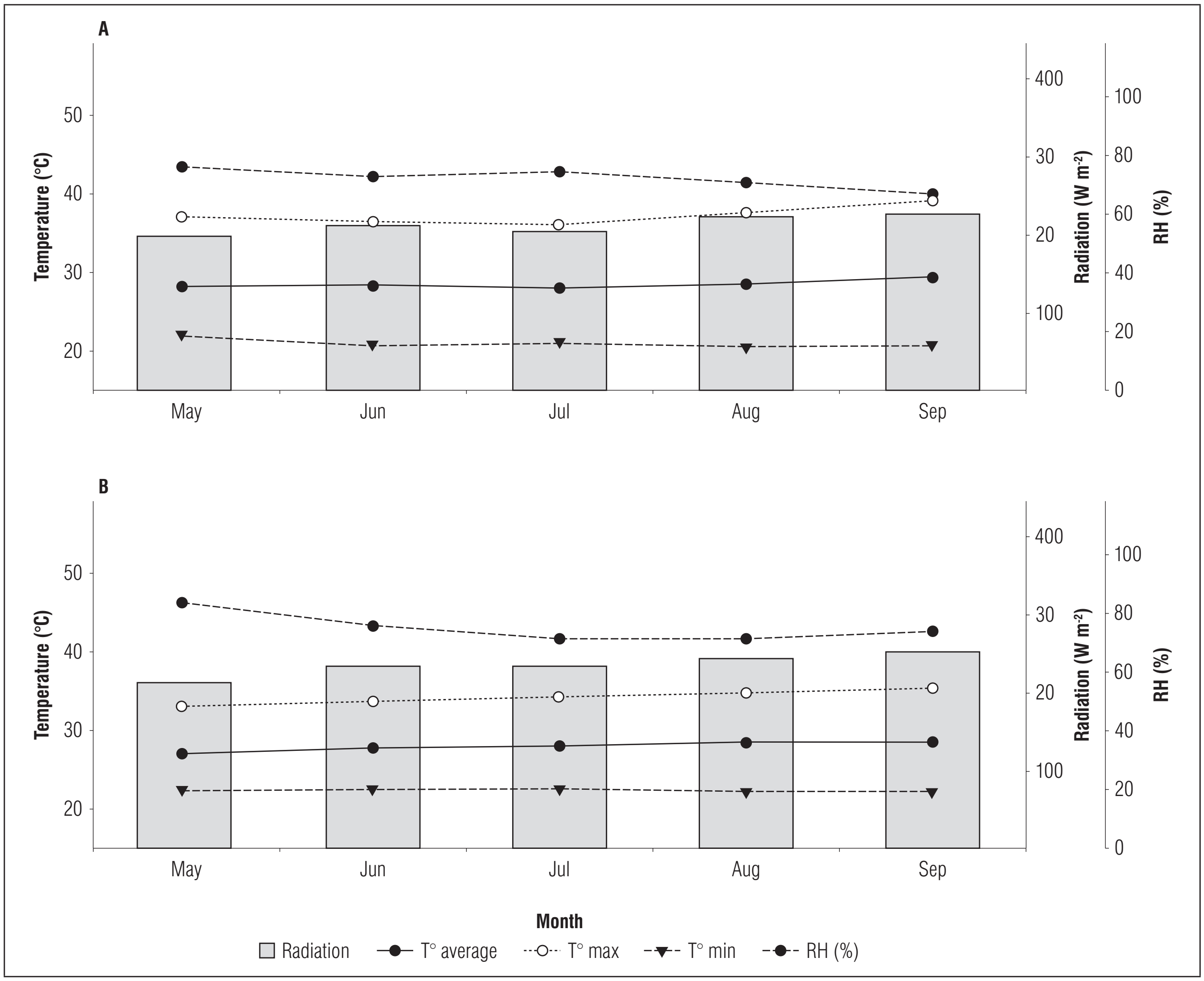

Figure 1. **Maximum, minimum and average temperature, solar radiation and relative humidity (RH) are recorded at the experiment locations in El Espinal (A) and Mariquita (B).**

were prepared using products in accordance with the type of nutrition: i) conventional fertilization (Mariquita): phosphoric acid (P_2O_2=65%), potassium nitrate (N=13% - K=43%), calcium nitrate (N=15.5% - Ca=26.5% - B=0.1%), magnesium sulfate (Mg=16 - S=13%) and microelements + ligninsulfonate (Fe=0.6% - Cu=0.8% - B=0.1%, Mn=0.7%, Zn=5%, Mo=1% and MgO=6%) applied via foliar. ii) alternative mineral fertilization (El Espinal): phosphoric acid (P_2O_2=65%), magnesium sulfate (Mg=16 - S=13%), iron sulfate (Fe=11 - S=19%), manganese sulfate (Mn=31% - S=18%), potassium sulfate (K=42% - S=18%), zinc sulfate (Zn=35 - S=6%), ammonium sulfate (N=20.5 - S=23.5%), copper sulfate (Cu=25 - S=12.8%) and colemanite (B=20.5%) according with Colombian Technical Standard (NTC) 5167 (Icontec, 2004). The weekly nutrient solution concentrations for each location are presented in table 2. Nutrient solution 1 was applied until the second week after field transplanting (32-40 d), whereas nutrient solution 2 was used from that point until the end of the experiment (94-105 d). Pest (chrysomelids and lepidopterans) and disease (*Peronospora sparsa*) management followed the technical recommendations specific to each farm, and weed control was carried out by mechanical weeding.

Table 2. **Nutrient solution applied by harvest stage in basil (*Ocimum basilicum*) in the localities of El Espinal and Mariquita.**

Nutrient	Initial stages		Productive stages	
	El Espinal	Mariquita	El Espinal	Mariquita
	mg L^{-1}			
N	108	92	392	103
P	127	25	265	15
K	232	396	608	442
Mg	51	43	169	41
S	101	63	371	55
Ca	0	124	23	98
Fe	0	2.05	12	2.02
Cu	0	0.08	23	0.07
Zn	0	0.08	11	0.07
Mn	0	1.03	7	0.92
B	0	0.76	7	1

Harvest and dry matter distribution

Harvesting was made using a group of 12 homogeneous plants from the central part of each experimental unit was selected, meeting the optimal phenological development stage for harvest. Six samplings were conducted for harvest cutting; the thermal time expressed in growing degree days (GDD) was calculated for each sampling point and counted from seed sowing in the nursery to the last commercial harvesting (Tab. 3). The first harvest in El Espinal was 32 d after transplanting, with an accumulation of 871 GDD, and in Mariquita it was 40 d (947 GDD) in six harvests or sampling points (Tab. 3). Then, leaves and stems were dissected and finally, the plant material was dried in an oven at 60°C for 72 h and the dry weight of each organ was recorded.

Growing degree days (GDD) calculation and growth determination

Physiological crop time, expressed as growing degree days (GDD), was calcuclated followwing the methodology described by Cheng *et al*. (2022). Temperature data were recorded at 5-min intervals using a remote weather station (WS-ZL6, METER Group Inc., Pullman,WA, USA) to determine daily maximum and minimum temperatures and the crop base temperature. GDD values were then calculated using equation (1).

Table 3. **Sampling points for determining macro- and micronutrient uptake curves in basil at two locations in the Department of Tolima.**

El Espinal			Mariquita		
Date	DAT	GDD	Date	DAT	GDD
5/07/2023	32	871	18/07/2023	40	947
12/07/2023	39	988	28/07/2023	50	1,129
31/07/2023	58	1,327	4/08/2023	57	1,252
15/08/2023	73	1,599	31/08/2023	84	1,725
29/08/2023	87	1,854	7/09/2023	91	1,848
5/09/2023	94	1,985	21/09/2023	105	2,100

DAT: days after transplanting. GDD: growing degree days.

$$\text{Rowing degree days } (GDD) = \frac{(T_{min} + T_{max})}{2} - T_{base} \qquad (1)$$

where, T_{min} is minimum temperature, T_{max} maximum temperature, T_{base} base temperature, below which growth stops. Accumulated growing degree days were calculated as the sum of the daily growing degree days over the evaluated period (Eq. 2).

$$\text{Accumulated growing degree days } (GDD) = \sum \mathrm{GD}_{1 \rightarrow n} \qquad (2)$$

where, ΣGD represents the summation and n is number of days considered.

Tissue minerals and uptake dynamics

A group of 12 central plants from each replicate were collected for tissue analysis for each sampling, using the same plants harvested for dry matter determination in the different plant organs. The 12 harvested plants in each experimental unit were divided into two groups of 6 plants to create two composite samples. The plants were cut into roots, stems, and leaves. The samples were collected at the time of each harvest, considering the thermal time at each sampling point (Tab. 2). The plant material was processed at the Soil, Water, and Plant Chemistry Laboratory of the Colombian Agricultural Research Corporation (AGROSAVIA) at the Tibaitatá Research Center, Bogota. The organic nitrogen (N) content was obtained using the Kjeldahl digestion method. The total phosphorus (P) content was determined colorimetrically using the phosphomolybdate-vanadate method. Calcium (Ca), potassium (K), magnesium (Mg), and sodium (Na) content, as well as the micronutrients copper (Cu), iron (Fe), manganese (Mn), and zinc

(Zn), were quantified through atomic absorption using the ashing method at 600°C and acid digestion with HCl. Finally, boron (B) was quantified using the colorimetric protocol according to the azomethine method (Agrosavia, 2025).

The nutrient content accumulated by each organ was calculated according to the methodology suggested by Bertsch (2009). The essential elements expressed as a percentage, using equation 3 (N, P, K, Ca, Mg, and S). Equation 4 was applied for elements with concentrations expressed in mg kg^{-1} (Fe, Cu, Mn, Zn, and B). Finally, the absolute accumulation of each nutrient in the different organs was graphed at each sampling point.

$$\left[Nutrient_{tissue}\left(\frac{kg}{ha}\right)\right] = \frac{Drymatter_{tissue}\left(\frac{kg}{ha}\right)x\left[Nutrient_{tissue}(\%)\right]}{100} \tag{3}$$

$$\left[Nutrient_{tissue}\left(\frac{kg}{ha}\right)\right] = \frac{Drymatter_{tissue}\left(\frac{kg}{ha}\right)x\left[Nutrient_{tissue}\left(\frac{mg}{kg}\right)\right]}{1{,}000{,}000} \tag{4}$$

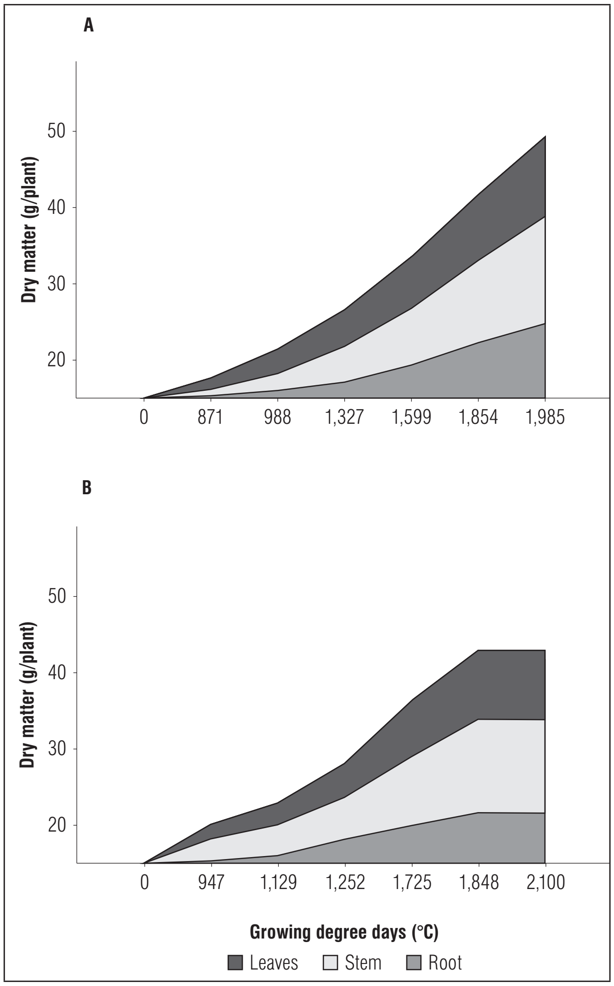

Figure 2. **Accumulation of growing degree days (GDD) and dry matter partitioning in a basil cultivar under two field conditions, El Espinal (A) and Mariquita (B).**

Statistical analysis of data

A regression design without treatment was conducted, consisting of three experimental units. Each experimental unit contained 72 plants, with a total of 216 plants used per location during the study. The data were analyzed using a polynomial regression model with the SigmaPlot statistical package (version 12.5; Systat Software, CA, USA), considering the determination coefficient value (R^2) for the fit of each selected model.

RESULTS

Plant biomass

The results indicate that the dynamics of dry biomass accumulation in basil plants are determined by plant density and the nutrition plan used in both locations. Overall, dry matter accumulation was higher in El Espinal (17,083.43 kg ha^{-1}), considering that the plant density in this commercial plot was 90,000 plants/ha. At the end of the six harvest stages, the plants reached a total accumulation of 189.82 g/plant (Fig. 2A). On the other hand, the crop established in Mariquita registered a biomass production of 11,522.86 kg ha^{-1} (171.98 g/plant) at a density of 67,000 plants/ha, as shown in figure 2B. The difference in accumulation per plant was 9.3% in favor of the fertilization system used in El Espinal (Tab. 4).

Likewise, differences in dry matter removal values during harvest (commercial stems and leaves) were observed in both localities, with higher averages in El Espinal compared to Mariquita, with values of 5,108.38 and 4,198.69 kg ha^{-1}, respectively. However, the harvest index showed an inverse trend, being higher in Mariquita with a value of 36.44%, compared to 29.9% in El Espinal.

Regarding the order of dry matter distribution by plant organ, the following pattern was observed: roots showed the least accumulation, followed by leaves, with stems having the highest accumulation (root < leaf < stem). According to this pattern, El Espinal presented the following percentage relationship: 28.4 < 29.9 < 41.6, while Mariquita showed 22.1 < 35.1 < 42.6, suggesting a higher leaf accumulation in the latter. The regression models for analyzing nutrient extraction dynamics showed correlation coefficients greater than 0.9%, indicating a high correlation between nutrient content in plant organs (leaves, stems and roots) and time at harvest (Tab. 3).

Nutrient dynamics

Nitrogen, phosphorus and potassium

The NPK macronutrients content by organ at each harvest was quantified in both locations (Fig. 3). El Espinal showed higher total absorption of NPK per evaluation period, with a linear growth indicating a direct relationship between the variability of uptake in its different organs and the accumulation of growing degree days (Tab. 3). The leaf was the organ that accumulated the most nitrogen, followed by the stem, with the root showing the least uptake. These nutrient dynamics patterns were similar in both localities.

The total NPK uptake in El Espinal was 4.63, 0.73, and 7.61 g/plant (Fig. 3A), while in Mariquita, it was 4.27, 0.55, and 7.81 g/plant, respectively (Fig. 3B). Potassium was the most uptake element, even surpassing nitrogen, and accumulated mainly in the stems, followed by leaves and roots. In contrast, leaves presented higher phosphorus and nitrogen content, followed by stems and roots. This uptake distribution pattern for NPK was similar in both localities. Additionally, absorption increased with the number of harvesting cuts, with the highest values registered in the last evaluation. Notably, El Espinal registered a 13% increase in nitrogen cumulation, 29.3% in phosphorus, and 6.8% in potassium compared to Mariquita.

Calcium, magnesium, sulfur and sodium

The content of secondary macronutrients Ca, Mg, and S by organ during the crop cycle was also analyzed in both localities. In El Espinal, magnesium uptake was 1.15 g/plant, and sulfur uptake was 0.46 g/plant, while in Mariquita, the averages were 1.04 and 0.36 g/plant for magnesium and sulfur, respectively.

Table 3. Coefficient of determination (R^2) obtained from regression analyses of nutrient uptake dynamics in different organs of basil evaluated at two locations.

Nutrient	El Espinal			Mariquita		
	Leaves	Stems	Roots	Leaves	Stems	Roots
N	0.990	0.992	0.980	0.969	0.958	0.953
P	0.981	0.994	0.992	0.968	0.951	0.950
K	0.988	0.990	0.983	0.974	0.955	0.952
Ca	0.987	0.980	0.985	0.968	0.957	0.957
Mg	0.993	0.987	0.995	0.973	0.957	0.951
S	0.993	0.995	0.985	0.966	0.958	0.938
Fe	0.979	0.976	0.995	0.938	0.939	0.928
Cu	0.969	0.996	0.980	0.955	0.928	0.901
Mn	0.985	0.977	0.997	0.968	0,958	0.944
Zn	0.989	0.980	0.981	0.977	0.959	0.949
B	0.995	0.995	0.987	0.948	0.957	0.947
Na	0.997	0.982	0.969	0.970	0.960	0.955

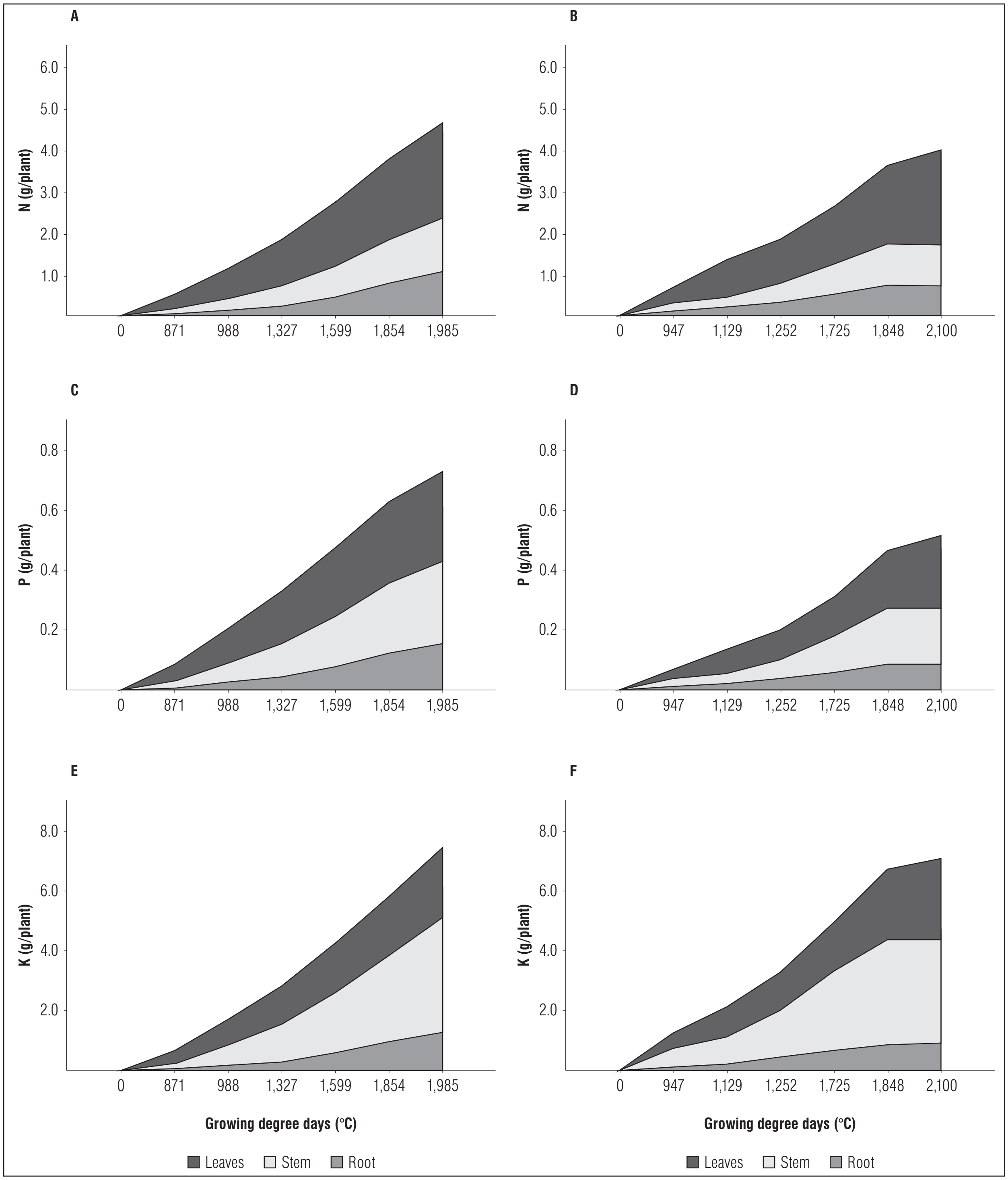

Figure 3. **Accumulation of growing degree days (GDD) and partitioning of N, P and K in basil under two field conditions, El Espinal (A, C and E) and Mariquita (B, D and F).**

On the other hand, calcium uptake was higher in Mariquita, with a 22.2% difference compared to El Espinal. Overall, El Espinal reached an uptake of 191.27 kg ha^{-1} of calcium, 103.52 kg ha^{-1} of magnesium, and 41.26 kg ha^{-1} of sulfur. In contrast, Mariquita recorded values of 183.81 kg ha^{-1} of calcium, 69.40 kg ha^{-1} of magnesium, and 24.30 kg ha^{-1} of sulfur (Fig. 4). Although total calcium uptake per plant was higher in Mariquita, total harvest extraction was higher in El Espinal, with a difference of 16.8%. Similarly, the harvest index for calcium, magnesium, and sulfur was higher in Mariquita. This indicates that although the total uptake in the cultivated area was higher in El Espinal, extraction per plant was higher in Mariquita (Tab. 4). Regarding sodium, El Espinal recorded a 10% higher uptake than Mariquita. Finally, the sodium compartmentalization ratio by structure was found to be 8.25, 39.2, and 52.4% for leaves, stems, and roots, respectively.

Iron, copper, manganese, zinc and boron

In El Espinal, higher content of iron and copper per plant were found, with differences of 47.5% and 18%, respectively, compared to Mariquita (Fig. 5). On the other hand, manganese levels were very similar between the two localities, with uptake levels of 13.39 mg/plant in El Espinal and 13.71 mg/plant in Mariquita (Fig. 5). In general, El Espinal showed higher amounts of these nutrients per hectare compared to Mariquita, which may indicate differences in fertilization practices and soil characteristics. Regarding the harvest index for copper and manganese, it was established in figure 5 that Mariquita had higher indices, with values of 51.47% for copper and 42.16% for manganese, suggesting greater retention of these elements.

In terms of plant uptake, basil demonstrates a high capacity to accumulate iron, with an average of 241.76 mg/plant, followed by manganese with 13.39 mg/plant and copper with 6.93 mg/plant (Tab. 4). In terms of distribution by plant organ, it was established that iron accumulates primarily in the roots, followed by the leaves and stems, with percentages of 76.23, 15.05, and 8.72%, respectively (Fig. 5). For copper, the highest content was found in the leaves, with an average of 46.26%, followed by the roots at 31.73%, and the stem at 22.01%, indicating a more uniform distribution compared to iron (Fig. 5).

Table 4. Comparative analysis of total uptake and harvest removal of macro- and micronutrients in basil across two production locations, based on dry weight estimates from complete harvested biomass.

	Total uptake				Harvest removal		Harvest index	
	El Espinal	Mariquita	El Espinal	Mariquita	El Espinal	Mariquita	El Espinal	Mariquita
Parameter	g/plant		kg ha^{-1}		kg ha^{-1}		%	
Dry biomass	189.82±0.95	171.98±0.80	17083.43±85.08	11522.86±53.90	5108.38±0.20	4198.69±0.28	29.90±0.97	36.44±0.58
N	4.63±0.02	4.27±0.02	417.13±1.63	286.22±1.16	205.66±0.75	155.56±0.67	49.30±0.96	54.35±0.61
P	0.73±0.00	0.55±0.00	65.91±0.25	36.73±0.21	27.76±0.12	16.52±0.09	42.12±1.02	44.99±0.65
K	7.61±0.03	7.81±0.04	685.22±2.93	523.51±2.30	219.12±0.84	186.09±0.87	31.98±1.09	35.55±0.51
Ca	2.13±0.01	2.74±0.01	191.27±0.87	183.81±0.85	87.29±0.33	104.94±0.53	45.64±0.91	57.10±0.62
Mg	1.15±0.01	1.04±0.00	103.52±0.50	69.40±0.28	36.58±0.13	32.29±0.14	35.33±1.01	46.52±0.65
S	0.46±0.00	0.36±0.00	41.26±0.22	24.30±0.12	18.94±0.01	14.32±0.00	45.90±1.07	58.94±0.65
	mg/plant		kg ha^{-1}		kg ha^{-1}		%	
Fe	241.76±2.27	114.85±1.02	21.76±0.20	7.69±0.07	3.06±0.07	1.18±0.07	14.04±1.21	15.31±0.60
Cu	6.93±0.06	5.68±0.05	0.62±0.01	0.38±0.00	0.25±0.03	0.20±0.01	39.53±1.13	51.47±0.86
Mn	13.39±0.08	13.71±0.07	1.20±0.01	0.92±0.00	0.34±0.00	0.39±0.00	28.09±1.16	42.16±0.82
Zn	15.35±0.10	19.42±0.09	1.38±0.01	1.30±0.01	0.43±0.00	0.58±0.00	30.86±0.91	44.76±0.86
B	8.47±0.06	7.75±0.05	0.76±0.01	0.52±0.00	0.37±0.00	0.28±0.00	48.02±0.88	53.50±0.70
Na	0.22±0.00	0.20±0.00	19.61±0.15	13.57±0.07	1.04±0.00	0.67±0.00	5.33±0.62	4.97±0.14

Mean values are followed by the standard error and are presented in the same units as the mean.

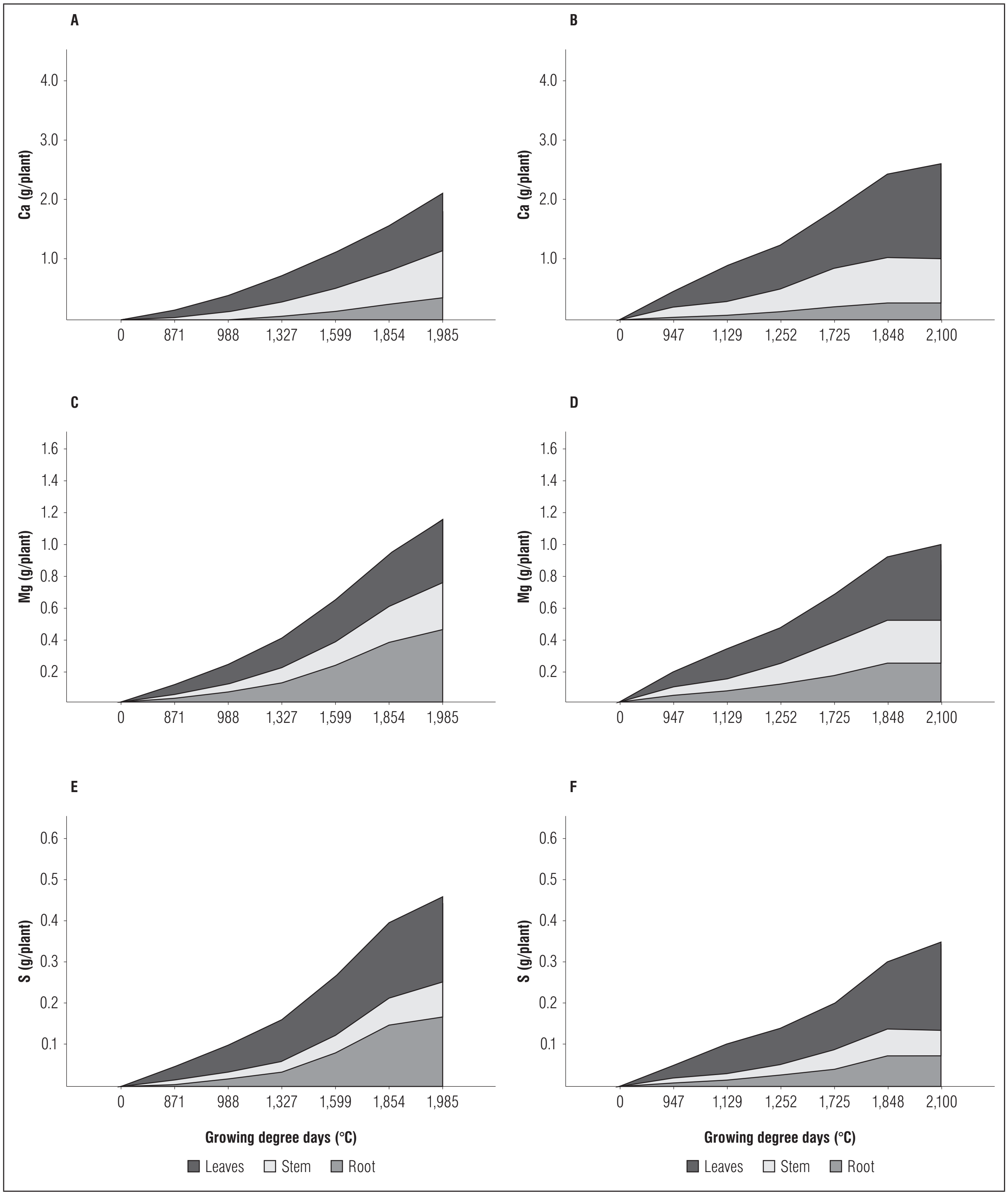

Figure 4. **Accumulation of growing degree days (GDD) and partitioning of Ca, Mg and S in basil under two field conditions, El Espinal (A, C and E) and Mariquita (B, D and F).**

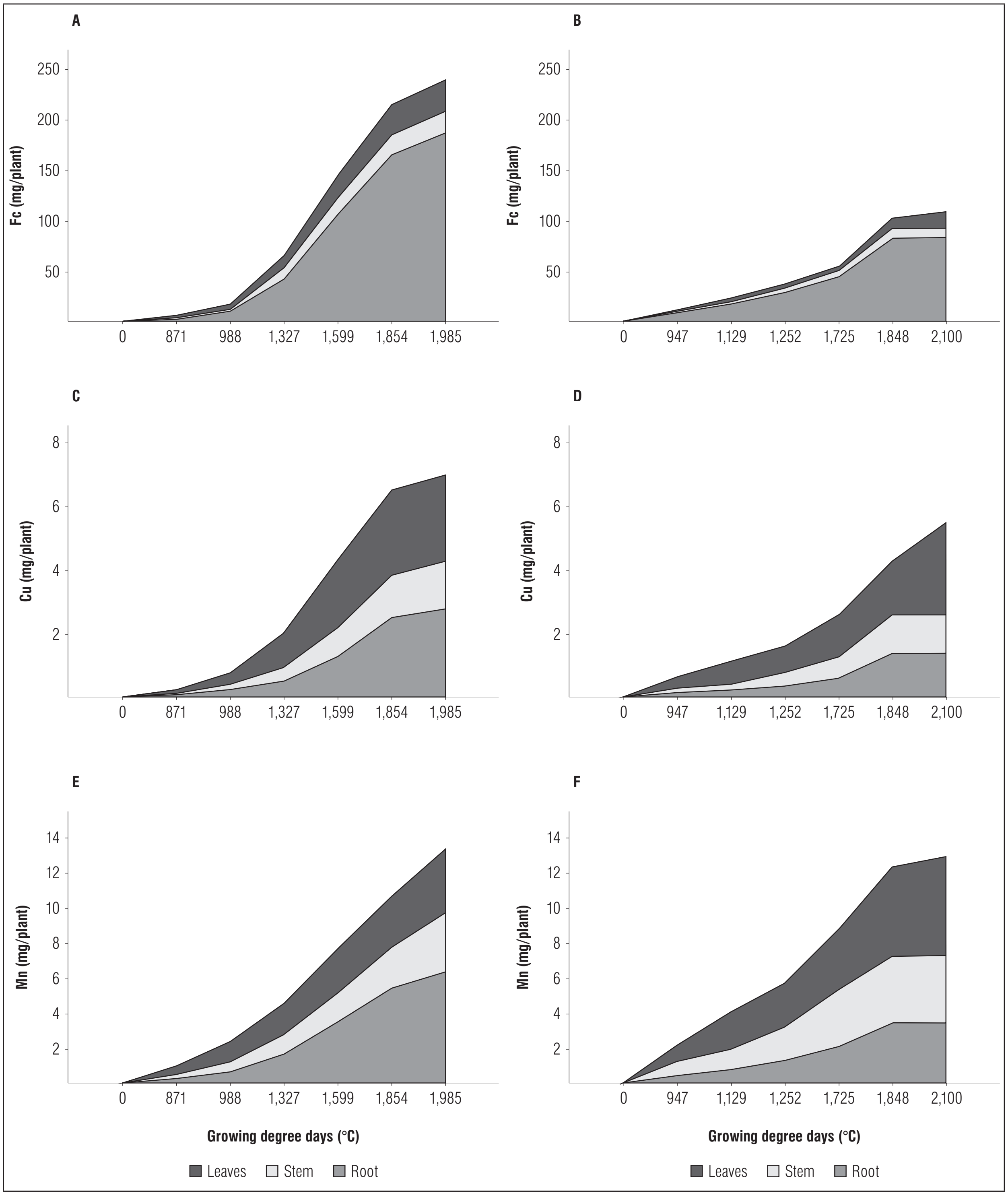

Figure 5. Accumulation of growing degree days (GDD) and partitioning of Fe, Cu and Mn in basil under two field conditions, El Espinal (A, C and E) and Mariquita (B, D and F).

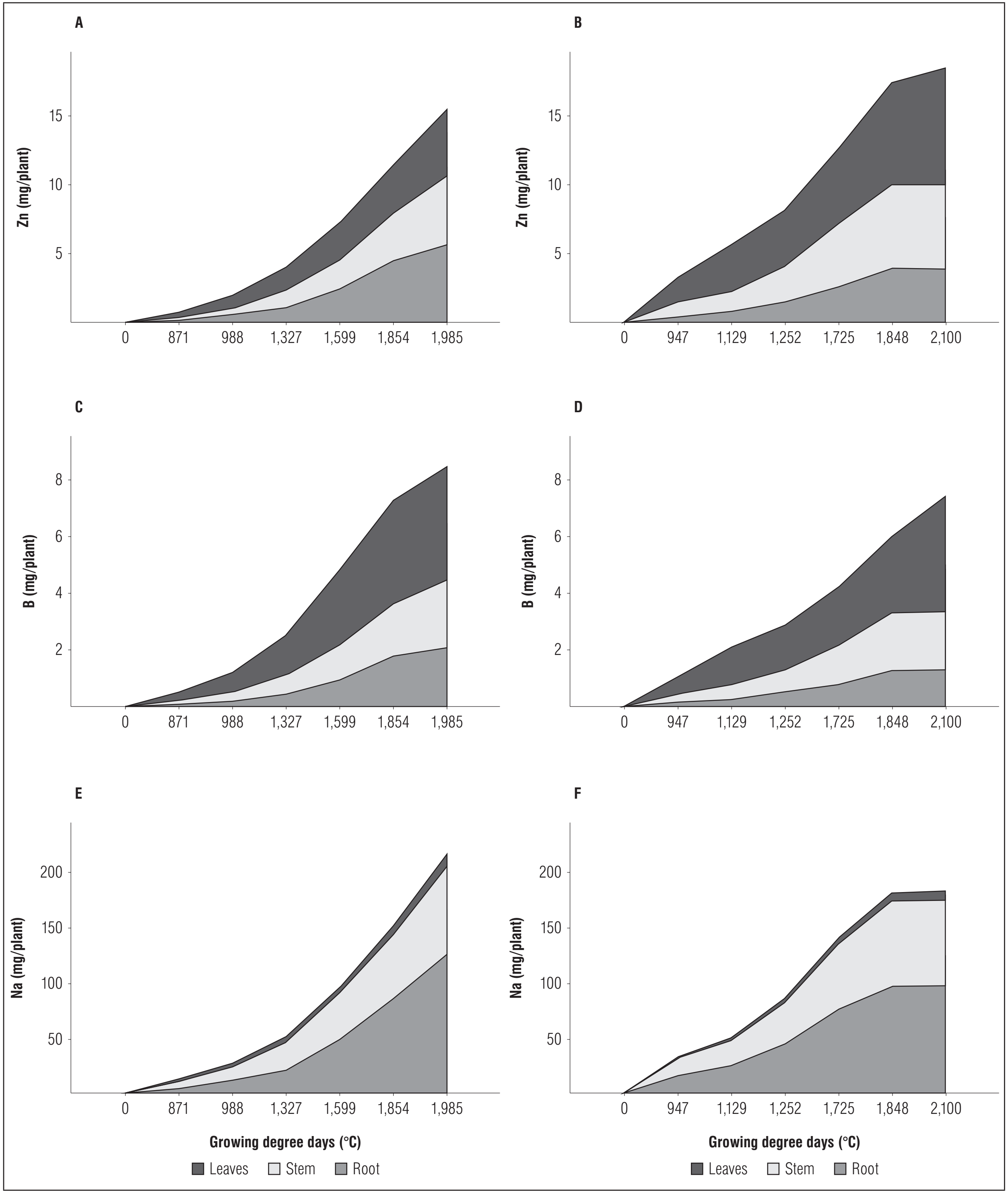

Figure 6. Accumulation of growing degree days (GDD) and partitioning of Zn, B and Na in basil under two field conditions, El Espinal (A, C and E) and Mariquita (B, D and F).

The manganese dynamic showed a contrast between the studied localities. In Mariquita, a higher concentration of manganese was observed in the leaves, with an average of 44.39%, followed by the stem at 29.49%, and the roots at 26.11%. In contrast, in El Espinal, the highest manganese content was in the roots, with an average of 46.86%, followed by the leaves at 28.10% and the stem at 25.04%, as evidenced in figure 5. Meanwhile, Mariquita showed a higher total content of zinc in the tissue, surpassing El Espinal by 21%, with a harvest index of 44.76%. The opposite trend was found for boron, as El Espinal content exceeded Mariquita's by 8.5%, with a harvest index of 53.50% (Tab. 4). The results suggest that the plants cultivated in the El Espinal production system exhibit higher micronutrient content, except for manganese and zinc, which were higher in Mariquita (Fig. 6).

DISCUSSION

Dry matter accumulation in basil plants under both fertilization schemes exhibited a quadratic trend throughout the productive stages, consistent with the crop's capacity to regenerate biomass after successive cuts. El Espinal, with higher planting density (90,000 plants/ha), accumulated ~17 t ha^{-1} of dry matter, compared with ~11,5 t ha^{-1} in Mariquita at 67,000 plants/ha. However, Mariquita plants accumulated slightly more biomass (189.8 g *vs*. 171.9 g), resulting in a higher harvest index (36.4% *vs*. 29.9%) (Tab. 4). These contrasting patterns emphasize the role of planting density and fertilization regime in shaping not only total productivity but also biomass partitioning between vegetative organs. Similar responses have been reported in basil and other aromatic herbs, where greater plant density increases yield per hectare but may reduce allocation efficiency to leaves, the main commercial organ (Colorado *et al*., 2013; Corrado *et al*., 2020). Such findings highlight the need to balance density-driven yield with harvest index optimization, since profitability is directly linked to leaf biomass.

The nutrient uptake order in both locations followed the pattern K > N > Ca > Mg > P > S, confirming the high demand of basil for potassium and nitrogen. In El Espinal, total uptake reached 685.2 kg ha^{-1} of K and 417.1 kg ha^{-1} of N, compared to 523.5 and 286.2 kg ha^{-1}, respectively, in Mariquita. These differences of 31% in K and 46% in N extraction are directly attributable to greater planting density and fertigation practices in El Espinal. Potassium was primarily accumulated in stems, supporting its role in carbohydrate transport, osmotic balance, and secondary metabolite biosynthesis (Singh *et al*., 2004; Halder *et al*., 2015). This has strong implications for essential oil quality, as K supply has been linked to improved oil content and modified composition in basil (Zheljazkov *et al*., 2008). Nitrogen and phosphorus were predominantly accumulated in leaves, consistent with their central role in photosynthesis and metabolic activity (Jin *et al*., 2015; Souri *et al*., 2019). Despite lower P uptake (65.9 and 36.7 kg ha^{-1} in El Espinal and Mariquita, respectively), its role in ATP and NADPH production means that deficiencies could disproportionately limit growth and oil biosynthesis.

Calcium uptake exceeded Mg and S, with values of 191.3 and 183.8 kg ha^{-1} for El Espinal and Mariquita, respectively. While total extraction was higher in El Espinal, Mariquita plants accumulated more Ca on a per-plant basis (2.74 g *vs*. 2.13 g), reflecting the influence of soil Ca content and lower competition among plants at reduced density. Calcium is critical for membrane stability and cell division (Hepler and Winship, 2010), and higher allocation to leaves in Mariquita could be advantageous for maintaining leaf structural integrity under multiple harvests. Magnesium and sulfur, although absorbed in lower amounts, remain vital for chlorophyll structure and protein synthesis (Dzida, 2010). El Espinal recorded 103.5 kg ha^{-1} of Mg compared to 69.4 kg ha^{-1} in Mariquita, a difference likely linked to higher soil Mg content at this site. These results align with findings by Aghamirzaei *et al*. (2024), who reported that basil grown under optimized nutrient supply (hydroponics) accumulated significantly more Mg, K, and N in leaves compared to field systems, indicating that nutrient availability strongly conditions uptake efficiency.

Micronutrient uptake patterns revealed iron as the most absorbed element, with 241.8 mg/plant in El Espinal compared to 114.9 mg/plant in Mariquita. Iron was preferentially partitioned to roots (76.2%), consistent with its limited phloem mobility and role in enzymatic redox processes (Zahra *et al*., 2021). Excess Fe in El Espinal may have reduced Mn uptake, as competitive interactions were evident: while El Espinal plants concentrated Mn in roots (46.9%), Mariquita plants partitioned it to leaves (44.4%), suggesting site-specific absorption strategies. Copper was more evenly distributed across organs, but its harvest index was markedly higher in Mariquita

(51.5%), indicating more efficient allocation to marketable tissues under lower density. Zinc showed the opposite trend: Mariquita registered 19.4 mg/plant, surpassing El Espinal by 21%. This result aligns with the higher organic matter content in Mariquita soils (6.1% *vs*. 0.9%), which increases Zn solubility but can reduce B availability (Navarro, 2013). Indeed, El Espinal recorded higher B uptake (8.5% more than Mariquita), reinforcing the strong influence of soil-nutrient interactions on micronutrient dynamics. Similar results were reported by Tolay (2021), where Zn supplementation not only increased Zn concentration but also improved uptake of K, Fe, and Mn, demonstrating the pivotal role of micronutrients in stabilizing nutrient balance under stress.

These nutrient interactions provide critical physiological insights. The Fe-Mn antagonism observed is consistent with previous reports of Fe toxicity reducing Mn absorption and enzymatic activity (Zahra *et al*., 2021). Similarly, the differential uptake of Ca and Mg suggests competitive interactions at the root level, a process noted in other aromatic herbs (Dzida, 2010). The N:K ratio also emerges as critical, since higher K accumulation relative to N, as found in both sites, may favor carbohydrate partitioning and secondary metabolite synthesis, supporting oil yield and quality (Singh *et al*., 2004). Furthermore, external factors such as light spectrum and nutrient quantity, as demonstrated by Ren *et al*. (2022), can modulate nutrient uptake efficiency and growth in basil. These results suggest that, beyond density and fertilization, environmental drivers such as radiation quality may partly explain the differential uptake observed between El Espinal and Mariquita.

From an agronomic perspective, our findings confirm that basil is a nutrient-demanding crop, particularly for N and K, supporting its classification as a high-extraction aromatic species. However, the magnitude of nutrient uptake and harvest index varied significantly between localities, demonstrating that fertilization strategy, planting density, and edaphoclimatic conditions strongly influence nutrient dynamics. These results are in line with Naiji and Souri (2018) and Bączek *et al*. (2019), who found that fertilization not only affects yield but also modifies phytochemical profiles and essential oil composition. Importantly, the high extraction rates of N and K observed in El Espinal highlight the risk of nutrient depletion under conventional intensive systems. Recent work by Beltrán-Medina *et al*., (2025) demonstrated that inoculation with plant growth-promoting bacterial consortia increased N and K uptake by more than 50% under reduced fertilization, showing that microbial approaches could enhance nutrient use efficiency and sustainability in basil. Likewise, the inclusion of non-traditional nutrients such as silicon has been shown to improve stress resilience and modify uptake of P, Mg, and micronutrients in basil (Li *et al*., 2020), suggesting new avenues for improving nutrient efficiency in tropical systems.

Altogether, this evidence emphasizes the importance of designing site-specific fertilization strategies for basil in tropical open-field conditions. Planting density must be considered when defining nutrient supply, as higher densities increase extraction per hectare but may reduce harvest index and efficiency. Regional differences in soil properties demand tailored fertilization, particularly for micronutrients such as Zn, B, and Mn, whose uptake is strongly influenced by organic matter and pH. Improved nutrient management could reduce fertilizer overuse, lower costs, and mitigating environmental impacts, while ensuring that export-oriented production systems maintain both yield and quality. By integrating uptake dynamics into fertilization plans, growers can fine-tune nutrient application schedules to crop stage and market objectives, ensuring both profitability and sustainability of basil cultivation in Colombia and similar tropical environments.

CONCLUSIONS

The assimilation of nutrients in the cultivation of the ‘Nufar’ basil, evaluated in two locations, showed that the dynamics of nutrient absorption, accumulation, and extraction are strongly influenced by planting density and fertilization scheme. Although differences were observed in the total amount of nutrients absorbed, these did not alter the physiological order of extraction, which was: K > N > Ca > Mg > P > S > Fe > Na > Zn > Mn > B > Cu (from highest to lowest). This pattern reflects the plant’s metabolic priority, in which potassium is the most demanded nutrient, followed by nitrogen, calcium, and magnesium.

The Espinal site showed greater nutritional efficiency, with higher absorption (46.22%) of macronutrients and micronutrients (25.25%) compared to the Mariquita site, associated with greater biomass accumulation (17 t ha^{-1}). It also had the highest rates of K (685.2 kg ha^{-1}) and N (417.1 kg ha^{-1}) absorption, which were 23.5% and 31.3% higher than in Mariquita, respectively. Nutrient distribution varied according to the organ: K predominated in stems, while N and P were concentrated in the leaves.

In addition, antagonistic interactions (Fe-Mn) and nutritional competition (Ca-Mg) were identified, highlighting the need to implement fertilization strategies based on nutritional plans tailored to local soil and climate conditions in order to improve crop yield, quality, and sustainability.

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