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Determination of Micronutrient Accumulation in Greenhouse Cucumber Crop Using a Modeling Approach

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Abstract: The control of micronutrient application in cucumber cultivation has great importance as they participate in many functions of metabolism. In addition, micronutrient application efficiency is fundamental to avoid periods of overconsumption or deficits in the crop. To determine micronutrient accumulation using a dynamic model, two cycles of Vitaly and Luxell cucumber crops were grown. During the development of the crop, micronutrient content (Fe, B, Mn, Cu, and Zn) in the different organs of the cucumber plant was quantified. The model dynamically simulated the accumulation of biomass and micronutrients using climatic variables recorded inside the greenhouse as inputs. It was found that a decrease in photosynthetically active radiation and temperature significantly diminished the accumulation of biomass by the cucumber plants. On the other hand, the results demonstrated that the model efficiently simulated both the accumulation of biomass and micronutrients in a cucumber crop. The efficiency evaluation showed values higher than $R^2 > 0.95$. This dynamic model can be useful to define adequate strategies for the management of cucumber cultivation in greenhouses as well as the application of micronutrients.

Keywords: mathematical modeling; *Cucumis sativus* L.; micronutrients accumulation; simulation

1. Introduction

At present, increasing crop productivity along with quality is essential for greater profitability. Protected agriculture (PA) is the most effective means of overcoming climate diversity, increasing yields, and at the same time significantly improving product quality as requested by market demand [1]. PA can be defined as an agricultural system that specializes in soil and climate ecosystem control where changes to certain conditions (soil, temperature, solar radiation, wind, humidity, and air composition) can be made, for example, greenhouses, shade houses, and macro tunnels. Cucumber (*Cucumis sativus* L.) is one of the most commonly produced crops under PA as it achieves higher yields, quality, and safety. In addition, the value of cucumber also lies in its form of consumption, since it can be consumed fresh or processed [2]. However, to obtain the greatest potential of this

crop under PA, it is necessary to be aware of the requirements concerning various climatic, water, and nutritional factors.

Macro and micronutrients are the essential elements found in plant tissues, but macronutrients are normally found in relatively higher concentrations than micronutrients. However, the essentiality of nutrients is so important, and this is not dependent on their concentration of dry biomass [3]. An adequate supply of nutrients according to the demand of each crop is essential to obtain higher yields and quality [4]. Therefore, the supply of nutrients must be carried out with higher efficiency [5,6] to maximize crop potential and avoid excessive application of chemical fertilizers that can cause environmental issues [7–9]. In addition, an adequate supply of nutrients avoids the toxic effects that reduce photosynthetic activity as well as damage the cell membranes and suppress enzyme activity [10]. Micronutrients participate in various physiological processes. For example, the biological significance of Fe results from its reversible oxidation state changes over a wide range of redox potentials. In addition, Fe is a component of a number of enzymes involved in various biological processes including respiration and photosynthesis [11]. Zn is an important component of many enzymes, and a structural stabilizer of proteins and plant membranes [12]. Mn is an active component of the water-splitting system of photosystem II, which provides the electrons necessary for photosynthesis [13]. In addition, Mn plays an important role in the biosynthesis of secondary metabolites such as flavonoids and lignin [14]. Cu is a redox transition element with an important function in photosynthesis, respiration, and metabolism of C and N. Cu also induces protection against oxidative stress. Like Fe, Cu forms highly stable complexes and participates in electron transfer reactions [15]. B participates in the transport of sugars, cell wall synthesis, lignification, carbohydrate and RNA metabolism, indole acetic acid metabolism (IAA), and phenols. Given their importance, the application of micronutrients to crops should be defined according to the characteristics of the crop of interest [16]. To assess the micronutrient demand, the accumulation of dry biomass to quantify the nutritional demand has been used [17]. However, biomass accumulation varies from cycle to cycle as crop growth is heavily dependent on climatic factors. Therefore, it is necessary to consider climatic characteristics when a crop is in a specific development stage, namely the vegetative, reproductive, fruit set, and harvest stages, to define the nutritional needs. Juárez-Maldonado et al. [18] showed that it was possible to accurately determine the demand of macronutrients (N, P, K, Ca, Mg, and S) in tomato cultivation from dynamic models that considered climate effects on crop growth. These models applied to crops under greenhouse could function as effective tools to increase crop productivity [19]. Among other things, mathematical models allow us to evaluate strategies for the possible management of a greenhouse without the need for expensive experiments [20]. However, it is important that these models are simple and easy to use. One way to do this is to use linear models, as they are simpler and can be very precise. The availability of nutrients is a factor that determines the growth and productivity of plants. With high availability, plants will perform mineral absorption according to their demand [21]. Under this condition, the nutrient uptake will remain constant according to the accumulation of biomass [22]. Moreover, it has been demonstrated that a high correlation exists between the accumulations of some macronutrients (N and P) with the amount of biomass [23,24]. Therefore, it is possible to use linear models to describe the nutrient accumulation in relation to biomass accumulation.

Although several models for essential macronutrients (N, P, K, Ca, Mg, and S), as well as for non-essential nutrients (Si, Se), in different crops (tomato, cucumber, peppers, lettuce, rice) have been developed and tested, there is little information about micronutrient modeling [25,26]. Therefore, the objectives of the present study were (1) to determine the micronutrient content in the cucumber crop throughout its growth, (2) to determine the correlation between micronutrient accumulation and amount of biomass, and (3) to use a dynamic model to determine micronutrient accumulation by the cucumber crop as a function of the climate variables.

2. Results and Discussion

2.1. Climatic Variables

Figure 1 shows the daily average climate data recorded inside the greenhouse during the development of the crops. In the second crop cycle, a clear decrease of the photosynthetically active radiation PAR and temperature could be observed. This represents a direct effect on crop biomass accumulation since both the PAR and temperature are environmental factors that directly influence photosynthesis [27–30]. It can be seen that PAR and temperature can proportionally decrease the accumulation of biomass.

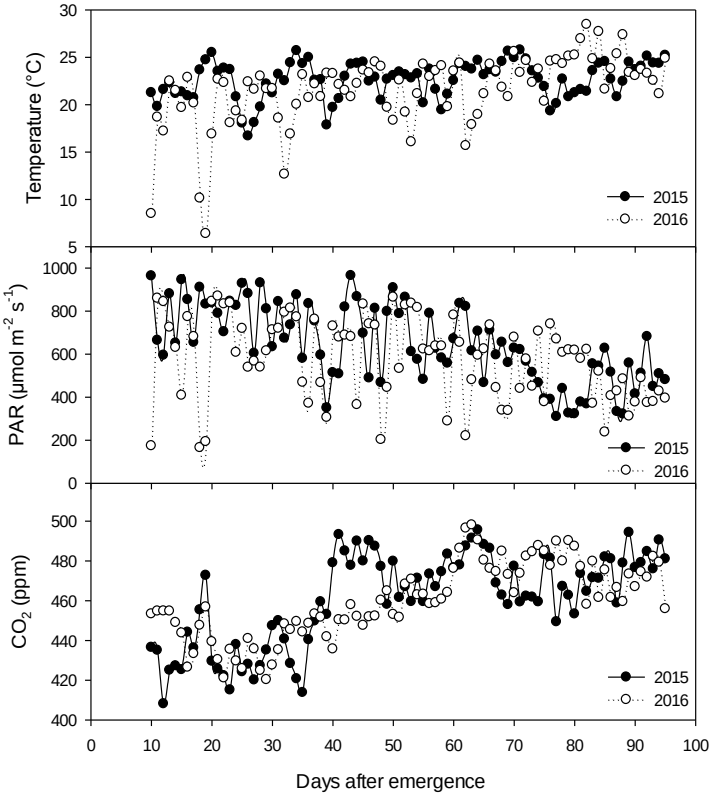

Figure 1. Climate data recorded during the development of tomato crops. The daily average is presented in the figure.

2.2. Biomass Accumulation

Figure 2 shows the total dry biomass accumulation for both cucumber varieties (Vitaly and Luxell) evaluated during the two cycles. The trend in biomass accumulation was similar across the varieties. However, the accumulation of biomass in the second cycle of study for both evaluated varieties decreased due to the effect of the climatic conditions recorded in 2016, as they directly influenced the rate of photosynthesis [31,32]. The climate conditions during 2016 were lower than in the 2015 cycle (Figure 1), which resulted in a reduction of biomass accumulation. Particularly, the PAR influenced photosynthetic activity leading to a reduction of the biomass production in the crop [27–30]. In addition, temperature also directly influenced plant growth, since there is a linear relationship between them [33]. This explains the accumulated biomass reduction observed in the 2016 crop cycle when compared to the previous cycle.

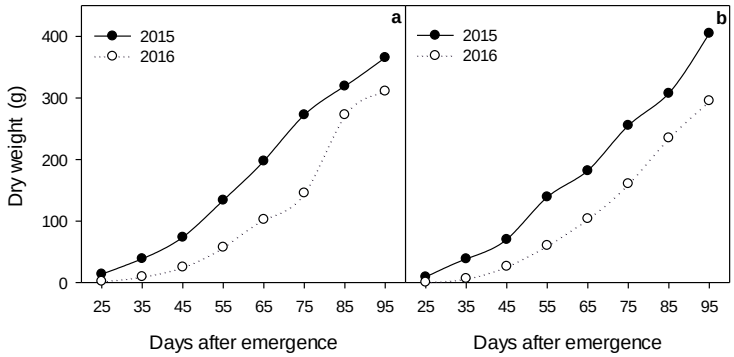

Figure 2. Accumulation of dry biomass recorded during the development of the cucumber crops Vitaly (**a**) and Luxell (**b**) varieties. The data are the average of four plants.

2.3. Micronutrient Accumulation

In Table 1, the concentrations of Fe, B, Mn, Cu, and Zn obtained during the different sampling periods in the two crop cycles (2015 and 2016) for both varieties of cucumber, are shown. The concentration of Fe in the Vitaly variety was maintained between 105.86 ± 25.49 and 106.12 ± 38.45 mg kg^{-1} of dry weight (DW) during the 2015 and 2016 cycles, respectively. Regarding the Luxell variety, the Fe content was maintained at 100.18 ± 9.11 and 94.82 ± 56 mg kg^{-1} DW during the 2015 and 2016 cycles, respectively. At the end of both crop cycles, the Fe accumulation was 34 mg and 25 mg per plant in the Vitaly variety, and 36 mg and 21 mg per plant in the Luxell variety. The reduction of Fe accumulation during the 2016 cycle was mainly due to the climatic conditions that prevailed during this cycle, which influenced the reduction in the rate of biomass accumulation. The concentrations of Fe were lower than those reported by Ghehsareh and Samadi [34], Kreij et al. [35], and Patidar et al. [1] as they found concentrations higher than 85 mg per plant. Although there is a high availability of this element in the applied nutrient solution, the plants did not accumulate higher concentrations. This was probably because cucumber plants optimize the use of Fe when the source is chelated [36,37].

The percentage of B was very similar for both varieties of cucumber, showing that for the Vitaly variety the concentration was 101.95 ± 17.1 and 109.27 ± 14.2 mg kg^{-1} DW, and for the Luxell variety, 116.08 ± 29.8 and 107.37 ± 12.62 mg kg^{-1} DW during the 2015 and 2016 cycles, respectively. At the end of both cycles, 37 mg and 32 mg B per plant accumulated in the Vitaly variety, and 35 mg and 31 mg B per plant accumulated in the Luxell. The concentration of B observed was 30% less than that reported by Ghehsareh and Samadi [34]. Despite this contrast, no symptoms of deficiency were observed, indicating that the concentrations throughout the growing cycle were within the range suitable for cucumber growth. In addition, the concentration found in this work agreed with that reported by Patidar et al. [1].

The concentration of Mn in the Vitaly variety was maintained between 55.73 ± 12.9 and 48.27 ± 11.6 mg kg^{-1} DW, and for the Luxell variety, 83.01 ± 14.5 and 50.03 ± 14.2 mg kg^{-1} DW during the 2015 and 2016 cycles, respectively. At the end of both cycles, 21 mg and 13 mg Mn per plant accumulated in the Vitaly variety, and 24 mg and 16 mg Mn per plant accumulated in the Luxell variety. The accumulation of Mn observed in this work was inferior to that reported by Ghehsareh and Samadi [34]. However, no symptoms of deficiency (chlorosis) were observed. Gopal [38] observed that increasing the concentration of Mn did not generate positive effects, possibly given that the plant will only take the amount of Mn it requires to perform its functions.

Table 1. Concentration of micronutrients in whole plant determined during the development of cucumber in Vitaly and Luxell varieties.

		Fe (mg kg^{-1} DW)		B (mg kg^{-1} DW)		Mn (mg kg^{-1} DW)		Cu (mg kg^{-1} DW)		Zn (mg kg^{-1} DW)	
cv	**DAE**	**2015**	**2016**	**2015**	**2016**	**2015**	**2016**	**2015**	**2016**	**2015**	**2016**
Vitaly	25	91.5 ± 13.6	187.0 ± 8.0	71.4 ± 9.1	100.0 ± 0.2	27.8 ± 4.2	53.1 ± 1.6	5.2 ± 0.3	4.4 ± 0.5	27.7 ± 1.3	44.0 ± 1.6
	35	167.0 ± 9.7	141.5 ± 3.8	82.0 ± 20.3	100.0 ± 0.8	63.3 ± 5.9	58.8 ± 2.3	7.8 ± 1.0	1.5 ± 0.2	38.3 ± 4.5	45.8 ± 2.1
	45	96.3 ± 10.7	99.1 ± 17.4	112.8 ± 22.5	100.0 ± 0.9	50.7 ± 6.5	63.3 ± 1.1	7.6 ± 0.7	5.8 ± 0.9	27.5 ± 2.1	43.7 ± 0.5
	55	95.5 ± 5.25	76.8 ± 29.6	120.2 ± 9.3	100.0 ± 0.9	53.9 ± 5.6	34.2 ± 1.8	9.1 ± 0.7	7.1 ± 0.5	25.1 ± 2.4	19.3 ± 2.5
	65	110.0 ± 12.5	89.2 ± 12.2	117.1 ± 8.7	118.9 ± 5.8	67.3 ± 2.4	33.8 ± 1.8	6.2 ± 0.3	5.0 ± 0.6	20.4 ± 0.7	18.3 ± 1.9
	75	102.4 ± 8.0	86.8 ± 9.0	107.7 ± 1.7	140.5 ± 15.9	68.5 ± 2.4	58.8 ± 2.9	6.9 ± 0.5	5.8 ± 0.7	28.8 ± 0.8	31.1 ± 2.8
	85	93.2 ± 5.9	88.1 ± 7.6	103.1 ± 4.1	107.7 ± 3.5	58.7 ± 4.6	42.3 ± 2.3	6.6 ± 0.4	5.3 ± 0.4	25.8 ± 2.5	19.4 ± 0.5
	95	91.0 ± 4.3	80.5 ± 3.1	101.3 ± 4.5	107.0 ± 4.8	55.7 ± 2.6	42.0 ± 5.9	5.9 ± 0.3	5.7 ± 0.5	24.2 ± 2.5	19.5 ± 1.5
Luxell	25	87.3 ± 6.1	207.6 ± 23.4	72.6 ± 6.7	100.0 ± 2.2	81.3 ± 7.2	67.5 ± 1.3	6.1 ± 0.5	1.8 ± 0.3	28.7 ± 1.4	40.6 ± 2.1
	35	106.2 ± 9.9	155.0 ± 11.0	164.7 ± 5.2	100.0 ± 1.9	99.0 ± 5.6	60.2 ± 2.5	8.7 ± 0.3	1.2 ± 0.1	35.7 ± 1.0	33.6 ± 1.8
	45	95.2 ± 2.6	74.1 ± 4.3	110.0 ± 11.8	100.0 ± 1.9	90.1 ± 2.8	62.4 ± 2.4	8.8 ± 0.3	4.7 ± 0.6	27.8 ± 0.9	37.5 ± 0.9
	55	111.6 ± 9.3	45.4 ± 7.7	142.7 ± 5.6	100.0 ± 2.1	97.9 ± 6.2	27.8 ± 1.7	9.2 ± 0.6	3.6 ± 0.2	24.7 ± 1.5	16.8 ± 1.7
	65	108.0 ± 10.4	61.4 ± 2.6	131.7 ± 5.8	100.0 ± 2.4	93.5 ± 1.9	31.4 ± 1.5	8.3 ± 0.5	6.7 ± 0.9	22.8 ± 0.3	21.1 ± 2.3
	75	105.4 ± 8.2	71.7 ± 4.1	113.4 ± 2.9	131.1 ± 10.5	71.3 ± 5.7	50.2 ± 4.8	9.1 ± 0.4	7.4 ± 0.5	24.7 ± 1.9	25.2 ± 1.4
	85	99.1 ± 12.9	74.8 ± 9.2	107.9 ± 7.0	123.8 ± 6.9	72.0 ± 4.7	48.3 ± 2.3	8.0 ± 0.7	6.3 ± 0.5	23.2 ± 1.0	22.9 ± 2.1
	95	88.6 ± 6.7	68.5 ± 12.0	85.8 ± 4.0	104.1 ± 2.2	59.0 ± 5.5	52.5 ± 2.3	7.9 ± 0.3	6.6 ± 0.7	19.8 ± 0.7	21.9 ± 2.6

cv: cucumber variety. DAE: days after seed emergence. DW: Dry weight. 2015 and 2016 represent the year of crop development. The data are the mean of four replicates ± standard error of the mean.

The concentration of Cu was maintained at 6.90 ± 1.2 and 5.06 ± 1.6 mg kg^{-1} DW in the Vitaly variety, and 8.26 ± 1.0 and 4.79 ± 2.3 mg kg^{-1} DW in the Luxell variety for the 2015 and 2016 cycles, respectively. At the end of both cycles, 3 mg and 2 mg per plant accumulated in the Vitaly variety, and 3.1 mg and 1.9 mg per plant in the Luxell variety. These results were lower than those reported by Ghehsareh and Samadi [34] and Kreij et al. [35] as they reported 5 mg per plant. However, during the experimental development no chlorosis was observed, indicating that the accumulated concentration was sufficient to carry out the physiological processes involving Cu [39], and reported that increasing the concentration of Cu did not show an increase in cucumber yield. This indicates that once the plant has met its needs, it is not necessary to accumulate more Cu in its tissues.

The concentration of Zn was maintained at 27.22 ± 5.1 and 30.16 ± 12.5 mg kg^{-1} DW in the Vitaly variety and 25.92 ± 4.84 and 27.45 ± 8.6 mg kg^{-1} DW in the Luxell variety for the 2015 and 2016 cycles, respectively. At the end of both cycles, Zn accumulated 9 mg and 6 mg per plant in the Vitaly variety, and 8 mg and 7 mg per plant in the Luxell variety. The observed Zn concentrations were lower than those reported by Ghehsareh and Samadi [34]. However, no deficiency symptoms were observed, indicating that the ability of plants to control Zn accumulation and avoid toxic effects depends on the plant genotype and that in the absence of high concentrations of Zn in the solution, the plant will activate the absorption channels according to Zn demand [40,41].

2.4. Relation between Biomass and Micronutrients

Table 2 shows the correlation matrix obtained between the accumulated biomass and the micronutrients Fe, B, Mn, Cu, and Zn accumulated during the 2015 and 2016 cycles. It can be observed that there is a highly significant correlation ($r \geq 0.97$) between the accumulation of biomass and the accumulation of all micronutrients. The high correlation observed showed that micronutrient accumulation had a directly proportional relationship to the accumulation of biomass as previously reported in Osvalde [22]. This means that a greater accumulation of biomass will result in a greater accumulation of nutrients by the plant. The accumulation of biomass depends on the photosynthetic activity which in turn is influenced by the climatic conditions. The accumulation of biomass requires the absorption of micronutrients since they are necessary in all physiological processes involved in growth and development [42].

Figure 3 shows the linear relationship between the accumulated micronutrients Fe, B, Mn, Cu, and Zn and the biomass of both the Vitaly and Luxell varieties considering all data. The linear relationship between all micronutrients and biomass were very high with R^2 values > 0.94. Although the relationship between Mn and biomass was R^2 = 8928, even so, this was a good fit to line. This relationship has also been demonstrated in macronutrients as N and P [23,24]. These results showed that the accumulation of micronutrients is highly dependent on cucumber growth, regardless of the variety or even the climate effects. Therefore, the micronutrient uptake remains constant according to the accumulation of cucumber biomass, as mentioned Osvalde [22]. Considering this relationship, it is possible to estimate the accumulation of micronutrients from biomass accumulation with great precision.

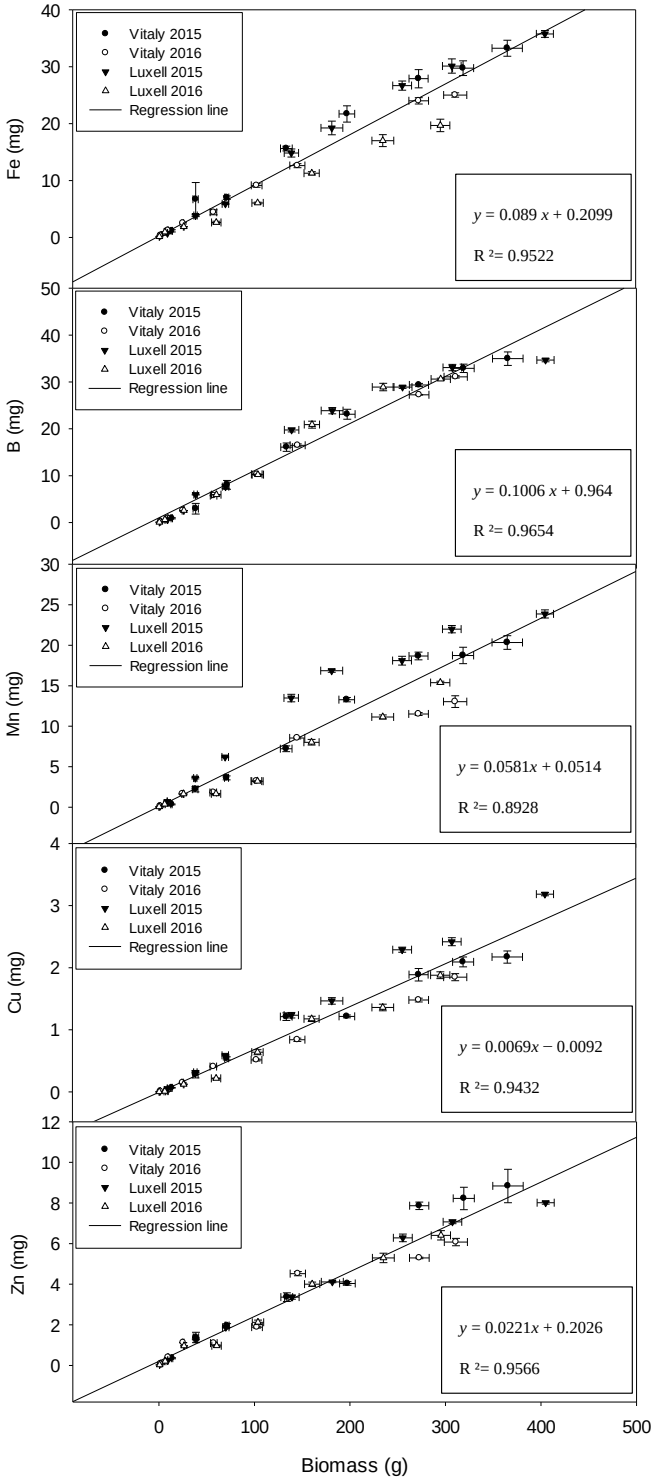

Figure 3. Linear relationship between the accumulated Fe, B, Mn, Cu, and Zn and the biomass of both Vitaly and Luxell varieties obtained from the 2015 to 2016 cycles. Data are the mean of four replicates ± standard error of the mean. The lineal model is included and the corresponding determination coefficient (R^2).

Table 2. Pearson correlation matrix for biomass and micronutrients accumulation in cucumber.

		Bio		Fe		B		Mn		Cu		Zn	
DAE		**2015**	**2016**	**2015**	**2016**	**2015**	**2016**	**2015**	**2016**	**2015**	**2016**	**2015**	**2016**
Bio	V	1	1	0.99	0.99	0.99	0.99	0.99	0.98	0.98	0.99	0.99	0.97
	L	1	1	0.99	0.99	0.99	0.97	0.99	0.97	0.99	0.99	0.99	0.99
Fe	V			1	1	0.99	0.99	0.99	0.98	0.99	0.99	0.98	0.97
	L			1	1	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99
B	V					1	1	0.99	0.99	0.99	0.99	0.97	0.98
	L					1	1	0.98	0.99	0.98	0.98	0.99	0.98
Mn	V							1	1	0.98	0.98	0.98	0.99
	L							1	1	0.99	0.98	0.99	0.98
Cu	V									1	1	0.98	0.97
	L									1	1	0.99	0.99
Zn	V											1	1
	L											1	1

Bio: dry biomass. DAE: days after seed emergence. V and L represent the Vitaly and Luxell varieties, respectively. 2015 and 2016 represent the year of crop development. In all cases, a highly significant correlation was obtained ($r \geq 0.97$).

2.5. Dynamic Modeling of Growth and Micronutrient Accumulation

Figure 4 presents the actual data corresponding to the accumulated total biomass and the resulting data of the simulation from the dynamic model. Figure 4a shows data from the Vitaly variety, while Figure 4b shows data from the Luxell variety. In both varieties, R^2 values greater than 0.98 (Table 3) were obtained for both calibration and validation, which represents a good fit between the simulated data and the actual data [18]. This demonstrated that the efficiency of crop growth simulation by the dynamic model used was very precise and can be used to predict the accumulation of biomass in the cucumber crop using the climatic variables (PAR, temperature, and concentration of CO_2). This is an important feature in dynamic models due to the variability of climatic conditions, where crop growth is also affected [43].

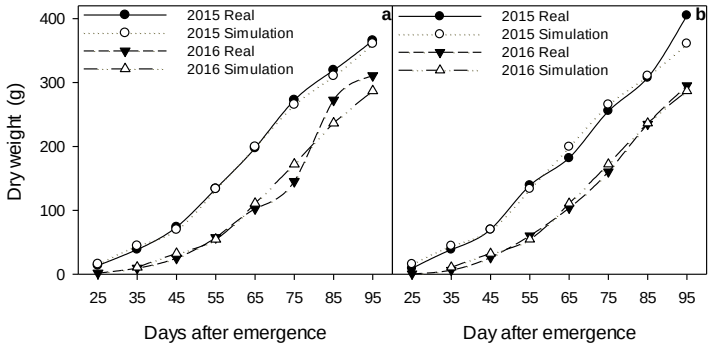

Figure 4. Comparison between the real and dynamically simulated data for the accumulation of dry biomass in cucumber plants for Vitaly (**a**) Luxell (**b**) varieties. The real data is the average of four replicates.

Figures 5 and 6 show the comparison between the actual accumulation of the micronutrients and the simulated output of the dynamic model. For both the calibration (Figure 5) and validation (Figure 6) process, R^2 values > 0.97 were observed. According to Wallach [44], a perfect efficiency is equal to 1, so the obtained efficiency was very good. This demonstrated that the dynamic model used could properly simulate the accumulation of micronutrients by cucumber plants. The efficiency

indexes observed in this study (Table 3) were similar to those reported by Juárez-Maldonado et al. [18], who obtained an efficiency greater than 0.95 for the accumulation of N, P, K, and S by a tomato crop. Although regression models have been obtained for the accumulation of macro and micronutrients in zucchini, tomato, thistle, and cereals [45–48] with good efficiency, this work used a dynamic model that considered the climatic variables measured inside the greenhouse (PAR, temperature and CO_2 concentration) as input variables, therefore enabling a more robust model for the determination of micronutrient accumulation.

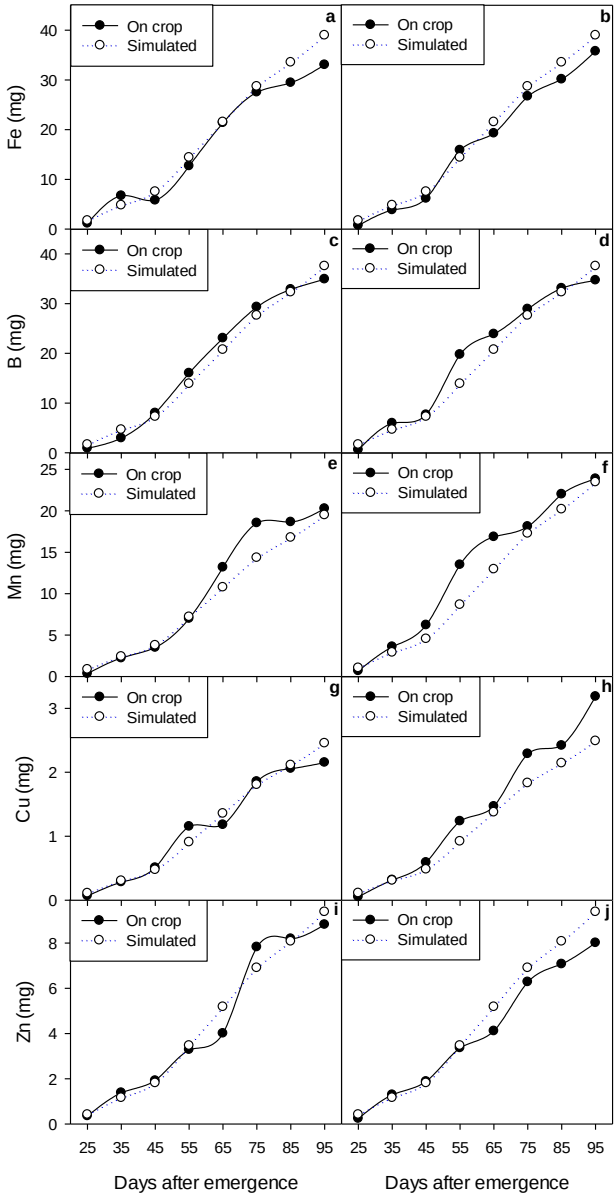

Figure 5. Comparison between the real and dynamically simulated data for micronutrient accumulation in the Vitaly (**a**,**c**,**e**,**g**,**i**) and Luxell (**b**,**d**,**f**,**h**,**j**) cucumber plant varieties. The data corresponding to the culture cycle used for the calibration are presented. The real data are the average of four replicates.

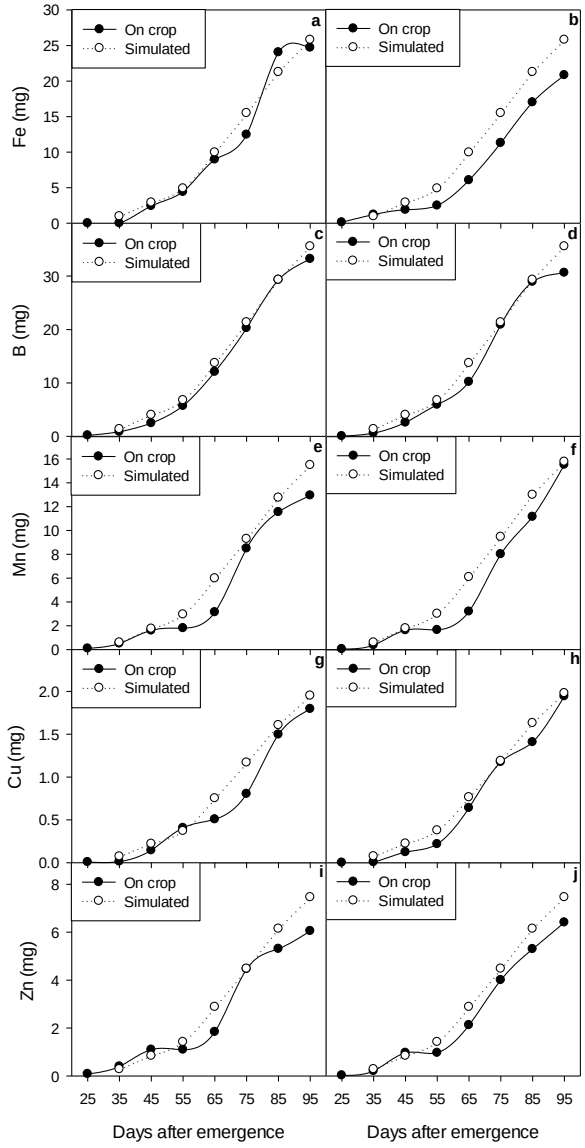

Figure 6. Comparison between the real and dynamically simulated data for micronutrient accumulation in the Vitaly (**a**,**c**,**e**,**g**,**i**) and Luxell (**b**,**d**,**f**,**h**,**j**) cucumber plant varieties. The data corresponding to the cultivation cycle used for the validation are presented. The real data are the average of four replicates.

Table 3. Values of the indices used to evaluate the simulation efficiency of the dynamic model during the calibration and validation process using the data obtained from the 2015 to 2016 crop cycles, respectively.

		Biomass		**Fe**		**B**		**Mn**		**Cu**		**Zn**	
	cv	**EF**	**Index**	**EF**	**Index**	**EF**	**Index**	**EF**	**Index**	**EF**	**Index**	**EF**	**Index**
2015	V	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99
	L	0.99	0.99	0.99	0.99	0.99	0.99	0.98	0.99	0.97	0.99	0.98	0.99
2016	V	0.99	0.99	0.99	0.99	0.95	0.99	0.93	0.99	0.95	0.99	0.96	0.99
	L	0.99	0.99	0.84	0.98	0.98	0.99	0.95	0.99	0.98	0.99	0.96	0.99

cv: variety. "EF" and "Index" are the indices proposed by Wallach et al. [44]. V and L represent the Vitaly and Luxell varieties, respectively. 2015 and 2016 represent the year of crop development. A R^2 value of 1 represents a perfect fit between the simulated and the actual data [44].

Considering the results found here, it is possible to plan the application of micronutrients (Fe, B, Mn, Cu, and Zn) in cucumber plants under greenhouse conditions more efficiently. This is possible as the accumulation of biomass and therefore the demand of micronutrients, as proposed by Bugarín-Montoya et al. [17], can be quantified per day using the dynamic model. In this way, it is possible to avoid the excess of micronutrients in cucumber plants, while increasing the efficiency in their use.

3. Materials and Methods

3.1. Greenhouse Description

The experiment was carried out in a multi-tunnel greenhouse oriented from north to south, with an area of 392 m^2, covered with polyethylene (25% shade) and side windows that were opened and closed manually. The windows were opened in the morning when the temperature of the greenhouse reached 24 °C and closed in the afternoon when the temperature dropped to 18 °C. The greenhouse is located within the facilities of the Universidad Autonoma Agraria Antonio Narro located in Saltillo, Coahuila, Mexico (25°21′ N, 101°01′ W).

3.2. Development of Cucumber Crop

Two cycles of cucumber cultivation were established in the greenhouse during 2015 and 2016. The first cycle started on 1 April and ended on 7 July 2015, while the second cycle was from 1 March to 7 June 2016. The cucumber varieties used in the experiment were Vitaly (Syngenta, Basel, Switzerland) and Luxell (Nunhems, Nunhem, The Netherlands), both of the slicer type. These varieties were selected as they have great performance and quality traits for the international export market. Direct seeding was carried out in 4-L black polyethene bags containing a mixture of peat moss-perlite as a substrate in a 1:1 (v:v) ratio. A seed density of five plants per square meter was implemented with an irrigation system. During the development of both cultures, four irrigations were performed at 9, 12, 15, and 18 h during the day. Irrigation was applied according to each phenological stage of crop, reaching approximately 2.2 L per plant in the higher consumption stages. Nutrients were applied based on Steiner's nutrient solution [49]. Different concentrations of Steiner's nutrient solution [49] were used according to the phenological stages of the crop following the nutrient requirements of these: 25% in vegetative growth 1–20 days after emergence (DAE), 50% in flowering (20–30 DAE), and 100% in fruiting (30–95 DAE). The plants were maintained with a single stem by pruning (removing the axillary buds). In addition, the first four flowers were removed, and from the fifth flower on, one for each leaf in the plant was left. Plant growth was limited to 75 days after emergence, eliminating apical growth. At this time, the plants had an average height of 3.5 m.

3.3. Recording Climate Variables

Climatic variables were measured inside the greenhouse during the development of both crop cycles. Sensors were installed 30 cm below growth apex and kept at that height to follow the development of the crop. A photosynthetic active radiation sensor (PAR) (LightScout Quantum Meter 3668I, Spectrum Technologies, Inc., Aurora, IL, USA) and an external temperature sensor (WatchDog External Temperature Sensor 3667-20, Spectrum Technologies, Inc., Plainfield, IL, USA) were connected to a datalogger (WatchDog 1650 Data Logger, Spectrum Technologies, Inc., Plainfield, IL, USA). To measure CO_2 concentration in the air, a CO_2 sensor (WatchDog A160 Temp/RH/CO_2 logger, Spectrum Technologies, Inc., Plainfield, IL, USA) was used. The PAR, temperature and CO_2 concentration data were recorded every 15 min.

3.4. Accumulated Biomass

The total accumulated biomass of cucumber crops was determined from the sum of the biomass of each plant organ (fruit, leaf, stem, and root). For this, destructive sampling was performed and

the total accumulated biomass was quantified starting at 25 days after emergence, and every 10 days during the development of each crop. Four plants were taken at random and separated into leaves, stems, fruits, and roots. Each organ was dehydrated in a drying oven at a constant temperature of 80 °C for four days to obtain the dry weight. The pruning and harvested fruits were also quantified to obtain the dry weights, and these were added to the weights of the total leaves and fruits.

3.5. Determination of Micronutrient Accumulation

The total micronutrient accumulation (Fe, B, Mn, Cu, and Zn) was determined by the sum of the content of these in each organ (leaf, stem, fruit, and root):

$$TMA = CMO_{\mathrm{L}} + CMO_{\mathrm{S}} + CMO_{\mathrm{F}} + CMO_{\mathrm{R}} \quad (1)$$

where *TMA* is the total accumulation of the micronutrient, and *CMO* is the content of the micronutrient in each organ: leaf (L), stem (S), fruit (F), and root (R). To determine *CMO*, the dry biomass per plant (*DW*, kg) and the micronutrient concentration (*CM*, mg kg^{-1}) of each organ were considered according to Quesada-Roldan and Bertsch-Hernández [46].

$$CMO = CM * DW \quad (2)$$

CMO is expressed in milligrams (mg), and *TMA* is expressed in milligrams per plant (mg plant).

The micronutrient concentration in whole plant (*MCP*) was determined using *TMA* and the dry weight per plant as follows, and the units are in milligrams per kilogram of dry weight (mg kg^{-1} *DW*):

$$MCP = \frac{TMA}{DW} \quad (3)$$

The determination of the micronutrients started 25 days after emergence, and every 10 days during the development of the crop. Quantification of Fe, B, Mn, Cu, and Zn was performed on an Inductively Coupled Plasma (Optima 8300 ICP-OES, PerkinElmer, Inc., Waltham, MA, USA). For this process, one gram of each sample was digested with HNO_3 and H_2O_2 at 400 °C following the standard method.

3.6. Description of the Dynamic Model

The dynamic tomato growth model proposed by Tap [43] and adapted by Juárez-Maldonado et al. [18] was used. This model starts at the flowering stage and consists of six state variables: mass balance for the buffer of assimilates (*B*), dry fruit weight (W_{F}), leaf dry weight (W_{L}), plant development (*DP*), dry weight of fruit harvest (W_{HF}), and dry weight of harvested leaves (W_{HL}). The full description of the model is presented in Juárez-Maldonado et al. [18].

Climate variables measured inside the greenhouse (temperature, PAR, and concentration of CO_2) were used as input variables for the model. The dry weight of leaves (g), the dry weight of fruits (g), the dry weight of harvested leaves (g), the dry weight of harvested fruits (g), and total biomass (g) were the output variables according to Juárez-Maldonado et al. [18]. As the growth and accumulation of biomass in cucumber fruits is greater than that of the tomato, a harvest parameter for cucumber fruit (*y*F*c*) was incorporated to the W_{HF} in the model adapted by Juárez-Maldonado et al. [18] as follows:

$$W_{\mathrm{HF}} = h_{\mathrm{F}} * W_{\mathrm{F}} * y\mathrm{F}c \quad (4)$$

where h_{F} is the fruit harvest coefficient function; and *y*F*c* represents a proportion of total fruit weight in relation to total leaf weight.

To determine the accumulation of micronutrients by cucumber plants as a function of crop growth in the dynamical model, a linear relationship between them was considered. To verify this, a correlation analysis was performed between the accumulation of Fe, B, Mn, Cu, and Zn with the

total biomass at each sampling moment. Furthermore, the linear adjustment between Fe, B, Mn, Cu, and Zn accumulated and the amount of biomass was verified. The Pearson correlation coefficient and linear adjustment were obtained using the SigmaPlot© 12.0 program. Based on this linear relationship, the average content of each micronutrient (Fe, B, Mn, Cu, and Zn) (Table A1 in Appendix A) was used throughout the development of the crop and the total biomass (Equation (5)).

$$TAM = BT * ACM \tag{5}$$

where *TAM* is the total accumulation of each micronutrient for a given time; *BT* is the total biomass of a plant for the corresponding time (kg); and *ACM* is the average content of the micronutrient based on dry weight (mg kg^{-1}). This applies when there is no nutrient limitation since the concentration of each micronutrient in the plant is equal to its demand [7,21]. Equation (5) was added to the growth model to simulate the accumulation of each micronutrient by the cucumber plants.

3.7. Calibration and Validation of the Dynamic Model

The calibration of the model consisted of fine tuning parameters to obtain a good fit between the simulated and real data [18]. The dynamic model was calibrated for the accumulation of crop biomass as well as for micronutrient accumulation (Fe, B, Mn, Cu, and Zn). This process was carried out during the 2015 cycle using the climatic variables measured inside the greenhouse (PAR, temperature, and concentration of CO_2) as the inputs of the dynamic model. Table A1 in Appendix A shows the complete list of the nominal and calibrated parameter values of the dynamic model.

The validation of the dynamic model was through a process that compared the simulated data to the real data and the adjustment between them was verified [18]. To validate the dynamic model, the climatic variables measured inside the greenhouse corresponding to the second crop cycle (year 2016) were taken as model inputs. After the simulation, the model outputs were compared with the actual data obtained from the second cycle of cucumber cultivation (biomass and micronutrient accumulation).

To evaluate the fit between the simulated data and the actual data in the calibration and validation of the dynamic model, the "EF" and "Index" indices proposed by Wallach et al. [44], described below, were used.

$$\mathrm{EF} = 1 - \frac{\sum_{i=1}^{N} (Y_i - \check{Y}_i)^2}{\sum_{i=1}^{N} (Y_i - \bar{Y})^2} \tag{6}$$

$$\mathrm{Index} = 1 - \frac{\sum_{i=1}^{N} (Y_i - \check{Y}_i)^2}{\sum_{i=1}^{N} \left(\left|Y_i - \bar{Y}\right|\right) + \left(\left|Y_i - \bar{Y}\right|\right)^2} \tag{7}$$

where Y_i is a value measured at moment i; and $\check{Y}_i$ is the corresponding value calculated by the model. These values vary between 0 and 1, where 1 is considered the perfect efficiency. A R^2 value of 0.98 was used to consider a model as calibrated. For validation, a R^2 value of 0.95 was considered a very good fit as per Juárez-Maldonado et al. [18] given that a value of 1 represents a perfect fit between the simulated and actual data [44].

4. Conclusions

Changes in the climatic conditions recorded inside the greenhouse directly influenced the accumulation of biomass by the cucumber plants. When the PAR and temperature decreased, the total biomass accumulation also decreased.

The accumulation of micronutrients by cucumber plants was directly proportional to the accumulation of biomass. Therefore, the accumulation of micronutrients was also directly influenced by changes in the climatic conditions recorded inside the greenhouse.

The dynamical model used simulated both the accumulation of biomass and the accumulation of micronutrients by the cucumber plants with great precision, since the indexes used presented values higher than 0.95.

The dynamic model used in this study can be used as a practical tool for planning the management of cucumber cultivation in greenhouses. In addition, from this model, it is possible to determine the micronutrient requirements (Fe, B, Mn, Cu, and Zn) of the cucumber plants, which allows a more adequate management of their application.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Description of model parameters, nominal value and calibrated value.

Parameters	Nominal Value	Calibrated Value	Units	Description
b1	2.7		$m^2\ g^{-1}$	Coefficient of the change buffer function
d1	2.13×10^{-7}	5.9332×10^{-7}	s^{-1}	Growth Rate Parameter
d2	2.47×10^{-7}	5.4664×10^{-7}	s^{-1}	Growth Rate Parameter
d3	20		°C	Growth Rate Parameter
d4	7.50×10^{-11}	3.46×10^{-13}	-	Growth Rate Parameter
F	1.2	1.5	-	Ratio of assimilated fruit requirements
f1	8.10×10^{-7}	6.1×10^{-6}	s^{-1}	Fruit growth rate coefficient
f2	4.63×10^{-6}		s^{-1}	Fruit growth rate coefficient
M	2.511		-	Correction-LAI function parameter
mF	1.157×10^{-7}	1.5×10^{-6}	s^{-1}	Breathing coefficient of maintenance of the fruit
mL	2.894×10^{-7}	2.89×10^{-9}	s^{-1}	Breathing coefficient of vegetative maintenance
p3	577		$W\ m^2$	Net photosynthesis parameter
p4	221		$g\ s^{-1}\ m^{-2}$	Net photosynthesis parameter
Pm	2.25×10^{-3}	2.6×10^{-3}	$g\ s^{-1}\ m^{-2}$	Maximum photosynthesis
QG	1		-	Temperature of the rate of growth of the fruit
QR	2		-	Respiration maintenance
T	86,400		S	Weather
TG	20		°C	Reference temperature of the growth rate
TR	25		°C	Reference temperature for maintenance breath
V	1.23	2.23	-	Ratio of requirements of vegetative assimilates
v1	1.3774	0.45	-	Relationship of growth vegetative fruit
v2	−0.168		$°C^{-1}$	Relationship of growth vegetative fruit
v3	19	20	°C	Relationship of growth vegetative fruit
WR	32.23		$g\ m^{-2}$	Parameter of the LAI correction function
yF	0.5983	1.05	-	Parameter of the fruit harvest coefficient
yFc		5.3	$g\ m^{-2}$	Parameter of cucumber fruit harvest
yL	0.5983	0.35	-	Leaf Harvest Coefficient Parameter
z	0.6081		-	Fraction of vegetative dry weight leaf
Fe		108	$mg\ kg^{-1}$	Average content of Fe on dry matter base
B		104	$mg\ kg^{-1}$	Average content of B on dry matter base
Mn		54	$mg\ kg^{-1}$	Average content of Mn on dry matter base
Cu		6.8	$mg\ kg^{-1}$	Average content of Cu on dry matter base
Zn		26	$mg\ kg^{-1}$	Average content of Zn on dry matter base

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