UNIVERSIDAD AUTÓNOMA AGRARIA ANTONIO NARRO

SUBDIRECCIÓN DE POSTGRADO

MODELO DINÁMICO DE LA EXTRACCION DE NUTRIENTES EN UN CULTIVO DE PEPINO BAJO INVERNADERO

TESIS

Que presenta LINO JEREMIAS RAMÍREZ PÉREZ

como requisito parcial para obtener el Grado de
DOCTOR EN CIENCIAS EN AGRICULTURA PROTEGIDA

Saltillo, Coahuila Noviembre 2017

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Dr. Antonio Juárez Maldonado	Dra. Susana González Morales

Saltillo, Coahuila

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Elaborada por LINO JEREMIAS RAMÍREZ PÉREZ como requisito parcial para obtener el Grado de Doctor en Ciencias en Agricultura Protegida con la supervisión y aprobación del comité de asesoría

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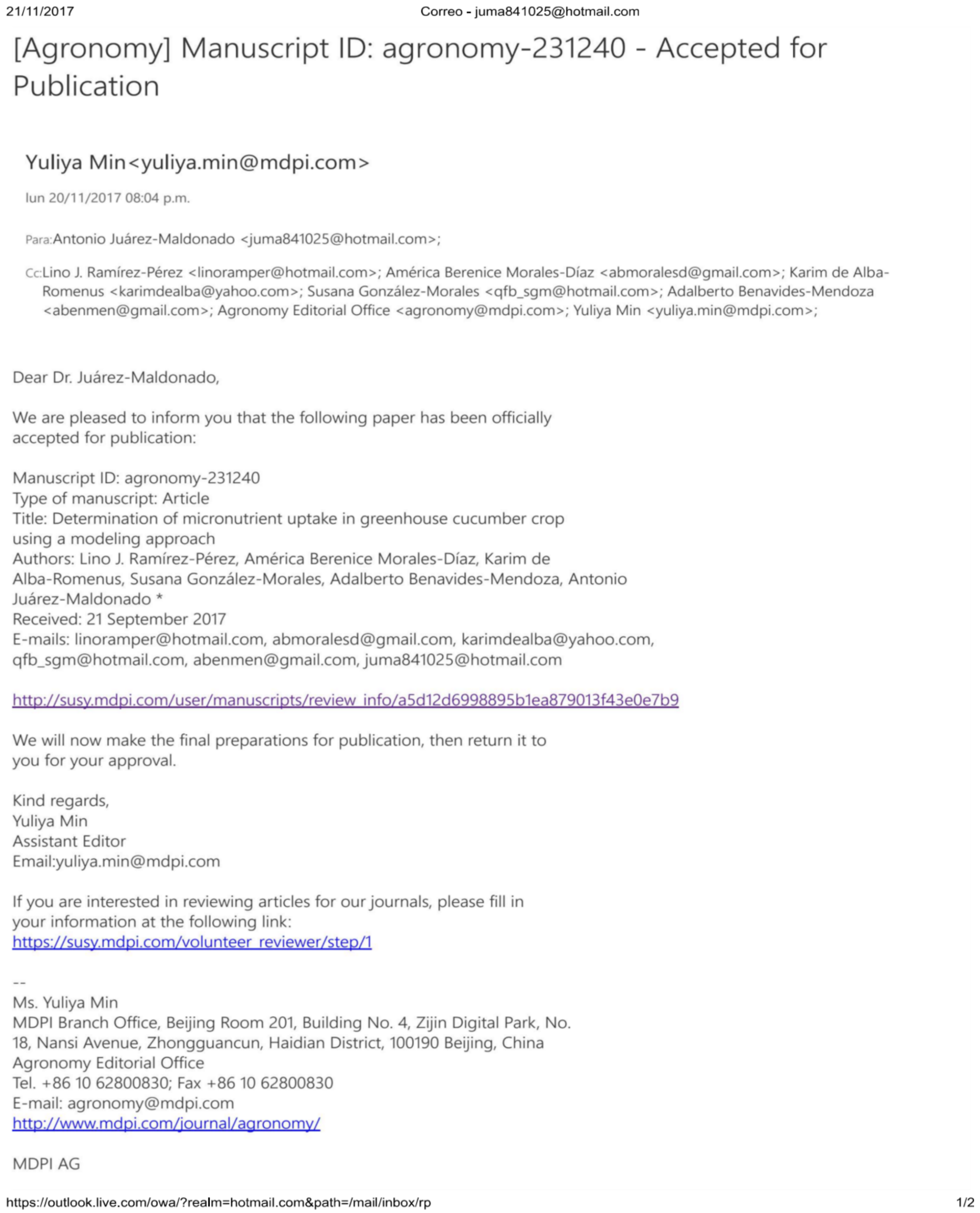

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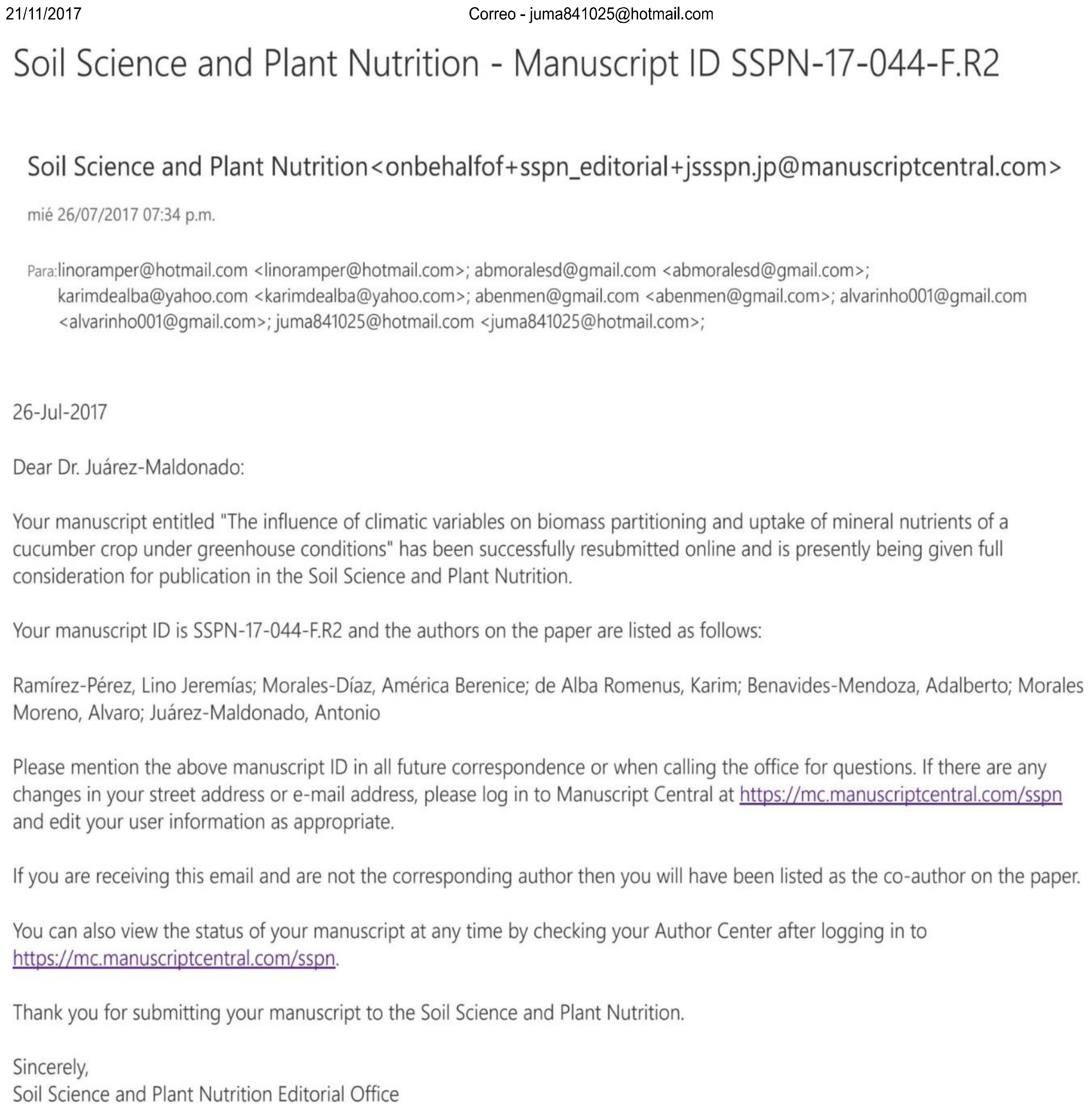

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Dear Dr. Juárez-Maldonado:

Your manuscript entitled "The influence of climatic variables on biomass partitioning and uptake of mineral nutrients of a cucumber crop under greenhouse conditions" has been successfully resubmitted online and is presently being given full consideration for publication in the Soil Science and Plant Nutrition.

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Ramírez-Pérez, Lino Jeremías; Morales-Díaz, América Berenice; de Alba Romenus, Karim; Benavides-Mendoza, Adalberto; Morales Moreno, Alvaro; Juárez-Maldonado, Antonio

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ÍNDICE

INTRODUCCIÓN

La agricultura protegida (AP) puede ser definida como un sistema agrícola especializado en el control del sistema sustrato-microclima, donde es posible modificar condiciones como el sustrato, temperatura, radiación solar, viento, humedad y composición del aire. El principal objetivo de la producción bajo AP es proporcionar condiciones óptimas de microclima para el crecimiento, desarrollo y productividad de las plantas a lo largo del año, y en base a este control lograr las exigencias de calidad, inocuidad y rendimiento que demanda el mercado comercial (Pignata *et al.,* 2017). La producción bajo AP se ha incrementado en todo el mundo, con un estimado de 489,214 ha distribuidos a través de cinco continentes (Hickman, 2017). En México, hay alrededor de 25,814 ha bajo agricultura protegida, donde aproximadamente el 65% son invernaderos y el resto son casas de sombra y macro túneles (SIAP, 2016).

La AP proporciona grandes ventajas como inocuidad, calidad y rendimiento de los cultivos, sin embargo, cuando no existe un manejo adecuado, se presenta el uso excesivo de fertilizante (He et al., 2008), el cual en su mayoría es liberado al medio ambiente, provocando impactos ambientales adversos (Gollany *et al.,* 2004; Beman *et al.,* 2005; Marcelis, 2005; Du *et al.,* 2014; Cao *et al.,* 2015). Por lo tanto, es de vital importancia optimizar el uso de los fertilizantes para reducir los riesgos ambientales y mantener los niveles óptimos de rendimientos.

En la actualidad existen sistemas complejos como el manejo integrado de nutrientes, lo cual es un concepto que trata principalmente sobre el mantenimiento del suministro de nutrientes de las plantas a un nivel óptimo mediante la optimización de todas las fuentes nutritivas posibles (Zhang *et al.,* 2012; Mondal *et al.,* 2016). Aunado a esto, existen métodos como la aplicación de sistemas cerrados para el suministro de agua y nutrientes para mejorar la eficiencia en el uso de nutrientes en invernaderos (Dwivedi *et al.,* 2016; Oliveira *et al.,* 2017). Esto se hace generalmente reciclando el agua de drenaje y controlando la concentración de los iones (Kudo *et al.,* 2014). Sin embargo, para lograr el uso adecuado de los fertilizantes, es necesario conocer la demanda de los nutrientes de acuerdo al proceso de crecimiento del cultivo, que a su vez es dependiente de las condiciones de microclima imperantes bajo el sistema de AP.

El pepino (*Cucumis sativus* L.) es uno de los cultivos más producidos bajo invernadero, ya que logra un mayor rendimiento y calidad. Además, la importancia del pepino radica también en su forma de consumo, ya que puede ser fresco o industrializado (USDA, 2017). Dentro de la clasificación mundial, México ocupa el octavo lugar en producción de pepino con 637, 395 toneladas, del cual el 43 % es producido en el estado de Sinaloa (SIAP, 2016).

El cultivo de pepino presenta un patrón de crecimiento cíclico en el que períodos de alta fructificación y crecimiento lento del fruto se alterna con períodos de escasa fijación de frutos y rápido crecimiento de frutos (Heuvelink, 1996; Wubs *et al.*, 2009b). Se cree que este patrón es derivado de la relación fuente/demanda (Marcelis *et al.*, 1998), así como por la regulación hormonal (Bangerth *et al.*, 2000), dependientes a su vez de factores ambientales (Kahlen, 2007) y de la arquitectura del dosel. Por lo tanto, predecir el comportamiento de crecimiento del pepino ha sido motivo de variadas investigaciones, de las cuales el uso de modelos matemáticos ha contribuido eficazmente en la optimización del manejo e incremento de la productividad del cultivo (Bar-Yosef *et al.*, 2004).

Los modelos matemáticos, se han utilizado para simular diversos procesos que influyen en el crecimiento y desarrollo de los cultivos, prueba de ello se encuentran la dinámica del agua, la distribución de los nutrientes, el crecimiento de los cultivos bajo distintos niveles de riego y fertilizantes (Ersahin y Karaman, 2001, Gallardo *et al.*, 2009, Zhang *et al.*, 2009, Hu *et al.*, 2010). En los últimos años, se han desarrollado diversos modelos que ayudan a predecir el crecimiento de los cultivos bajo invernadero (Heuvelink, 1999; Boote *et al.*, 2002; Liu *et al.*, 2007), el rendimiento (López *et al.*, 2008) y la etapa de cosecha (Wurr *et al.*, 1988, Marcelis y Gijzen, 1998). En el cultivo de pepino se han aplicado modelos que integran procesos fisiológicos como morfológicos que ayudan a simular el crecimiento. Evidencia de ello se encuentra en los modelos estructurales funcionales (FSPMs) (Wiechers *et al.*, 2011). Por su parte, Kahlen *et al.* (2011) aplicaron un modelo basado en la cantidad de luz para estimar la longitud final de los entrenudos del pepino. Respecto a los requerimientos de nutrientes, se han reportado modelos que determinan la demanda de N en función del crecimiento de los frutos y rendimiento de pepino (Dai *et al.*, 2011). Por su parte, Guo *et al.* (2010) y Sun *et al.* (2012) calibraron y validaron el modelo EU-Rotate N en el cultivo de pepino para determinar el movimiento del agua y destino de N, el cual funcionó bajo diferentes niveles de irrigación y fertilización.

Son variados los modelos aplicados para la predicción del crecimiento y la demanda de nutrientes como el N, sin embargo, estos no integran ambos procesos. Por ello, se han utilizado modelos como el VegSyst para calcular la producción de materia seca así como la absorción de N en el cultivo de pepino (Gallardo *et al.,* 2016). Sin embargo, no se realizado la simulación de absorción de la totalidad de los macro y micro-elementos. Por esta razón, el objetivo del presente estudio fue adaptar el modelo dinámico de crecimiento del tomate validado por Tap (2000), para determinar los requerimientos minerales del cultivo del pepino.

REVISIÓN DE LITERATURA

Producción de cultivos bajo agricultura protegida

La agricultura protegida puede definirse como un sistema agrícola especializado en el control del ecosistema de suelos y climas en el que se pueden realizar cambios en ciertas condiciones (suelo, temperatura, radiación solar, viento, humedad y composición del aire). El principal objetivo de la producción bajo este sistema es proporcionar condiciones favorables de microclima para el crecimiento, desarrollo y productividad de las plantas a lo largo del año (Ali, 2012). La producción bajo invernadero se encuentra en crecimiento constante en todo el mundo, con aproximadamente 489,214 ha distribuidas en los cinco continentes (Hickman, 2017). En México, hay aproximadamente 23,500 hectáreas bajo agricultura protegida (AP), de las cuales aproximadamente 12,000 corresponden a invernaderos y el resto corresponde principalmente a casas de sombra y macro túneles (Secretaría de Agricultura, Ganadería, Desarrollo Rural, Pesca y Alimentación, 2014).

La producción de cultivos protegidos era originalmente una práctica común en regiones de climas fríos, ya que se puede extender la temporada de cultivo y también se puede incrementar la producción de las plantas donde no pueden crecer de manera óptima (Fitz-Rodriguez, 2008; Papadopoulos y Hao, 2000). Sin embargo, por las ventajas que proporcionan, la producción bajo este sistema se ha expandido a regiones con diferentes condiciones climáticas.

El manejo del microclima dentro del invernadero, es uno de los factores más importantes a considerar para obtener el máximo potencial de este sistema de producción, ya que una baja o alta temperatura son factores limitantes para la obtención de crecimiento y rendimiento óptimos de los cultivos.

Influencia de factores ambientales en la producción bajo invernadero

Las especies vegetales han evolucionado para funcionar en condiciones ambientales óptimas, como la luz y la temperatura. En los últimos años, los fenómenos meteorológicos extremos se han producido con frecuencia, causando una severa pérdida de rendimiento en todo el mundo, principalmente en invernaderos donde no existe un control sobre los factores microclimáticos (Long y Ort, 2010).

Radiación

La radiación solar de una región determinada es el primer factor climático a considerar antes de iniciar un proyecto de cultivo protegido (Castilla, 2013). Kittas *et al.* (1999) observaron que la calidad de la radiación permitida por los materiales de cobertura para entrar en el invernadero es importante para evaluar su influencia en el crecimiento y desarrollo de la planta. Abdel-Ghany *et al.*, (2012) analizaron los efectos del tipo de cobertura de invernadero sobre la transmitancia de la radiación fotoinsinteticamente activa (PAR), la reflectancia o absorción del infrarrojo cercano (NIR) y la temperatura del aire del invernadero. Concluyeron que las láminas plásticas reflectoras de NIR parecen ser la cubierta más adecuada, de bajo costo y simple para invernaderos bajo condiciones áridas. Los materiales plásticos más comunes utilizados como películas agrícolas incluyen el polietileno de baja densidad (LDPE), el copolímero de etileno y acetato de vinilo (EVA) y cloruro de polivinilo (PVC) (Castilla, 2013).

Temperatura

La temperatura es una de las variables ambientales más influyentes que determinan el crecimiento, desarrollo y rendimiento de las plantas. La temperatura desfavorable puede influir negativamente en muchas características de la función de las células vegetales, incluyendo la actividad enzimática, la fluidez de la membrana, los complejos proteínicos y el citoesqueleto, la respiración, la fotosíntesis, la síntesis de clorofila y el estado redox (Long y Ort, 2010; Sage, 2007; Lambers *et al.*, 2008).

Marcelis y Baan Hofman-Eijer (1993) demostraron que la temperatura influye directamente en el crecimiento del pepino, ya que afecta la tasa de producción y el área foliar que forma el dosel vegetal a través del cual el cultivo intercepta la radiación solar y realiza los procesos metabólicos relacionados con la acumulación de fotoasimilados.

El pepino es una planta nativa de regiones subtropicales y templadas, por lo tanto, su crecimiento se ve afectado por diferentes temperaturas diurnas y nocturnas, así como la temperatura media diaria. La temperatura óptima para la fase generativa del pepino difiere de la fase vegetativa. El crecimiento máximo de la planta de pepino ocurre a 28-35 °C aunque también se ve afectado por otros factores (edad de la planta e intensidad de la luz). La producción de frutos requiere alta temperatura nocturna 19-20 °C y temperatura diurna de 20-22 °C. Las plántulas requieren de 9-16 días para emerger a 15 °C, mientras que a 21 ° C, sólo toma 5-6 días (Alam, 2016). En general, la planta de pepino es muy sensible a la temperatura fría, además, bajo estas condiciones durante la temporada de crecimiento puede causar frutos amargos. Por otra parte, temperaturas superiores a 35 °C, pueden causar lesiones fisiológicas a los lípidos de la membrana, al metabolismo del carbono y del nitrógeno, fotosíntesis, el crecimiento de las raíces y por lo tanto, afectar la calidad y rendimiento (Du y Tachibana, 1994; Zhou y Ye, 1999; Li *et al.*, 2007a; Sun *et al.*, 2005; Tewari y Tripathy, 1998; Abd-el-baky *et al.*, 2010; Meng *et al.*, 2003).

Humedad relativa

El frecuente incremento de la temperatura dentro de los invernaderos reduce la humedad relativa, aumenta el déficit de presión de vapor de agua (DPV) y un consiguiente estrés termo-hídrico en los cultivos. La humedad relativa óptima para el crecimiento del pepino, oscila entre el 70 % y el 90 %. Humedades relativas muy elevadas favorecen el desarrollo de enfermedades aéreas y dificultan la fecundación. La coincidencia de altas temperaturas y baja humedad relativa puede ocasionar la caída de flores y de frutos recién cuajados. En periodo de crecimiento admite HR superiores a 70 %. Con humedades superiores a 90 % se corre el riesgo de padecer enfermedades criptogámicas. Si la humedad relativa es baja produce frutos asurados mal llamados "asoleados" (Bakker, 1990). La humedad relativa también puede ser una causa de aborto de flores y frutos, lo cual aumenta al disminuir la humedad de aire; por ello se deben mantener humedades relativas por encima del 80 % para que no sea un factor que provoque la abscisión de órganos en la planta (Marcelis *et al.*, 2004).

CO_2

La concentración de CO_2 ambiental es uno de los principales factores determinantes de la producción vegetal. La actual concentración de dióxido de carbono atmosférica es inferior a la óptima para el crecimiento y desarrollo de los cultivos; su evolución es objeto de numerosos estudios encaminados a predecir por una parte, las variaciones climáticas y por otra, el efecto del progresivo incremento de la concentración de CO_2 sobre los sistemas naturales y agrícolas. El cultivo en invernadero se desarrolla en un ambiente semicerrado, y está sujeto a una concentración de CO_2 fluctuante. El contenido de carbono (C) en el tejido vegetal representa alrededor del 40 % de la materia seca. El carbono procede del dióxido de carbono (CO_2) presente en la atmósfera y se incorpora al tejido vegetal a través del proceso de la fotosíntesis, por tanto, se puede afirmar que el CO_2 es una de las principales fuentes de la fotosíntesis (Sánchez-Guerrero *et al.*, 2005; Alonso, 2011). En la atmósfera actualidad, la concentración de CO_2 está en torno a 385 µmol mol^{-1}, mientras que la concentración óptima para la fotosíntesis se sitúa entre 900-1000 µmol mol^{-1}, lo que significa que la tasa de asimilación de carbono potencial está muy limitada por la actual concentración de CO_2 atmosférico.

Producción de pepino

El pepino es un cultivo vegetal importante perteneciente a la familia de las cucurbitáceas. Las frutas de pepino contienen aproximadamente 95 % de agua, 3,6 % de carbohidratos y 0,65 % de proteínas y son bajas en calorías (150 kcal kg^{-1}). Son una buena fuente de los siguientes nutrientes (en mg kg^{-1}): ácido pantoténico (B5) (0.026), vitamina C (0.28) y magnesio (1.3). Además, la importancia del pepino radica también en su forma de consumo, ya que puede ser fresco o industrializado (USDA, 2017). Dentro del ranking mundial, México ocupa el octavo lugar en producción de pepino con 637,395 toneladas, del cual el 43 % es producido en el estado de Sinaloa, 14 % en Sonora y 9.3 % en Baja California, con una producción promedio de 179 toneladas por hectárea (SIAP, 2016).

Manejo de la nutrición

Actualmente para otorgar los niveles de nutrición adecuada para el cultivo de pepino, la mayoría de los sistemas establecidos se aplica el riego por goteo con una solución nutritiva que contiene fertilizantes disueltos con todos los nutrientes minerales esenciales para las plantas, en concentraciones óptimas para su crecimiento y desarrollo. Para que las plantas de pepino crezcan sin limitaciones nutricionales, la solución nutritiva debe tener un pH entre 5.5 a 6.5, una conductividad eléctrica (CE) entre 1.5 y 3 dS m^{-1}, y los nutrimentos minerales deben estar disociados en proporciones y concentraciones que eviten precipitados y antagonismos (Adams, 2004). La planta modifica el consumo de nutrimentos en función de sus fases de crecimiento y desarrollo, condiciones climáticas, y características de la solución nutritiva como la CE, pH y oxígeno disuelto (Terabayashi *et al.*, 2004; Jones, 2005; Sonneveld y Voogt, 2009).

En México la nutrición mineral del cultivo de pepino en invernadero se suministra principalmente con base en la solución nutritiva universal de Steiner, utilizada a diferentes concentraciones de acuerdo con el criterio de los productores, sin tener en cuenta a qué concentración presenta mejor comportamiento de la calidad y rendimiento de los frutos (Barraza, 2015). Sin embargo, debido a los altos costos de los fertilizantes (Huang, 2009) y al impacto negativo en el ambiente (Giuffrida y Leonardi, 2009; Nakano *et al.,* 2010; Massa *et al.*, 2010), es necesario buscar sistemas más eficientes. El manejo de la nutrición de las plantas es un aspecto crucial desde el punto de vista fisiológico y económico, pues en la producción agrícola bajo condiciones protegidas aprovechar al máximo la expresión del potencial genético es fundamental. Aunque existen técnicas exitosas como el fertirriego, aún hay problemas con la dosificación de fertilizantes que deben aplicarse (Bugarín-Montoya *et al.*, 2002), ya que pocas veces se sigue un adecuado plan de fertilización que sea acorde a las necesidades reales de consumo de nutrientes del cultivo a lo largo de su ciclo de producción (Quesada-Roldán y Bertsh-Hernández, 2013).

Modelos matemáticos

Los avances tecnológicos brindan técnicas novedosas como la simulación de cultivos bajo invernadero. Un modelo de simulación de crecimiento de un cultivo es la aplicación de análisis sistemáticos y tecnología computacional, la cual integra a investigadores de diferentes disciplinas como la fisiología del cultivo, ecología, agrometeorología y agricultura (Zhang y Wang, 2011).

Los modelos como abstracción de la realidad son una herramienta que los seres humanos han desarrollado en muchas disciplinas y también, con cierto retraso, en el campo de la producción de alimentos. Es en la industria donde los modelos han tenido un enorme desarrollo, especialmente en comparación con la agricultura.

Los modelos matemáticos son herramientas eficaces para poner a prueba hipótesis, para sintetizar los conocimientos, para describir y comprender los sistemas complejos y para comparar diferentes escenarios (Marcelis *et al.*, 2006). Los modelos en la agricultura son un conjunto de ecuaciones matemáticas que representan las reacciones que ocurren dentro de la planta así como las interacciones entre la planta y su ambiente (Cheeroo-Nayamuth, 1999). Por lo tanto, los modelos de crecimiento y desarrollo son herramientas que sirven para obtener información básica de la planta y sus interacciones con el ambiente, lo cual permite maximizar el uso de los recursos en invernadero, y así mismo facilita un mejor manejo del cultivo (López-Cruz, 2004).

En la agricultura, existen varias familias de modelos: Descriptivos, teleonómicos, basados en procesos y funcional-estructural. Los modelos descriptivos incluyen regresión estadística y los empíricos. Este tipo de modelos realizan descripciones directas de los datos e indican la relación entre las variables de un sistema, pero no dan ninguna explicación sobre los mecanismos de esas relaciones.

Los modelos basados en procesos, también llamados explicativos o mecanicistas, contienen submodelos con al menos un nivel jerárquico de mayor profundidad para la respuesta descrita (Larsen, 1990). En un modelo fisiológico, cada profundidad adicional aumenta el poder explicativo del modelo. El modelo mecanicista sigue el método tradicional reduccionista, que ha sido aplicado con éxito en las Ciencias Físicas, Biología Molecular y Bioquímica (Thornley, 1976).

Los modelos empíricos son descripciones directas de los datos observados, que pueden ser de gran utilidad en ciertas circunstancias (Thornley, 1976). En un modelo empírico, cualquier relación matemática propuesta no está restringida por leyes físicas tales como la conservación de la energía o las leyes de la información termodinámica o biológica, o por cualquier conocimiento de la estructura del sistema (Thornley, 1976).

Por otra parte, los modelos teleonómicos, están claramente formulados en términos de objetivos (Thornley, 1976). Aun cuando este punto de vista ha sido cuestionado, algunos autores afirman que la importancia de estos modelos es modelar los procesos de los organismos vivos e indican que los procesos orientados con un objetivo son intrínsecos a la vida misma y no a las formas no vivas (Pross, 2002). Por lo tanto, estos modelos de modelos pueden ser útiles como un vínculo entre modelos empíricos y modelos explicativos (Thornley, 1976), y se han aplicado en muchos aspectos, entre ellos la distribución de la materia seca entre la raíz y el tallo (Vincent, 1996) y modelización a nivel celular (Ji y Ciobanu, 2003).

Otro enfoque son los modelos funcionales-estructurales, estos modelos están orientados a combinar modelos geométricos de visualización de plantas con modelos basados en procesos. En este enfoque, el objetivo es controlar el desarrollo de toda la planta en su organogénesis y fotosíntesis. Los órganos actúan como fuentes y sumideros y tienen interacción entre la arquitectura y el funcionamiento durante el desarrollo de las plantas (de Reffye y Hu, 2003), este enfoque ha surgido relativamente recientemente y representa uno de los retos clave para la modelización de plantas (Tardieu, 2010).

La mayoría de los modelos explicativos se basan en la fotosíntesis. Los principales componentes de los modelos basados en la fotosíntesis son: Desarrollo del área foliar, interceptación de luz, fotosíntesis y respiración (Marcelis, 1998).

Modelos matemáticos en la horticultura

Los modelos en cultivos tienen varias aplicaciones. Es posible utilizarlos en sistemas de ayuda para la toma de decisiones en la producción agrícola (Gary *et al.,* 1998), y también en el control climático de los invernaderos (Rodríguez, 2003; van Straten *et al.*, 1999; Tap, 2000).

Los modelos en cultivos tienen una variedad de aplicaciones, tales como la predicción del rendimiento y manejo del cultivo, sistemas de apoyo para la toma de decisiones, en la investigación científica, en la definición de políticas para el desarrollo agrícola, en la enseñanza agrícola, control climático del invernadero, así como el ambiente de la raíz, etc. (Gary *et al.*, 1998; Marcelis *et al.*, 2006). Los modelos de cultivos proporcionan información cuantitativa a partir de la cual decisiones tales como la calendarización de las fechas de siembra de cultivos, riegos, fertilización, protección del cultivo, control del clima, etc., pueden ser tomadas a nivel de campo (Gary, 1999).

En la práctica de la horticultura, los modelos matemáticos permiten evaluar estrategias sobre el posible manejo de cultivos en invernadero, y en base a esto optimizar la producción (Marcelis *et al.*, 2006). Por ejemplo, para tratar de controlar el clima de un invernadero o el ambiente de la raíz del cultivo se requieren modelos matemáticos de ambos procesos (Gary, 1999).

Modelos matemáticos en el cultivo de pepino

En el cultivo de pepino se han realizado diversos modelos tanto para simular el crecimiento vegetativo, acumulación de biomasa por los distintos órganos y la acumulación de minerales.

Modelos de crecimiento vegetativo en pepino

Respecto al crecimiento vegetativo del pepino, Liebig (1989), generó un modelo para predecir la producción semanal del número de frutos en el cultivo de pepino usando ecuaciones derivadas de análisis de regresión múltiple.

Kahlen y Stützel (2011), modelaron el crecimiento de los entrenudos de las plantas de pepino basando en fotomodulación, observándose que al utilizar el modelo de crecimiento estructural funcional considerando las variaciones tanto en PAR como en rojo: rojo lejano (R:RF), proporcionó predicciones de longitud de entrenudo considerablemente mejores.

Modelos para acumulación de biomasa

Heuvelink y Marcelis (1989) y Marcelis (1994), simularon dinámicamente la distribución de materia seca entre hojas, tallo, raíz y frutos de las plantas, incluyendo la distribución para frutos individuales en el caso de pepino. En la simulación encontraron resultados aceptables para la distribución de materia seca entre los diferentes órganos comparados con los datos medidos en el experimento. Adicionalmente, determinaron que la distribución de materia seca entre los diferentes órganos como hojas, tallos y raíz es independiente de la carga del fruto. Por su parte, Nederhoff *et al.* (1989), describieron un trabajo en el que validaron el submodelo de fotosíntesis en el cultivo de pepino en invernadero, el cual se puede aplicar de manera práctica bajo niveles de CO_2 controlados. Chamont (1993), propuso un modelo simple de la distribución de carbono para la simulación del desarrollo de la raíz en el cultivo de pepino. Marcelis y Gijzen (1998), desarrollaron un modelo conocido como KOSI para predecir semanalmente el peso fresco de cosecha de los frutos de pepino así como su calidad. Los resultados presentados fueron satisfactorios, ya que los datos simulados comparados contra los datos medidos fueron aceptables.

Mathieu *et al.* (2007), basándose en la partición de biomasa de acuerdo a la fuente-demanda, aplicaron el modelo GreenLab, donde observaron que es posible simular el crecimiento y partición de biomasa de las plantas de pepino, ya que simuló con éxito la competencia de asimilación entre órganos y con ello confirmaron la hipótesis de que el crecimiento y el aborto de los frutos depende de la disponibilidad de asimilados. Wiechers *et al.* (2011) al utilizar un modelo estructural-funcional (FSPM) para simular el crecimiento de los frutos de pepino, observaron que el modelo es capaz de simular el crecimiento de los frutos de acuerdo a las variaciones de la arquitectura de la planta, así como de las condiciones ambientales.

Modelos para acumulación de nutrientes

Como se ha manifestado, una producción eficiente de los cultivos depende de un suministro adecuado de los principales nutrientes minerales. Por ello, Dai *et al.* (2011) desarrollaron un modelo para predecir los efectos del N sobre el crecimiento de las hojas, frutos y rendimiento del pepino, en el cual obtuvieron resultados satisfactorios, ya que el modelo logró simular el crecimiento de los frutos y rendimiento bajo diferentes niveles de N y etapas de crecimiento. Gallardo *et al.* (2016) utilizaron el modelo VegSyst para simular la producción diaria de materia seca (DMP), absorción de N y la evapotranspiración de varios cultivos, los autores observaron una alta eficiencia del modelo al simular la DMP en el cultivo de pepino, sin embargo, al simular la absorción de N, este era consistentemente más baja que las observadas.

ARTÍCULO I

The influence of climatic variables on biomass partitioning and uptake of mineral nutrients of a cucumber crop under greenhouse conditions

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Abstract

Due to its benefits, greenhouse production has grown significantly around the world. One of the most highly produced crops under this system is the cucumber. The optimal yield and accumulation of biomass of this vegetable basically depends on the climatic and nutritional conditions during crop development. Therefore, the aim of this study was to determine the influence of climatic variables and mineral absorption levels on cucumber plants under greenhouse conditions. Vitaly and Luxell cucumber varieties were planted in peat moss-perlite substrate (1:1) in a tunnel-type greenhouse. Destructive sampling was performed to determine the dry biomass of each organ of the plant. The concentrations of the nutrient elements N, P, K, Ca, Mg and S in different plant tissues were determined every 10 days. Temperature (to determine the heat units) and radiation measurements were obtained by using instrumentation. The daily water consumption per cucumber plant was assessed to determine the transpiration. The results showed that the climatic variables are significantly correlated with the biomass accumulation and mineral absorption. Low radiation conditions, heat and transpiration units significantly reduced the rate of biomass accumulation and mineral absorption, and consequently, they lowered the cucumber yields.

Key words: *Cucumis sativus*, PAR, temperature, transpiration, macronutrients

1. Introduction

Protected agriculture has grown significantly. Protected agriculture can be defined as an agricultural system that is specialized in soil and climate ecosystem control in which changes to certain conditions (the soil, temperature, solar radiation, wind, humidity and air composition) can be made. The primary objective of production under this system is to provide optimal microclimate conditions for plant growth, development and productivity throughout the year (Ali 2012). Greenhouse production is increasing worldwide, with an estimated 473,466 ha distributed across five continents (Hickman 2016). In Mexico, there are approximately 23,500 ha under protected agriculture (PA), of which approximately 12,000 ha correspond to greenhouses and the rest corresponds primarily to shade houses and macro tunnels (Secretaría de Agricultura, Ganadería, Desarrollo Rural, Pesca y Alimentación 2014).

The cucumber (*Cucumis sativus* L.) stands out as one of the most highly produced crops under greenhouse systems, because it achieves a high yield and quality. In addition, the importance of the cucumber is also related to the way in which it is consumed, since it can be fresh or processed (Lucier and Jerardo 2007). The cucumber yield, like that of other vegetables, is related to the dynamics of plant growth and to the constant accumulation of dry matter; these variables depend on the climatic, nutritional and water conditions (Haque et al. 2009).

Fertigation has been shown to be successful at increasing the water use efficiency and yields in a wide range of crops thanks to its ability to provide small and frequent amounts of water (Rahil and Antonopoulos 2007). However, the success of this method depends on irrigation scheduling, since excessive irrigation reduces yields, while inadequate irrigation causes water stress, which therefore affects the nutrient contribution to the crop. For this reason, practices such as fertilization and irrigation should be defined according to the specific growth characteristics of the crop of interest (Enriquez et al. 2003). In fact, the water requirements vary during the different phases of growth, primarily due to the growth of the crop foliage and the changing conditions of the climate. Zhang et al. (2010) noted that evapotranspiration in cucumbers increases significantly with increasing temperatures, solar radiation and vapor pressure deficits. In addition, the temperature is one of the factors that directly influence the development of each crop stage, such as vegetative development or fruit maturation (Li et al. 2007a, 2007b). Marcelis and Baan Hofman-Eijer (1993) showed that the temperature directly influenced cucumber growth, since it affects the rate of production and the leaf area that forms the plant canopy through which the crop intercepts solar radiation and performs the metabolic processes related to the accumulation of photoassimilates (García and López, 2002). Similarly, Medrano et al. (2005) mentioned that under high and low radiation conditions, the rate of transpiration in cucumber plants, and consequently the inhibition of water and mineral absorption, is reduced.

Accurate knowledge of the developmental stages as well as their interactions with environmental factors are essential to reach the highest yields in cultivated plants, because the developmental stages determine factors such as nutrient absorption and fruit filling that directly affect the productivity of the crop (Prabhakar et al. 2007).

For this reason, the aim of this research is to assess the influence of climatic variables on the accumulation of biomass and mineral absorption in two cucumber cultivars that were grown under greenhouse conditions.

2. Materials and methods

2.1. Greenhouse description

The experiment was performed in a multi-tunnel greenhouse that was oriented from north to south, with an area of 392 m^2, a polyethylene cover (for 25 % shade), and zenith (0.80 * 28 m) and lateral windows (1.30 * 28 m). Whenever air temperature exceeded 24 °C the vents were opened. When air temperature dropped below 18 °C vents were closed. Opening and closing of the windows was performed manually. The greenhouse is located inside the facilities of the Universidad Autónoma Agraria Antonio Narro, Saltillo, Coahuila, México (25°21′N, 101°01′W).

2.2. Development of the cucumber crop

To assess the dynamics of cucumber (*Cucumis sativus* L.) biomass accumulation under protected farming conditions, two crop cycles were established in 2015 and 2016. The first cycle was performed from April 1st to July 7th 2015, and the second cycle was performed from March 1st to June 7th 2016. Vitaly (Syngenta, Basel, Switzerland) and Luxell (Nunhems, Nunhem, The Netherlands) cucumber varieties, which are slicer types, were used for the experiment. These varieties have great performance and quality traits for the export market.

Direct seeding was performed in 4-liter plastic bags containing a mixture of peat moss (pH 6.0, Premier Horticulture Inc. Red Hill, PA, Canada) and perlite (inert and neutral pH, Termolita, Nuevo León, México) as the substrate at a 1:1 ratio (v:v). The seed density was five plants m^{-2}. A directed irrigation system was used for irrigation. The irrigation application was programmed with a timer in which 4 irrigations were established during the day (at 9, 12, 15 and 18 h). Different amounts of irrigation water were applied to correspond to each phenological stage, reaching approximately 2.2 L per plant at the higher consumption stages. The selected crop nutrition was based on the Steiner solution (Steiner 1961), and it was applied at 25, 50 and 100 % according to the following stages of the crop: vegetative 1-20 days after emergence (DAE), flowering (20-30 DAE) and fruiting (30-95 DAE), respectively. The plants were managed on a single stem, the first 4 fruits were removed, and later, one fruit was left for each leaf that developed. The plant growth was limited to 75 days after emergence, and the apical parts were removed at an average height of 3.5 m.

2.3. Measurement of climatic variables

The climatic variables were measured inside the greenhouse during the development of both cultures. For this purpose, sensors were installed at 30 cm below the growth apex and maintained there during crop development. Two photosynthetic active radiation sensor (PAR) (LightScout Quantum Meter 3668I, Spectrum Technologies, Inc., Aurora, IL, USA) and two 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). Data were collected every 15 minutes, and the average of the two sensors was obtained. The heat units (HU) were determined using the simple triangle method in the Degday 2002 program (Snyder 2005), in which the maximum and minimum temperatures of the crop cycle were used (10 and 40 °C).

2.4. Determination of transpiration

To determine the water consumption and transpiration per cucumber plant, 10 randomly chosen pots for each cucumber variety were placed on a container to collect the drained water. To avoid the evaporation of the collected water, the containers along with the lower parts of the pot were covered with black polyethylene. Five out of the 10 pots were covered with white wadding on top to prevent evaporation in the plant. This setup allowed only the measurement of transpiration by the plant. To assess the volume of applied irrigation solution, a vessel connected to the irrigation system collected the drainage water from each pot. On a daily basis, the drained water and the total irrigation water of the applied irrigation were measured after the first irrigation. To determine the evapotranspiration (ET), the volume of drained water (VDW) was subtracted from the total volume of water that was applied via irrigation in the pots without a wadding cover (WAwwc) (Equation 1). To determine the transpired water (TW), the volume of drained water was subtracted from the total volume of water that was applied to the wadding-covered pots (WAwcp) (Equation 2).

$$ET = WAwwc - VDW \tag{1}$$

$$TW = WAwcp - VDW \tag{2}$$

2.5. Biomass partitioning

To determine the biomass accumulation of the crop, destructive sampling was performed every five days, starting from 10 DAE. For this purpose, four plants were taken at random, and they were separated into leaves, stems, fruits and roots to obtain their fresh weights. They were subsequently placed in a drying oven at a constant temperature of 80 °C for 4 days to obtain the dry weight. The prunings and harvested fruits were also quantified to obtain the fresh and dry weights. These results were added to the total leaf and fruit weights.

2.6. Contents of Mineral Elements

The mineral element contents were determined in the leaves, stems, fruits and roots for the first time at 25 DAE and then every 10 days. The micro-Kjeldhal method was used to determine the N content (Muller, 1961). Moreover, the P, K, Ca, Mg and S contents were determined with ICP equipment (Optima 8300 ICP-OES, PerkinElmer, Inc, Waltham, MA, USA).

The mineral extraction of each organ was calculated according to Quesada and Bertsh (2013) from the data on dry weight per plant and mineral concentrations.

$$ME = \frac{CMO * DWO}{100}$$

where ME is the mineral extraction (gram per plant), CMO is the mineral content for each organ (*10 g kg^{-1}) and DWO is the dry weight of each organ of the plant (gram per plant).

2.7. Statistical analysis

To determine the degree of correlation between the different climatic variables, minerals and dry biomass, the Pearson correlation coefficient was obtained. The SigmaPlot 12.0 (Systat Software Inc., San Jose, California, USA) program was used for this purpose. To determine the influence of climatic conditions on transpiration, crop development and uptake of mineral elements (N, P, K, Ca, Mg and S), the data collected in the two years were compared, for this an ANOVA and a mean test (Tukey $P \leq 0.05$) were performed using SAS (SAS Institute, Cary, North Carolina, USA) program V9.1. To this purpose, four plants were taken at random at the end of each crop, considering one plant as one replicate. Completely randomized design was used, and the treatments were the year of cultivation.

3. Results

3.1. *Plant Responses to Climatic Conditions*

During the 2015 cycle, a total of 1358 heat units and 2744.7 mol m^{-2} of accumulated PAR were obtained. However, during the 2016 cycle, there were reductions of 10.9 % and 18.5 %, respectively. For both cycles, harvesting began when 750 heat units were reached (60 DAE for the 2015 cycle and 70 DAE for 2016) (Table 1).

Regarding transpiration, a reduction was found during the 2016 cycle in comparison to the 2015 cycle (Table 1). At 25 DAE, transpiration rate decreases of 78 % and 80 % were observed in the Vitaly and Luxell varieties, respectively, compared to the 2015 cycle. When the volume of transpired water was added at the end of the 2016 crop cycle, significant reductions ($P \leq 0.05$) of 6.16 % and 5.5 % were found in these varieties, respectively, compared to the 2015 cycle (Table 4).

3.2. *Growth Analysis*

The rate of dry biomass accumulation for each organ in Vitaly variety cucumber plants during the 2015 (a) and 2016 (b) were different (Figure 1). The accumulation of total biomass was higher in 2015 cycle, yielding up to 71.4 g of total dry biomass at 45 DAE. Conversely, the total accumulated biomass during the 2016 cycle was 64.5 % less over the same number of DAE. The fruiting began at 45 DAE during the 2015 cycle and for the second cycle at 55 DAE (at 531 HU); moreover, the harvest began at 740 HU (60 and 70 DAE) (Figure 1). At 75 DAE, when the apical part was removed, 46 % less total biomass was observed in the second cycle than in the first one. At the end of the 2016 cycle, 310 g of total biomass plant was reached, or 15 % less biomass than the 2015 cycle.

The same trend was observed in the Luxell variety (Figure 2), since 70 g of accumulated total biomass was obtained at 45 DAE of the first cycle. However, during the 2016 cycle, the total biomass was 62 % less than that of the 2015 cycle. The beginning of the fruiting appeared at 531 heat units during the 2015 cycle (45

DAE); however, for the 2016 cycle, fruiting appeared at 55 DAE. At the end of the 2016 cycle, an average of 295 g of total accumulated biomass per plant was obtained, which was 26.9 % less than that found during the first cycle (404 gram per plant).

The total dry biomass obtained at the end of the 2015 and 2016 cycle represented 4.33 % and 4.52 % of the total fresh weights in the Vitaly variety. However, Luxell reached 4.44 % and 4.53 % of the total fresh weight. The highest amount of biomass was distributed in the fruits, followed by the leaves, stems and roots, in both varieties. The Vitaly variety accumulated average total dry biomasses for the 2015 and 2016 cycles of 69.7 % and 74.9 % in the fruits, 21.5 % and 17.5 % in the leaves, 7.4 % and 6.5 % in the stems, and 1.3 % and 1.2 % in the roots, respectively. Similar percentages were observed in the Luxell variety, at 70.3 % and 73.1 % in the fruits, 20.7 % and 18.1 % in the leaves, 7.9 % and 7.3 % in the stems, and 1.1 % and 1.3 % in roots for the cycles 2015 and 2016 (Figure 2).

During the 2015 production cycle, average yields of 7.586 and 7.349 gram per plant were obtained in the Vitaly and Luxell varieties, respectively (Figure 3). However, during the 2016 cycle, the yields were significant reduced ($P \leq 0.05$) by 16.7 % and 11.4 %, respectively, in the two varieties (Table 4).

3.3. *Absorption of Mineral Elements*

The correlation matrices obtained for the PAR, heat units, transpiration, biomass and mineral elements (N, P, K, Ca, Mg and S) during the 2015 and 2016 cycles have a highly significant correlation (Pearson, $P \leq 0.01$) (Table 2). Based on this finding, it can be surmised that the reduction in the biomass accumulation rate and mineral absorption found in both varieties during the 2016 cycle occurred because they basically depend on the climate characteristics, since they are significantly correlated.

3.3.1. *Nitrogen*

The highest accumulation of N appeared in the fruits, with 60.3 and 70.3 % in the Vitaly variety and 60.2 and 71.2 % in the Luxell variety out of the total accumulated by the plants during the 2015 and 2016 cycles, respectively (Figure 4a, b and 5a, b). Vitaly variety leaves absorbed 30.8 and 23.6 %, stems absorbed 6.1 and 5.3 % and roots absorbed 1.2 and 1 % of the total N for the two cycles (2015 and 2016), respectively. Regarding the Luxell variety, the leaves accumulated 27.9 and 20 %, stems 9.1 and 6.2 % and roots 1 and 0.8 % of the total absorbed nitrogen. The total nitrogen accumulation between cycles and varieties was not significantly different ($P \leq 0.05$) (Table 4).

3.3.2. Phosphorus

As with N, P accumulated primarily in the fruits, with 65.2 and 83.4 % for the Vitaly variety, 75 % and 87.2 % for the Luxell variety during the 2015 and 2016 cycles, respectively (Figures 4c, d and 5c, d). The leaves were 27 and 10 %, stems 7 and 5.7 % and roots 0.72 and 1 % in the Vitaly variety during the 2015 and 2016 cycles, respectively (Figures 4c, d). In the Luxell variety, 18.2 and 5.4 % were found in the leaves, 6 and 5.9 % in the stems, and 0.7 and 2.2 % in the roots during the 2015 and 2016 cycles, respectively (Figure 5c, d).

The accumulated levels of P at 55 DAE were lower during the 2016 cycle than in 2015, at 60 and 68 % less accumulated P for the Vitaly and Luxell varieties, respectively. At the end of both cycles, 1.2 and 1.1 gram per plant of P in the Vitaly variety were reached and there were 1 and 0.9 gram per plant of P for the Luxell variety. However, the total phosphorus accumulation between cycles and varieties was not significantly different ($P \leq 0.05$) (Table 4).

3.3.3. Potassium

Like N and P, K was primarily concentrated in the fruits with 82 and 80.4 % in the Vitaly variety, and 82.5 % and 83.5 % in the Luxell variety out of the total K absorbed by the plants during the 2015 and 2016 cycles, respectively (Figures 4e, f and 5e, f). Regarding the Vitaly variety, 10.6 and 13.7 % were found in the leaves, 7.6 and 5.1 % in the stems, and 0.34 and 0.40 % in the roots out of the total K accumulated during the 2015 and 2016 cycles, respectively. In the Luxell variety, 7.2 and 9.6 % were found in the leaves, 9.8 and 4.6 % in the stems and 0.31 and 0.99 % in the roots of the total K accumulated during the 2015 and 2016 cycles, respectively (Figures 4e, f and 5e, f).

The accumulations of potassium by Vitaly and Luxell varieties at 55 DAE were 3.59 and 4.2 gram per plant during the 2015 cycle. However, during the 2016 cycle at the same DAE, 71 and 82 % less accumulation were observed, respectively. At the end of both cycles, the behavior was different from that of N and P, since significant reductions ($P \leq 0.05$) of 37.5 and 45 % K were found in the Vitaly and Luxell varieties respectively (Table 4). The total accumulations of K during the 2015 cycle were 7.5 and 8.1 gram per plant for both cucumber varieties.

3.3.4. Calcium

Unlike N, P and K, the highest Ca concentration was present in the leaves at averages of 91 and 70 %, followed by 3.2 and 24.6 % in the fruits, 5.25 and 4 % in the stems and 0.71 and 0.6 % in the roots in the Vitaly variety during the 2015 and 2016 cycles, respectively (Figure 4 g, h). The distribution of Ca in the Luxell variety was 71 and 36 % in the leaves, 23.8 and 58 % in the fruits, 4.4 and 3.9 % in the stems and 0.6 and 1 % in the roots during the 2015 and 2016 cycles, respectively (Figure 5 g, h). The total calcium accumulation at the end of the 2016 cycle was significantly different compared to that of the 2015 cycle (Table 4). During the 2016 cycle, 72 and 68 % less calcium was accumulated in cvs. Vítaly and Luxell, respectively (Figures 4 g, h and 5 g, h).

3.3.5. Magnesium

The highest accumulation of Mg was found in the leaves (54.5 and 36 %), and then in the fruits (34.7 and 56.8 %) in the Vitaly variety. However, the Luxell variety accumulated 29.8 and 16.5 % in the leaves and 58.6 and 78.7 % in the fruits during the 2015 and 2016 cycles, respectively (Figure 4i, j and 5i, j). The Mg concentrations for the Vitaly variety in the stems were 9.4 and 5.4 % and 1.06 and 1.01 % in the roots. Regarding the Luxell variety, 10.5 and 3.04 % were found in the stems, and 0.7 and 1.6 % were in the roots during the 2015 and 2016 cycles, respectively. During the 2016 cycle, significant reductions ($P \leq 0.05$) of 57 and 55.4 % were observed in the Mg uptake at the end of the cycle in Vitaly and Luxell, respectively, based on the 2015 cycle (Table 4).

3.3.6. Sulfur

The distribution of S, like that of Ca and Mg, is mostly in the leaves at 44.8 and 35 %, the fruits at 47 and 65 %, the stems at 4.4 and 3.6 % and the roots at 3.3 and 1.13 % in the Vitaly variety. The Luxell variety presented 47.4 and 9.3 % in the leaves, 47 and 86.7 % in the fruits, 4.3 and 2.5 % in the stems, and 1.19 and 1.39 % in the roots during the 2015 and 2016 cycles, respectively (Figures 4 k, l and 5 k, l). During the 2015 cycle, 0.82 and 0.98 gram per plant were obtained at the end of the cycle in the Vitaly and Luxell varieties, respectively. However, during the 2016 cycle, this amount was significant reduced ($P \leq 0.05$) to 52 and 41 % (Figure 4 k, l and 5 k, l) (Table 4).

4. Discussion

4.1. Growth Analysis

Photosynthesis depends on several internal and external factors. The internal factors are the characteristics of the leaf (the structure and chlorophyll content) and the availability of water, nutrients and enzymes. However, external factors include the incidence of radiation on the leaves (the quantity and quality), temperature, humidity and CO_2 concentration (Baker 1996; Li et al. 2013). In particular, the PAR influences the photosynthetic activity, the production of dry matter and the crop yield (Rao and Mittra 1998), making it a very important variable for cucumber cultivation. Some authors mention that with a lower PAR, the photosynthetic activity is lower, and therefore, the accumulation of biomass and the cucumber plant yields are reduced (Alsadon et al. 2016; Krizek 2004;

Haque et al. 2009). This explains the biomass and yield results obtained during the 2016 cycle, with significant decreases of 15 % and 26.9 % in biomass and 16 % and 11 % in yield for the Vitaly and Luxell, varieties respectively (Table 4), while the PAR decreased by 18.5 % (Table 1).

The energy required for water evaporation basically comes from solar radiation (Castilla, 2013). Therefore, a reduction in radiation leads to a reduction in the transpiration process in the same proportion, because the transpiration rate changes linearly with the radiation (Sonneveld, 2002). Moreover, the transpiration rate is directly influenced by the incidence of solar radiation as well as the temperature, humidity and wind speed (Stanghellini, 1987). Therefore, with low temperature and radiation, the rate of transpiration is reduced (Yang et al. 1990), which explains the reduction in transpiration during the 2016 cycle (Table 4).

Transpiration is a key process for plant cooling. The dynamics of this process can determine the maximum efficiency for performing photosynthesis. Also affect the efficiency at which nutrients are introduced into the plant and how these products are distributed during plant growth. An increase in the transpiration rate can improve the absorption and translocation of the elements through the xylem (Campbell and Norman 2000; White 2012). This fact explains the differences observed here in the accumulation of mineral elements (K, Ca, Mg and S) on cucumber plants (Table 4).

The dynamics of biomass accumulation in crops is determined primarily by environmental factors, in which the temperature is one of the most influential factors in this process. This is because the temperature has a direct impact during the photosynthetic process, as in the chloroplasts, electron transport, carbon reduction cycle and the control of the stomatal conductance (Lambers et al. 2008). Exposure to sub or supra-optimal temperatures leads to a lower assimilation of CO_2 that could be attributed to stomatal factors, photoinhibition, changes in transcription, and the expression of enzymes related to photosynthesis (Allen and Ort 2001; Yamori et al. 2012). This fact was demonstrated here, the total accumulated biomass was different in both cycles (2015 and 2016), probably due to changes in temperature and PAR. The dry biomass distribution data found here are similar to those reported by Marcelis (1992a) for cucumber plants. The highest accumulation of biomass in the fruits is because they are the organs with the highest demand, and their growth potential basically depends on the environmental conditions (Marcelis 1992b). Marcelis (1993) mentioned that after an extended period of high radiation levels, the number of fruits per plant increases, and as a result, there is a greater distribution of biomass in the fruits. This finding is consistent with the highest percentage of biomass distribution found in the fruits of both cucumber varieties during the 2015 and 2016 cycles (Figures 1 and 2).

During the early stages of cucumber development, the rate of biomass accumulation was relatively slow due to the small leaf area and interception of light; however, this rate increased proportionally as the leaf area increased. In addition, due to the low accumulation of heat and radiation units (Table 1), the accumulation of dry biomass is reduced (Alsadon et al. 2016), as observed in the 2016 cycle (Figures 1 and 2).

Fruit set began at 531 HU as mentioned Perry and Wehner (1996). Moreover, the harvest began at 745 HU, as mentioned Perry and Wehner (1990). The variation observed in the days to harvest was due to the variations in temperatures and the characteristics of the chosen varieties (Wehner y Guner 2004).

Challa et al. (1995) and Papadopoulos and Hao (2000) mentioned that plant growth and fruit yield in cucumbers decrease with reduced PAR and temperature levels. The reduction of heat units (10.9 %) and PAR (18.5 %) during the 2016 cycle compared to the 2015 cycle (Table 1) explains the significant yield reduction observed during the 2016 cycle (Figure 3). These results were also consistent with those reported by Haque et al. (2009), and 75, 50 and 25 % of the total PAR levels were reduced to 67, 18 and 10 %, respectively.

4.2. Nutrient Absorption

The nutritional status of the plants, the growth rate, transpiration rate and root growth are factors that correlate and interact with the temperature (Barber 1984), as was in this work (Table 2). Moreover, mineral extractions change in each organ (Figures 4 and 5), primarily because of the mineral mobility and mineral demand of the organs during the development of the plants, as well as by the influence of the climate (White 2012; Quesada and Bertsh 2013).

Nitrogen is a highly mobile element, so translocation occurs from the leaves and stems to the fruits in formation (Barker and Bryson 2007; Tanemura et al. 2008). As the biomass of the fruits increases (as observed in both cucumber varieties, Figures 4 and 5) the N translocation to this organ occurs at a greater percentage (Tanemura et al. 2008). The results found for the N mobility to fruits are similar to those reported by Fukutoku et al. (2000). They mentioned that 76 % of the absorbed nitrogen was distributed to melon fruits. Besides, Tanemura et al. (2008) found 74 % of the nitrogen concentration was distributed to the cucumber fruits. In addition, the rate of N uptake is affected by factors such as the balance with other nutrients, the water supply and the temperature (Barker and Bryson 2007). The accumulated lower levels of N at 55 DAE during the 2016 cycle compared to 2015 (Figures 4 and 5) was because during this stage, 20 % less HU was found (Table 1). Therefore, upon observing a low HU accumulation during 2016, the N uptake was also reduced.

Regarding phosphorus, it has been reported that the average concentration in the tissue varies from 0.1 % to 1 % (Sánchez 2007). The optimal ranges of P in developed cucumber leaves vary from 0.3 % to 0.7 % (Mills et al. 1996). According to the data obtained here, the phosphorus levels are within the sufficiency range (Table 3). P is considered as a mobile element, and thus it moved from the young leaves to the fruits (Sánchez 2007), it explains that the higher accumulation of this element is in the fruits (Figures 4c, d and 5c, d). The lower accumulated levels of P observed during the 2016 cycle for both varieties, was because the HU values were lower than those observed in the 2015 cycle (Table 1). This resulting in a decrease in the temperature of the same magnitude in the substrate (Islam et al.

2015), which in turn decreases the accumulation of P in a linear fashion (Klock et al. 1996).

K is also considered as a highly mobile element and is therefore translocated to developing fruits (Mengel 2007), causing its accumulation. The optimal levels of K in fully developed cucumber leaves are 3.5 % to 4.5 % (Maynard and Hochmuth 2007). The results obtained in this work appear to be low (Table 3). However, these levels did not adversely affect the biomass production of the cucumber crop. K absorption, as with that of N and P, is also reduced at a low temperature (Tachibana 1987; Qiuyan et al. 2012). This effect is the same as that observed in this study; the decrease in heat units (Table 1) caused a decrease in the accumulation of K (Table 4).

The calcium accumulation observed in this work was consistent with that reported by De Freitas et al. (2011). They mentioned that the Ca content is usually lower in tomato fruits. There is a high accumulation of Ca in the leaves and a low accumulation in the fruits (Figures 4g, h and 5g, h). This nutrient is transported through the xylem by transpired water, and because the transpiration rate of the fruits is very low compared to that of the leaves, it results in these differences (Suzuki et al. 2015). As observed, the Ca levels obtained here were within the optimal sufficiency range (Table 3), which should be 1.2 to 1.5 % according to Maynard and Hochmuth (2007). The accumulation of Ca basically depends on the soil solution availability and transpiration rate; therefore, as the transpiration flow rises, the Ca mobility increases and vice versa (Jones 2005). The temperature and radiation strongly affect the Ca absorption also; that is, when the temperature and the radiation levels are low, the transpiration rate is reduced (Sonneveld and Voogt 2009). Therefore, the decrease in the transpiration rate observed during the 2016 cycle (Table 1) explains the reduction of 64.5 and 73 % in Ca accumulation for the two cucumber varieties (Figures 4 g, h and 5 g, h). Lorenzo et al. (2003) also reported this effect when applying shading to tomato plants. Adams (1988) mentioned that when increasing the temperature from 14 to 25 °C in the root zone of the tomato plants, the Ca absorption goes higher.

Besides, when there are low temperatures, the Ca absorption is reduced in pepper plants (Benoit and Ceustermans 2001).

Grzebisz (2015) mentioned that the amount of Mg reaching the surface of the shoot was due to the following two factors: the transpiration rate and the accumulation of Mg in the solution. Therefore, the decrease in the Mg uptake is attributed to the reduction of the transpiration rate obtained during the 2016 cycle (Table 4). The higher concentration of Mg in the leaves occurs because this element is part of the chlorophyll molecule, making up between 15 and 30 %. In addition, the remaining 70 to 85 % of this element played a very important role as a cofactor of several enzymatic processes and receptor proteins. It plays a role in protein stabilization and DNA and RNA configuration (Jones 2005; Merhaut 2007). According to the Mg concentration based on the dry biomass (Table 3), it is within the optimal range of sufficiency, which is 0.45 to 75 % (Maynard and Hochmuth 2007).

Sulfur is a component of essential amino acids such as cysteine and methionine, and it is present in all proteins. It is also a component of ferredoxin and therefore participates in photosynthesis, N_2 fixation and nitrate reduction (Mills et al. 1996). Sulfur is absorbed from the root, then charged to the xylem vessels and finally transported to the aerial part through transpiration. Therefore, by reducing the transpiration, the absorption levels are reduced (Haneklaus et al. 2007), which is an effect that was observed during the 2016 cycle (Table 3). In addition, S is a precursor for the synthesis of glutathione (GSH). This compound is usually higher in leaves (50 %) because it is located in chloroplasts where it participates as an antioxidant (Rennenberg et al. 1990). Besides, the major proportion of sulfur is present in reduced form in cysteine and methionine (Haneklaus et al. 2007). Therefore the sulfur is present in the organs of major growth as leafs and fruits.

5. Conclusions

Heat units, PAR and transpiration are variables that significantly influence the biomass accumulation rate and mineral absorption and thereby influence the cucumber yields of the Vitaly and Luxell varieties. Therefore, it is essential to know the behavior, and, if necessary, to control the climatic variables inside the greenhouse to obtain optimum yields.

As the temperature and PAR decreased, the rate of transpiration was reduced proportionally, so the rates of biomass accumulation and uptake of mineral elements also decreased.

Mineral element accumulation is dynamic and depends on climatic conditions as well as biomass accumulation in plants; however, it is greatly correlated to these conditions.

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Table 1. Behavior of Heat Units, PAR and transpiration accumulated during the greenhouse production 2015 and 2016 cycles, in cucumber Vitaly and Luxell varieties.

	Cycle 2015				Cycle 2016			
DAE	HU (°C)	PAR (Mol m^{-2})	TVit (ml/plant)	TLux (ml/plant)	HU	PAR (Mol m^{-2})	TVit (ml/plant)	TLux (ml/plant)
25	242	670	2717	2669	164	424	574	524
35	378	1030	8684	9007	284	730	2841	2773
45	531	1358	15292	15935	435	1012	8234	7611
55	688	1685	23502	24311	574	1297	13539	13035
65	835	2011	33719	34070	710	1560	25551	26318
75	1004	2287	45921	44532	867	1803	40355	40534
85	1173	2498	55215	52296	1049	2061	52912	52487
95	1359	2745	63843	61300	1209	2235	61431	60633

DAE: Days After Emergence, HU: Heat Units, PAR: Photosynthetically Active Radiation, TVit: transpiration Vitaly, TLux: Transpiration Luxell.

Table 2. Matrix of correlations between climatic and mineral variables.

		Bio		Tras		HU		PAR		N		P		K		Ca		Mg		S	
		15	16	15	16	15	16	15	16	15	16	15	16	15	16	15	16	15	16	15	16
Bio	V	1	1	0.999	0.98	0.995	0.966	0.985	0.936	0.975	0.995	0.971	0.83	0.967	0.993	0.99	0.97	0.981	0.992	0.988	0.988
	L	1	1	0.994	0.99	0.993	0.968	0.975	0.937	0.979	0.994	0.931	0.982	0.911	0.967	0.95	0.95	0.977	0.972	0.984	0.990
Tras	V			1	1	0.997	0.986	0.986	0.966	0.973	0.989	0.966	0.822	0.962	0.984	0.99	0.98	0.978	0.986	0.986	0.989
	L			1	1	0.999	0.986	0.991	0.966	0.985	0.997	0.952	0.988	0.938	0.984	0.97	0.97	0.986	0.990	0.980	0.987
UT	V					1	1	0.992	0.994	0.981	0.97	0.949	0.824	0.954	0.965	0.98	0.96	0.974	0.977	0.981	0.986
	L					1	1	0.992	0.994	0.987	0.977	0.936	0.959	0.928	0.961	0.96	0.96	0.982	0.976	0.984	0.969
PAR	V							1	1	0.991	0.938	0.947	0.832	0.964	0.939	0.97	0.94	0.981	0.955	0.980	0.970
	L							1	1	0.991	0.951	0.946	0.932	0.955	0.946	0.97	0.95	0.987	0.964	0.975	0.939
N	V									1	1	0.942	0.804	0.964	0.989	0.96	0.97	0.979	0.99	0.983	0.982
	L									1	1	0.93	0.991	0.947	0.979	0.96	0.97	0.992	0.983	0.992	0.988
P	V											1	1	0.988	0.875	0.99	0.9	0.984	0.873	0.981	0.859
	L											1	1	0.969	0.992	0.99	0.99	0.964	0.99	0.902	0.969
K	V													1	1	0.98	0.99	0.987	0.998	0.985	0.988
	L													1	1	0.97	1	0.971	0.998	0.908	0.951
Ca	V															1	1	0.991	0.992	0.985	0.975
	L															1	1	0.979	0.995	0.937	0.933
Mg	V																	1	1	0.987	0.991
	L																	1	1	0.98	0.961
S	V																			1	1
	L																			1	1

15 and 16 correspond to cycles of cucumber cultivation (cycle 2015 and 2016). V and L corresponds to cultivated varieties (Vitaly and Luxell variety). The correlation coefficients presented are highly significant (Pearson, P ≤ 0.01). Bio: Biomass, Trans: Transpiration, HU: Heat Units, PAR: Photosynthetically active radiation.

Table 3. Concentration percentages based on the dry matter of N, P, K, Ca, Mg and S in cucumber plants for Vitaly and Luxel varieties during the 2015 and 2016 production cycles. DAE: Days After Emergency.

		N (%)		**P (%)**		**K (%)**		**Ca (%)**		**Mg (%)**		**S (%)**	
	DAE	**2015**	**2016**	**2015**	**2016**	**2015**	**2016**	**2015**	**2016**	**2015**	**2016**	**2015**	**2016**
Vitaly	25	2.77	4.14	0.24	0.46	1.88	2.4	1.5	0.94	0.27	0.42	0.27	0.19
	35	3.77	3.47	0.2	0.39	2.36	2.23	2.08	1.19	0.41	0.47	0.4	0.31
	45	3.39	3.45	0.15	0.53	2.53	2.7	1.59	1.88	0.31	0.51	0.27	0.35
	55	3.9	3.14	0.3	0.28	2.7	1.35	1.49	0.62	0.44	0.22	0.33	0.15
	65	2.88	2.55	0.35	0.29	2.29	1.44	1.98	0.58	0.44	0.19	0.26	0.18
	75	2.5	3.29	0.34	0.43	2.01	1.86	1.97	0.95	0.43	0.23	0.29	0.15
	85	2.41	2.68	0.38	0.38	2.13	1.66	1.74	0.56	0.35	0.19	0.28	0.13
	95	2.23	2.95	0.33	0.37	2.08	1.48	1.56	0.49	0.33	0.17	0.24	0.12
Luxell	25	2.94	4.32	0.29	0.45	2.03	2.3	1.71	1.13	0.31	0.45	0.24	0.22
	35	4.08	4.29	0.25	0.42	2.64	2.19	1.74	1.33	0.33	0.46	0.24	0.26
	45	3.59	4.05	0.14	0.56	2.91	2.69	1.65	1.77	0.34	0.51	0.28	0.3
	55	3.18	3.57	0.32	0.25	3.12	1.18	2.43	0.62	0.49	0.2	0.4	0.12
	65	3.03	3.24	0.39	0.32	2.81	1.74	2.19	0.74	0.48	0.25	0.34	0.2
	75	2.61	3.46	0.37	0.4	2.6	2.51	2.05	1.04	0.41	0.3	0.3	0.15
	85	2.34	2.77	0.33	0.33	2.44	1.72	1.89	0.71	0.38	0.21	0.27	0.14
	95	2.31	2.74	0.26	0.31	2.0	1.5	1.47	0.62	0.34	0.19	0.24	0.2

Table 4. Comparison of means of transpiration, biomass and total yield, as well as the minerals (N, P, K, Ca, Mg and S) obtained during the 2015 and 2016 cycles in Vítaly and Luxell variety cucumber plants.

Vítaly									
	Transpiration (ml/plant)	Biomass (g/plant)	Total Yield (g/plant)	N (g/plant)	P (g/plant)	K (g/plant)	Ca (g/plant)	Mg (g/plant)	S (g/plant)
2015	65691 a^z	365.39 a	7592.4 a	8.11 a	1.21 a	7.51 a	4.54 a	1.1391 a	0.826 a
2016	61638 b	310.95 b	6337.5 b	9.10 a	1.16 a	4.69 b	1.61 b	0.626 b	0.396 b
V.C. %	4.11*	17.3*	11.01*	12.29 ns	21.8 ns	3.67*	12.5*	16.92*	17.62*
Luxell									
	Transpiration (ml/plant)	Biomass (g/plant)	Total Yield (g/plant)	N (g/plant)	P (g/plant)	K (g/plant)	Ca (g/plant)	Mg (g/plant)	S (g/plant)
2015	64168 a	404.93 a	7369 a	8.95 a	1.06 a	8.11a	5.93 a	1.38 a	0.98 a
2016	60633 b	294.24 b	6511.3 b	8.09 a	0.89 a	4.41 b	1.58 b	0.54 b	0.57 b
V.C. %	4.56*	8.35*	14.5*	6.28 ns	21.29 ns	10.05*	19.1*	8.51*	9.07*

ns: not significant, *: significanse at *P≤0.05*, V.C.: variation coefficient, z In columns values with different letter are statistically different as Tukey at *P≤0.05.*

Figure 1. Behavior of accumulated biomass in each organ in cucumber plants for Vitaly variety during the production cycles 2015 (a) and 2016 (b).

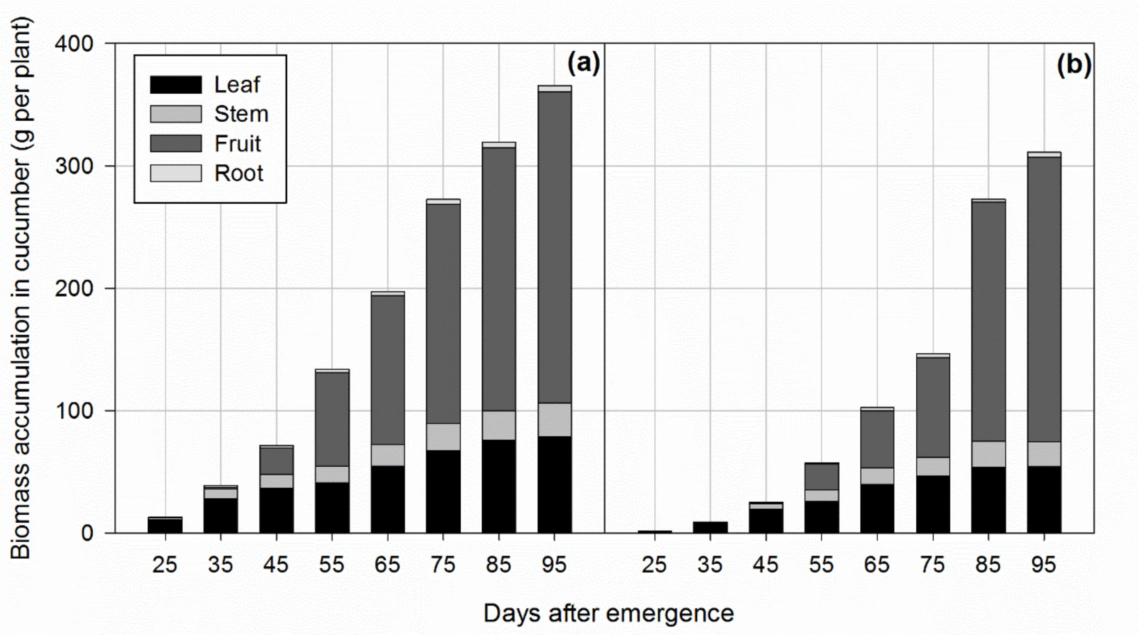
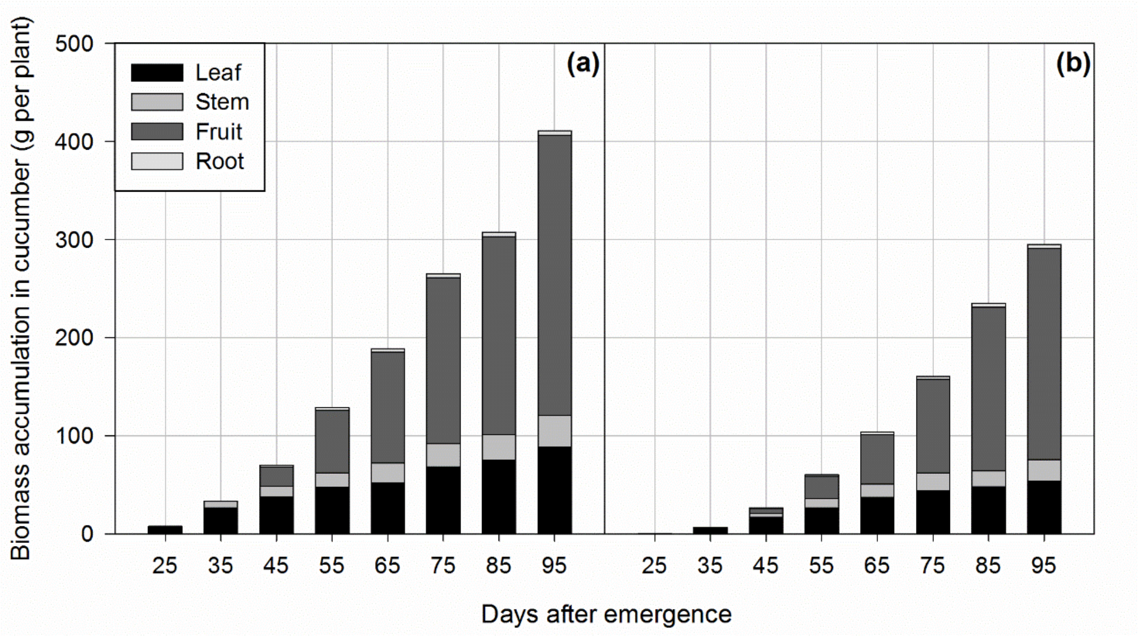


Figure 2. Behavior of accumulated biomass in each organ in cucumber plants for Luxell variety during the production cycles 2015 (a) and 2016 (b).



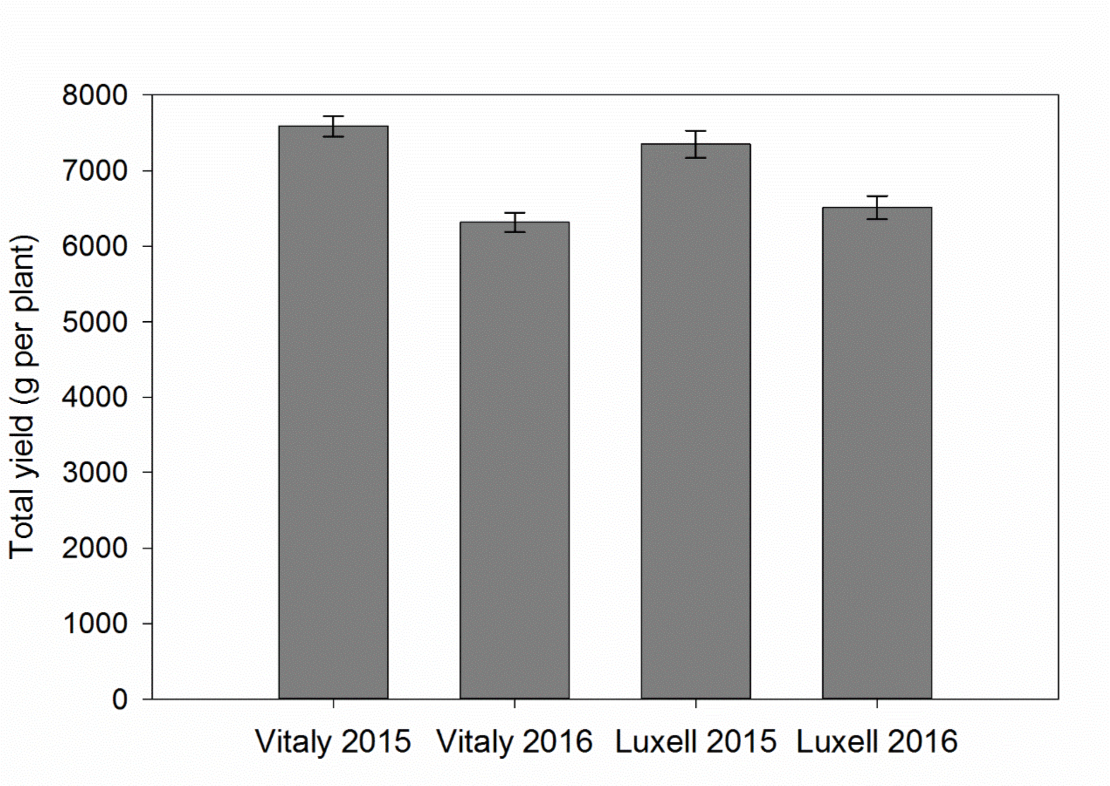


Figure 3. Yield for cucumber plants Vitaly and Luxell varieties, during the 2015 and 2016 production cycles. Each bar represents an average of 40 plants ± standard error**.**

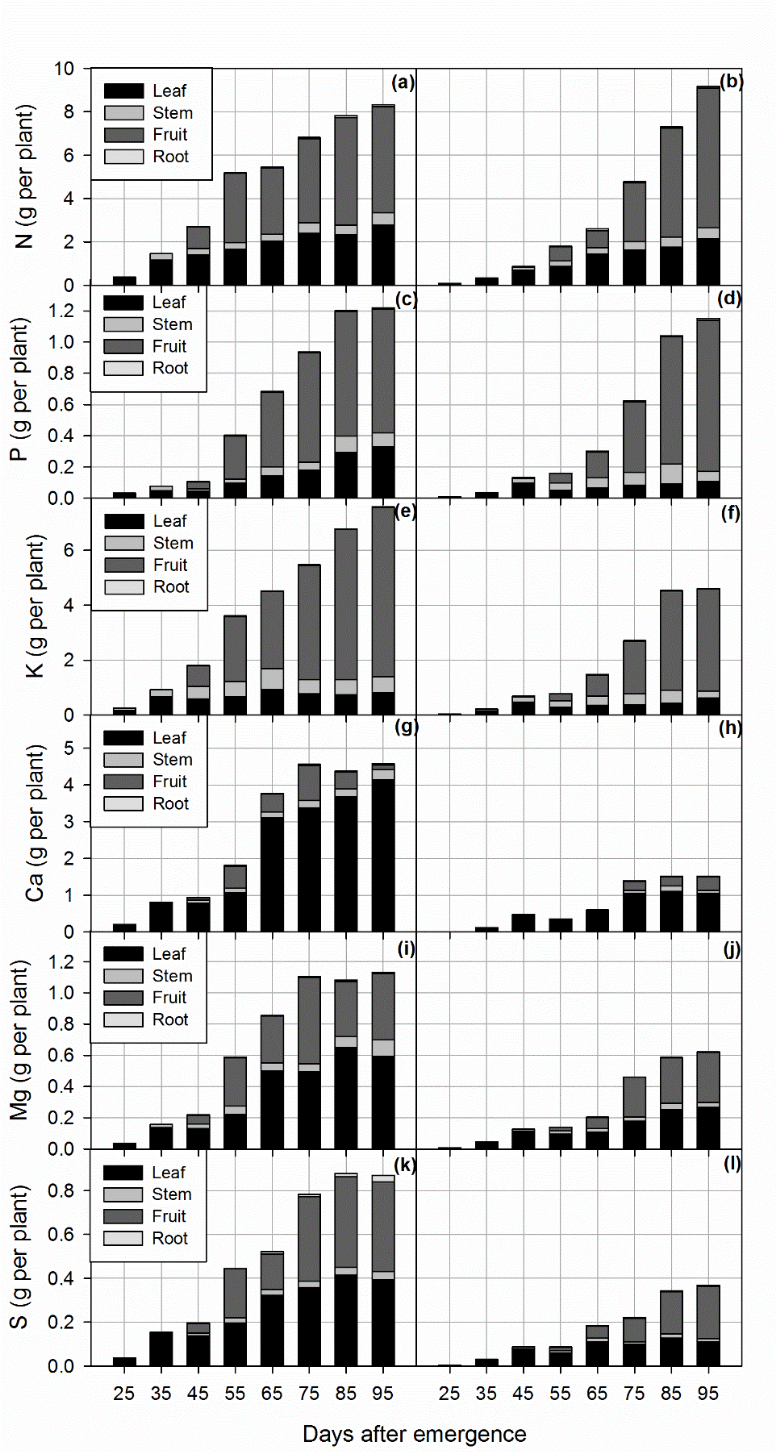


Figure 4 Accumulation rate of N, P, K, Ca, Mg and S by organ in cucumber plants for Vitaly variety during the 2015 cycle (a, c, e, g, i, k) and 2016 (b, d, f, h, j, l). Each bar represents the average of 4 replicates.

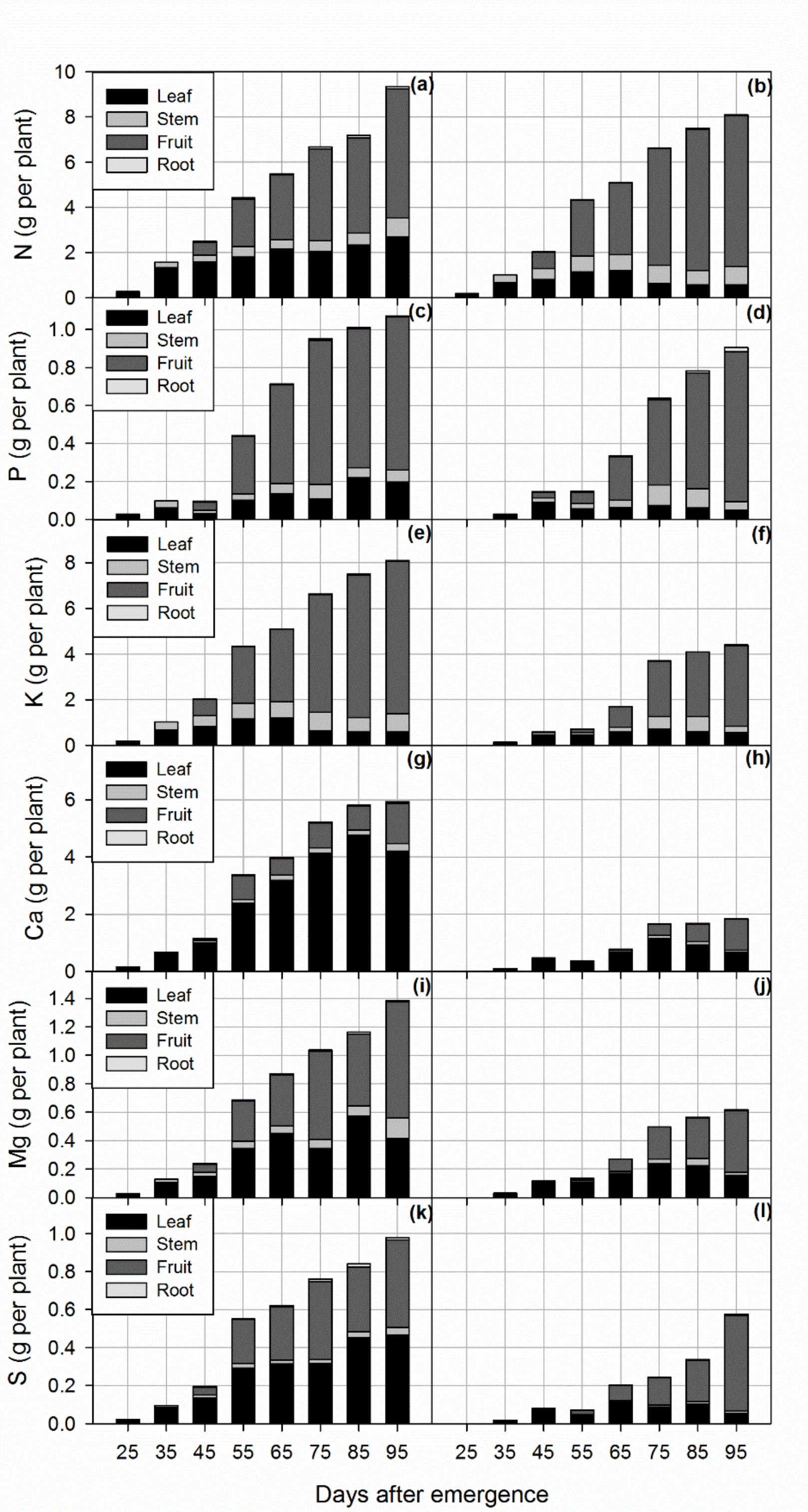


Figure 5 Accumulation rate of N, P, K, Ca, Mg and S by organ in cucumber plants for Luxell variety during the 2015 cycle (a, c, e, g, i, k) and 2016 (b, d, f, h, j, l). Each bar represents the average of 4 replicates.

ARTÍCULO II

Dynamic modeling of cucumber crop growth and uptake of N, P and K under greenhouse conditions

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Abstract

One of the available tools used to increase the productivity of crops is the mathematical modeling. This allows us to design management strategies without the need for expensive experiments; however, this technology has been applied mainly to tomato under greenhouse conditions. For other crops, there is not enough information available. As to generate the necessary information for the calibration and validation of a dynamic growth and mineral absorption model –originally implemented in tomato cultivation– two cycles of cucumber (Vitaly and Luxell varieties) were carried out mainly because cucumber stands out as one of the crops that is mostly grown under greenhouse conditions. Mineral analyzes (N, P and K) were performed to determine their behavior in the different cucumber organs during the development of the crop. The percentages of minerals contained in each organ and in the whole plant were obtained. These percentages were included in the mathematical model in order to dynamically simulate their behavior. The results show that the growth model output adequately simulates leaf and fruit weight (*EF* >0.95 and *Index* >0.95), as well as indices above 0.95 for harvested fruit and leaves. Regarding minerals, indices above 0.90 were obtained, where N was the element that showed the lowest indices during the validation process of the model (0.90). This model can be useful to define adequate nutrition strategies for Vitaly and Luxell cucumber varieties.

Keywords: Mathematical modeling, *Cucumis sativus* L., simulation, macronutrient.

1. Introduction

Production under greenhouses is increasing worldwide, with an estimated of 489,214 ha distributed across five continents (Hickman, 2017). In Mexico, there are about 25,814 ha under protected agriculture, where approximately 65% are greenhouses and the rest are shade houses and macro tunnels (SIAP, 2016). The production of crops under greenhouse conditions gives advantages as food safety, quality and more yields. However, when not exist an adequate management, problems as excessive nutrition could appear (He et al., 2008), excess fertilizer is released to environment, causing ecological problems (Gollany et al., 2004; Beman et al., 2005; Marcelis, 2005; Du et al., 2014; Cao et al., 2015). For example, N fertilizer applications can contribute to a supply of N that exceeds crop requirements, this can be resulting in NO_3^- contamination of water bodies (Thompson et al., 2017). Therefore, is very important to optimize the use of fertilizers in crop production, this will diminish environmental risks and maintained the adequate yield. To achieve this, it is necessary to know the nutrient demand for crops.

The cucumber (*Cucumis sativus* L.) is one of the most produced crops under greenhouse, as it achieves a higher yield and quality. In addition, the importance of cucumber also lies in its form of consumption, since it can be fresh or industrialized (USDA, 2017). Cucumber cultivation presents a non-uniform growth pattern in which periods of high fruiting and slow growth of the fruit, alternate with periods of poor fruit fixation and fast fruit growth (Heuvelink, 1996; Wubs et al., 2009). This is due to source/sink relationship (Marcelis et al., 1998), hormonal regulation (Bangerth et al., 2000), environmental factors (Kahlen, 2007) and canopy architecture. Therefore, to predict the cucumber crop growth has been the subject of several researches. Mathematical modeling has contributed to optimization of management and increasing cucumber crop yield (Bar-Yosef et al., 2004). In recent years, have been developed several models to predict the crop growth (Heuvelink, 1999; Boote et al., 2002; Liu et al., 2007), crop yield (López et al., 2008) and harvest stage (Wurr et al., 1988, Marcelis y Gijzen, 1998) under greenhouse conditions. In crop growth have been applied models that include physiological and morphological process to simulate the crop growth. For example, functional structural models (FSPMs) (Wiechers et al. 2011), and others that include light quantity to estimate the final length of cucumber internodes (Kahlen et al., 2011). Have been reported model to determine N demand depending of fruit growth and cucumber yield (Dai et al., 2011). Other authors calibrated and validated the EU-Rotate N model in cucumber crop, with this determine the water movement and fate of N (Guo et al., 2010; Sun et al., 2012). Gallardo et al. (2016), use the VegSyst model to calculate the dry matter production and N uptake in cucumber crop, however, do not consider anymore nutrients. Zhang et al. (2015) described a dynamic model to evaluate the effects of N, P and K on yield of four crops in open field conditions, therefore, the main inputs of the model were daily rainfall, pan evaporation and temperature. This model is not applicable to greenhouse conditions. Juárez-Maldonado et al. (2014) demonstrated that it is possible to determine the nutritional demand in tomato crop using dynamic models. However, in cucumber crop this tool has not been applied. For this reason, the objective of the present study was to adapt a tomato growth dynamic model to determine the mineral (N, P and K) uptake by cucumber cultivation under greenhouse conditions.

2. Materials and methods

2.1. Greenhouse description

The experiment was performed in a multi-tunnel greenhouse that was oriented from north to south, with an area of 392 m^2, a polyethylene cover (for 25 % shade), and zenith (0.80 * 28 m) and lateral windows (1.30 * 28 m). The opening and closing of the windows was performed manually, and when the temperature reached 24 and 18 °C, the opening and closing were performed, respectively. The greenhouse is located inside the facilities of the Universidad Autónoma Agraria Antonio Narro, Saltillo, Coahuila, México (25°21′N, 101°01′W).

2.2. *Development of the cucumber crop*

Two crop cycles were established in 2015 and 2016. The first cycle was performed from April 1st to July 7th 2015, and the second cycle was performed from March 1st to June 7th 2016. Vitaly (Syngenta) and Luxell (Nuhems) cucumber varieties, which are slicer types, were used for the experiment. These varieties have great performance and quality traits for the export market.

Direct seeding was performed in 4-liter plastic bags containing a mixture of peat moss-perlite as the substrate at a 1:1 ratio (v/v), considering one plant per bag. The experimental design was fully randomized, and one plant per replicate was considered. For the measurements four replicates were considered. The seed density was five plants m^{-2}. A directed irrigation system was used for irrigation. The irrigation application was programmed with a timer in which 4 irrigations were established during the day (at 9, 12, 15 and 18 h). Different amounts of irrigation were applied to correspond to each phenological stage, reaching approximately 2.2 L per plant at the higher consumption stages. The selected crop nutrition was based on the Steiner solution (Steiner, 1961), and it was applied at 25, 50 and 100 % according to the following stages of the crop: vegetative 1-20 days after seed emergence (DAE), flowering (20-30 DAE) and fruiting (30-95 DAE), respectively. The plants were managed on a single stem, the first 4 fruits were removed, and later, one fruit was left for each leaf. The pruning consisted on remove mature or damaged leaves, keeping only two leafs below the last mature fruit of the plant. The plant growth was limited to 75 days after emergence (DAE), and the apical parts were removed at an average height of 3.5 m.

2.3. Measurement of climatic variables

The climatic variables were measured inside the greenhouse during the development of both cultures. For this purpose, sensors were installed at 30 cm below the growth apex and maintained there during crop development. 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). Data were collected every 15 minutes. To measure the 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. Data were collected every 15 minutes.

2.4. *Growth Analysis*

To determine crop growth, destructive sampling was carried out every five days, starting 10 days after the emergency, when the plant had two true leafs. Four plants were randomly selected, considering plants with full competition. Leaves, stem, fruit and root were separated from the plant to obtain fresh weights. The root was washed with water to remove all substrate. Subsequently they were placed in a drying oven at a constant temperature of 80° C during 4 days to obtain the dry weight of each organ. Likewise, the total pruning of each plant and the total harvested fruits were quantified, fresh and dry weight were also obtained and these values were added to total from leaves and fruits.

2.5. Contents of Mineral Elements

The mineral content was determined in leaf, stem, fruit and root 25 days after the seed emergence, when the plants have the sufficient dry weight to mineral analysis (approximately 1 gram per organ), and every 10 days during the development of the crop. The micro Kjeldhal method was used to determine the total N content (AOAC, 1990). For the determination of P and K, an ICP (Optima 8300 ICP-OES, PerkinElmer, Inc., Waltham, MA, USA) equipment was used. For this, one gram of each sample was digested with HNO_3 y H_2O_2 at 400 °C following the standard method (AOAC, 1990).

The data obtained about the dry weight per plant and the mineral concentration were used to determine the mineral uptake of each organ according to Quesada-Roldan and Bertsch-Hernández (2013).

$$MU = \frac{MCO * 10 * DWO}{100} \tag{1}$$

where MU is the mineral uptake (g), MCO is the mineral content for each organ (g kg^{-1}) and DWO is the dry weight of each organ of the plant (gram per plant). The mineral uptake by plant is the sum of uptake by all organs.

2.6. Description of the cucumber growth model.

The dynamic tomato growth model proposed by Tap (2000) was used. This model starts from the flowering stage and consists of six state variables: mass balance for the assimilated buffer (B), dry weight of fruit (W_F), leaf dry weight (W_L), plant development stage (D_P) (this variable represents the begin of harvest, it is when D_P is equal to 1), dry weight of harvested fruit (W_{HF}) and dry weight of harvested leaves (W_{HL}). The corresponding equations are described below:

$$\frac{dB}{dt} = P_g - b\left(f g_F W_F + v g_F \frac{W_L}{z}\right) - bR$$

(2)

$$\frac{dW_F}{dt} = b g_F W_F - (1 - b) r_F W_F - h_F W_F \tag{3}$$

$$\frac{dW_L}{dt} = bg_LW_L - (1-b)r_LW_L - h_LW_L$$

(4)

$$\frac{dD_P}{dt} = d_1 + d_2 \ln\left(\frac{T_g}{d_3}\right) - d_4t - h \tag{5}$$

$$\frac{dW_{H_F}}{dt} = h_FW_F * yFc \tag{6}$$

$$\frac{dW_{H_L}}{dt} = h_LW_L \tag{7}$$

These state variables are composed by the follow functions (equations 8-18), where P_g is the gross photosynthesis, l is a monotonously rising function of W_L, r_F is the relative fruit respiration rate and r_L is the relative leaf respiration rate, R is the crop respiration, b is a buffer switching function, g_F is the relative fruit growth rate and $g_L$is the relative leaf growth rate, h is the harvest coefficient, h_F is the fruit harvest coefficient and h_L is the leaf harvest coefficient.

$$P_g = P_m l \frac{I}{p_3+I}\frac{C}{p_4+C} \tag{8}$$

$$l = \frac{\left(\frac{W_L}{W_R}\right)^m}{1+\left(\frac{W_L}{W_R}\right)^m} \tag{9}$$

$$r_F = m_FQ_R^{\frac{T_g-T_R}{10}} \tag{10}$$

$$r_L = m_LQ_R^{\frac{T_g-T_R}{10}} \tag{11}$$

$$R = r_FW_F + r_L\frac{W_L}{z} \tag{12}$$

$$b = 1 - e^{-b_1B} \tag{13}$$

$$g_F = (f_1 - f_2D_P)Q_G^{\frac{T_g-T_G}{10}} \tag{14}$$

$$\frac{g_L}{g_F} = v_1e^{v_2(T_g-v_3)} \tag{15}$$

$$\begin{cases} h = 0 & if\ 0 < D_P < 1 \\ h = d_1 + d_2 \ln\left(\frac{T_g}{d_3}\right) - d_4 t & if\ D_P = 1 \end{cases} \tag{16}$$

$$h_F = y_F h \tag{17}$$

$$h_L = y_L h \tag{18}$$

The climate variables measured inside the greenhouse (temperature [T_g], PAR [I] and CO_2 [C]) were used as inputs to the model. The dry weight of leaves (g m^{-2}), dry weight of fruits (g m^{-2}), dry weight of harvested leaves (g m^{-2}) and dry weight of harvested fruits (g m^{-2}), root dry weight (g m^{-2}) and total biomass (g m^{-2}) as proposed by Juárez-Maldonado et al. (2014) were obtained as outputs of the model. Because cucumber distribution of biomass is different than tomato, since its accumulation of biomass in fruits is greater (Gallardo et al., 2016), a harvest parameter of the cucumber fruit (*yFc*) was incorporated in equation 6. This parameter was obtained as a proportion of total fruit weight in relation to total leaf weight.

2.7. Calibration and validation of the cucumber growth model

The calibration of the model consisted of modifying the nominal values of a subset of parameters, selected according to the sensitivity analysis performed by Tap (2000). The adjustment was made by modifying the nominal values of the parameters of the model and then performing simulations using as input the climatic variables measured inside the greenhouse (PAR, temperature and concentration of CO_2) obtained during the first crop cycle until the best fit between the simulated outputs and those observed was obtained. For the comparison were used the real values of accumulated biomass and N, P and K uptake of the first crop cycle (2015). To evaluate the fit between the simulated data and the actual data in the calibration of the dynamic model the root mean square error (*RMSE*), Nash–Sutcliffe Root modelling efficiency (*EF*) (Nash and Sutcliffe, 1970), and Agreement index (*Index*) (Willmott, 1981) were calculated as follow:

$$RMSE = \sqrt{\sum_{i=1}^{n} \frac{(P_i - O_i)^2}{n}} \tag{19}$$

$$EF = 1 - \left(\frac{\sum_{I=1}^{n} (O_i - P_i)^2}{\sum_{I=1}^{n} (O_i - O_i)^2} \right) \tag{20}$$

$$Index = 1 - \left(\frac{\sum_{I=1}^{n} (O_i - P_i)^2}{\sum_{I=1}^{n} (P_i - O_i) + (O_i - O_i)^2} \right) \tag{21}$$

where *n* is the number of samples, *Pi* and *Oi* are the predicted and observed values, and *O* is the mean of the observed data. The closer the value of root mean square error (*RMSE*) is to 0, the more accurate is the model. Modeling efficiency (*EF*) ranges from 0 to 1. An efficiency of 1 corresponds to a perfect match between modeled values and observed data. Agreement *Index* represents the ratio of the mean square error and the potential error. A perfect match between prediction and measurement results in *Index* = 1. Based on Van Liew and Garbrecht (2003), an acceptable simulation should have *EF* and *Index* > 0.75.

For model validation, the climatic data (PAR, temperature and concentration of CO_2) obtained of the second crop cycle were taken as inputs to the model. The outputs (accumulated biomass and N, P and K uptake) were compared to the actual data obtained from the second crop cycle (2016). To assess the efficiency of the simulation for the validation process, were used the *RMSE*, *EF* and *Index* too.

2.8. Modeling of mineral content in cucumber

It was verified the existence of a linear relation between the biomass and the minerals, to simplify the modeling of mineral content in cucumber on biomass base. This is possible since nutrient uptake is related to growth rate (Vos et al. 2007), and it has high correlation with biomass accumulation (Macduff and Jackson, 1992; Zhang et al., 2015). Therefore, to determine the degree of correlation between the accumulated extraction of N, P and K with respect to total biomass, Pearson correlation coefficient was obtained using the SigmaPlot© 12.0 program. This to allow use the concentration of each mineral as percentage on dry matter base. This percentage was incorporated as a parameter into the dynamic growth model of cucumber to simulate the mineral uptake. Since there is no nutrient limitation, the simulated concentration for the plant will be equal to its uptake (Marcelis et al., 2005). This is expressed as follows:

$$TMU = Biomass * \%m \tag{22}$$

where *TMU* is the total mineral uptake (g m^{-2}), *Biomass* is the total biomass (g m^{-2}) and *%m* is the percentage of the mineral.

Therefore, the *TMU* was used for the simulation of the three nutrients uptake (N, P and K). Regarding mineral uptake, the first crop cycle (2015) was used for model calibration and the second crop cycle (2016) for model validation. The dynamic programming and simulation process was performed in Matlab-Simulink © R2013a.

3. Results

3.1. Cucumber growth modeling

During the calibration process of the model, 13 out of 27 parameters of the original tomato model proposed by Tap (2000) were modified. Table 1 shows the model parameters with their nominal values (Tap, 2000) and the values obtained during the calibration process for cucumber cultivation. Because the original model was proposed and validated for tomato, parameters underwent significant modifications (Table 1) when applied to cucumber. The use of parameter *yFc* in Eq. 6 during the calibration phase of the model showed a good fit of the simulation with respect to the experimental data for both varieties. Figures 1 and 2 show the comparison between the real data obtained for both, Vitaly and Luxell, varieties during 2015 cycle, against the simulation data obtained from the calibration process. Table 2 shows the indices used to assess the simulation efficiency for outputs of the model, namely fruits on plant, leaves on plant, harvested fruits and harvested leaves. In general, it is possible to observe that both *EF* and *Index* in all outputs are greater than 0.95 for both varieties of cucumber (Vitaly and Luxell). The values of RMSE for the outputs were from 1.32 to 90.84 in Vitaly variety, and 0.79 to 211.81 in Luxell variey. It can be considered a good fit, a result that is verified with greater than 0.95 indices values as shown in Table 2.

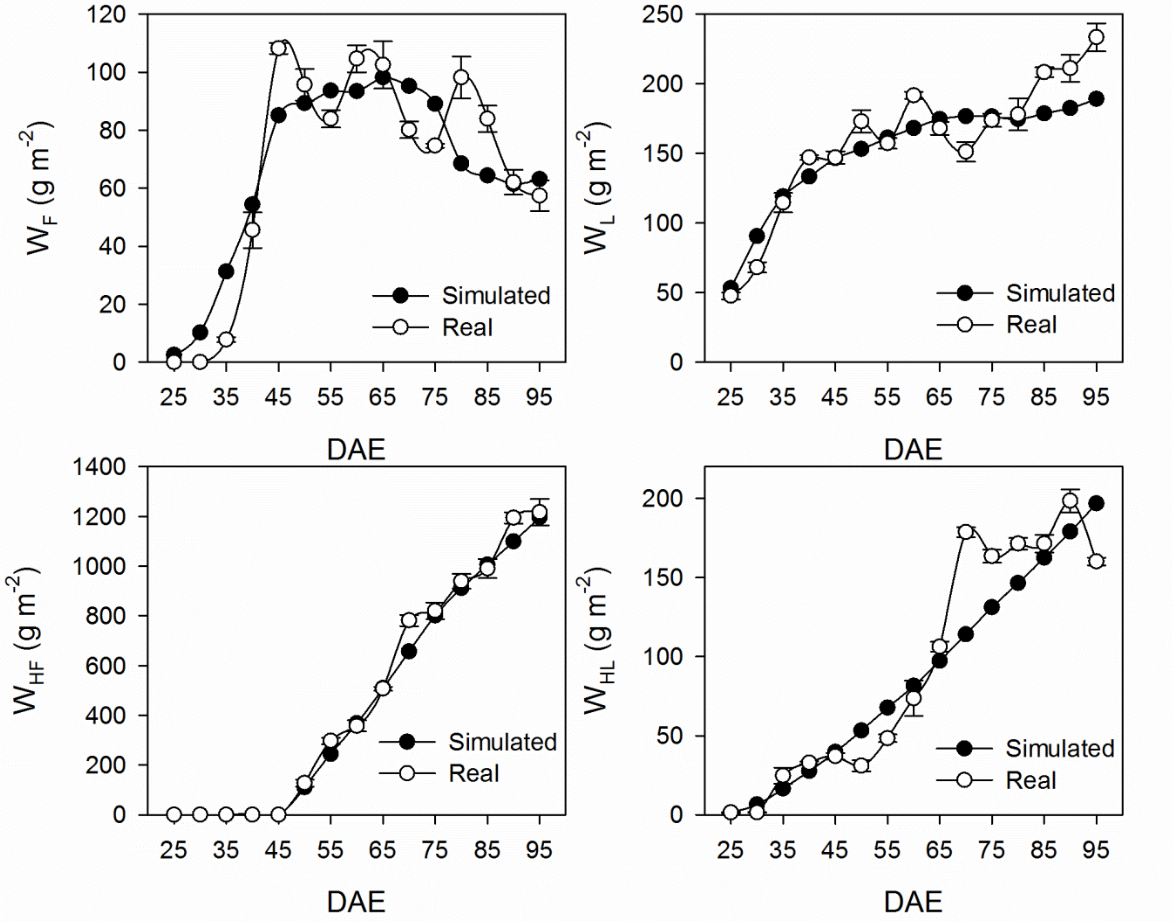

Figure 1. Calibration graphs for the model outputs in the Vitaly variety. The real data obtained from the 2015 cycle vs the simulated data are compared. DAE: Days after seed emergence.

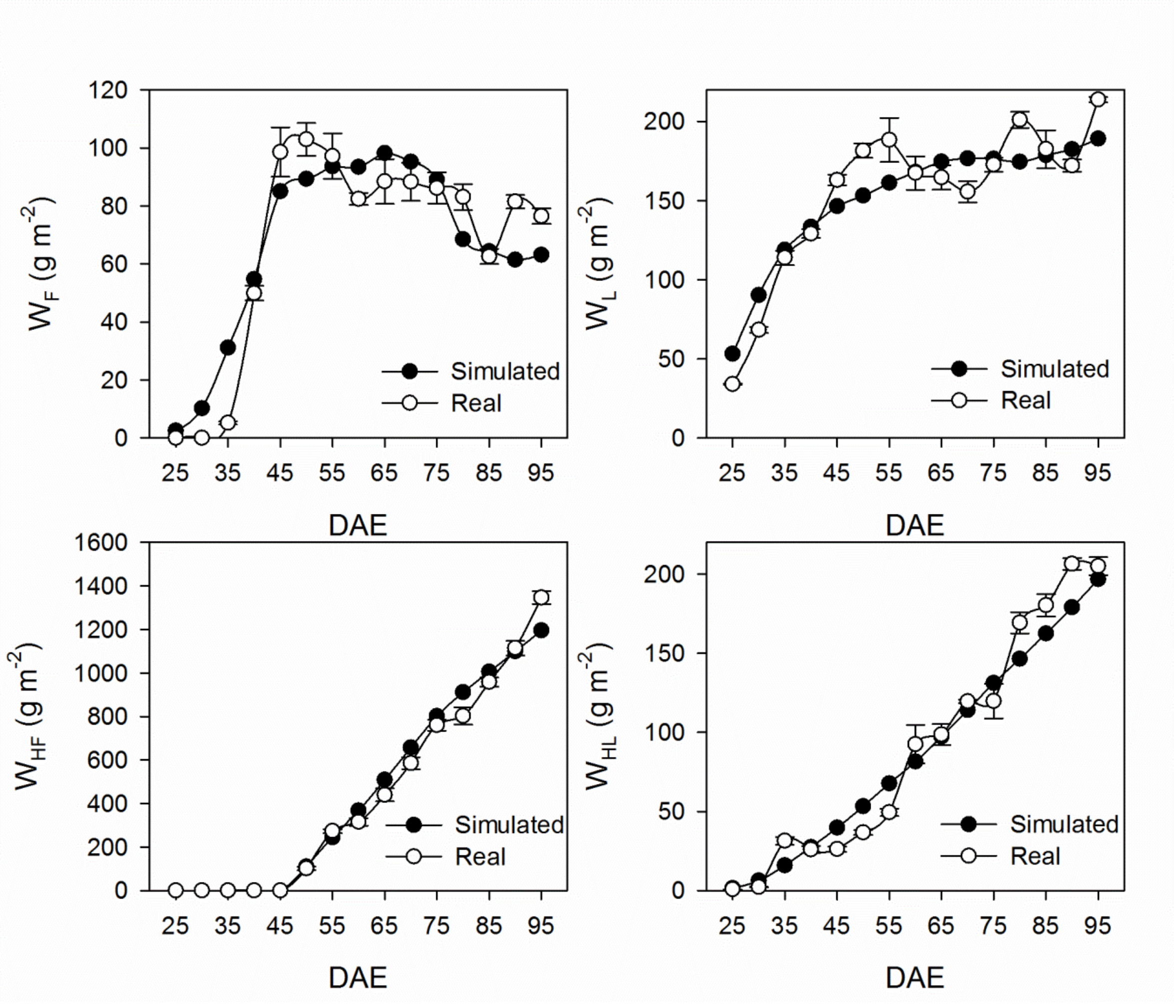

Figure 2. Calibration graphs for the model outputs in the Luxell variety. The real data obtained from the 2015 cycle versus the simulated data are compared. DAE: Days after seed emergence.

Figures 3 and 4 show the graphical behavior of real data against simulated in the Vitaly and Luxell varieties respectively during the validation process of the model (cycle 2016). From these graphs and Table 2, it can be mentioned that the model presents a good fit for growth simulation of cucumber for Vitaly and Luxell varieties. It can also be observed that the W_F in both varieties was underestimated by the model, because the W_{HF} was simulated 5 days before the beginning of the harvest period compared to the experimental data (Figures 3 and 4). This behavior is due to the fact that during the calibration process of the model, the climatic conditions (radiation and temperature) were higher with respect to the validation cycle, this caused growth of the cucumber was slower in the validation cycle, and therefore the beginning of harvest showed a delay of 5 days. Regarding the output variable W_{HL}, an underestimation by the model was also observed at 40 DAE in both varieties.

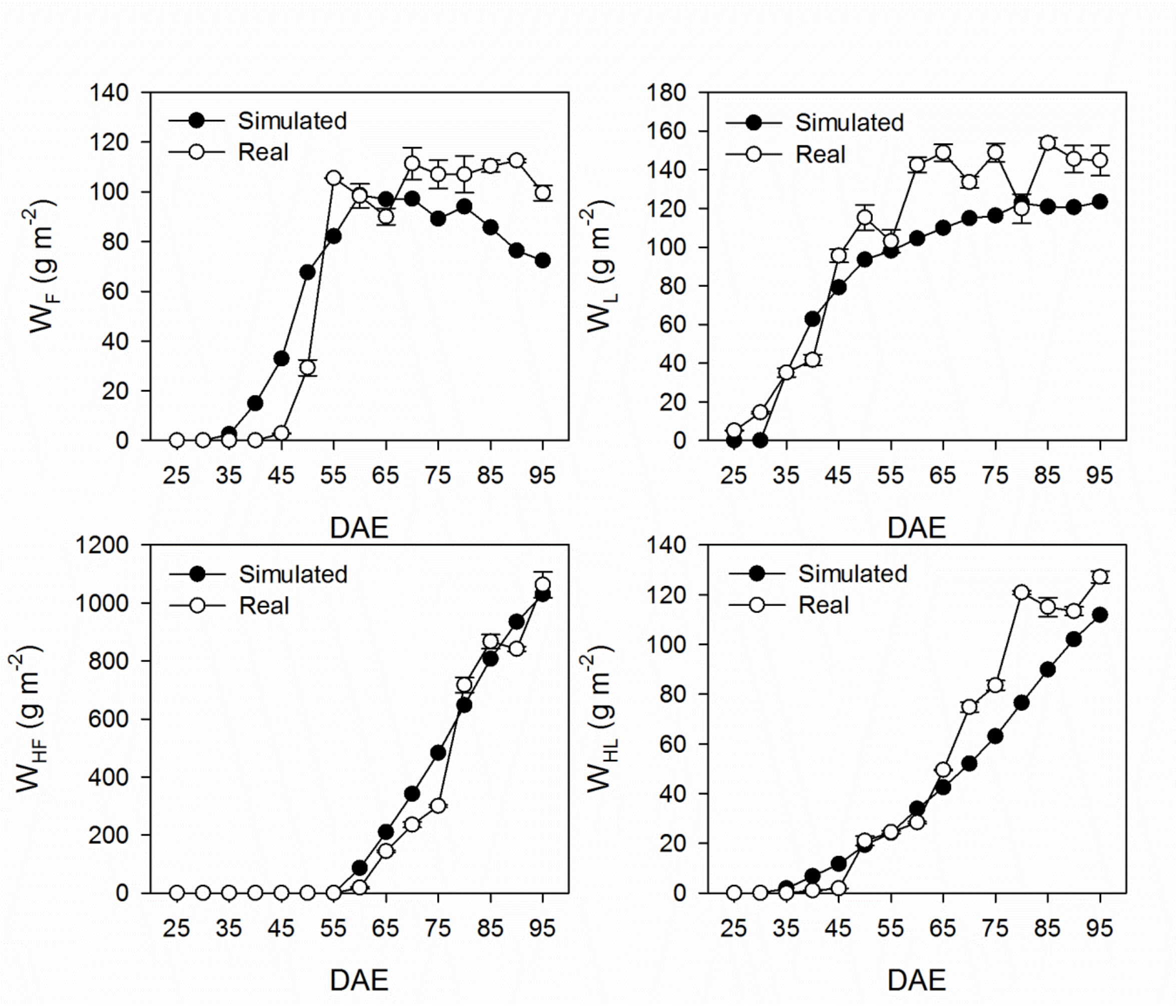

Figure 3. Validation graphs for the outputs of the model in the Vitaly variety. The real

data obtained from the 2016 cycle versus the simulated data are compared. DAE: Days after seed emergence.

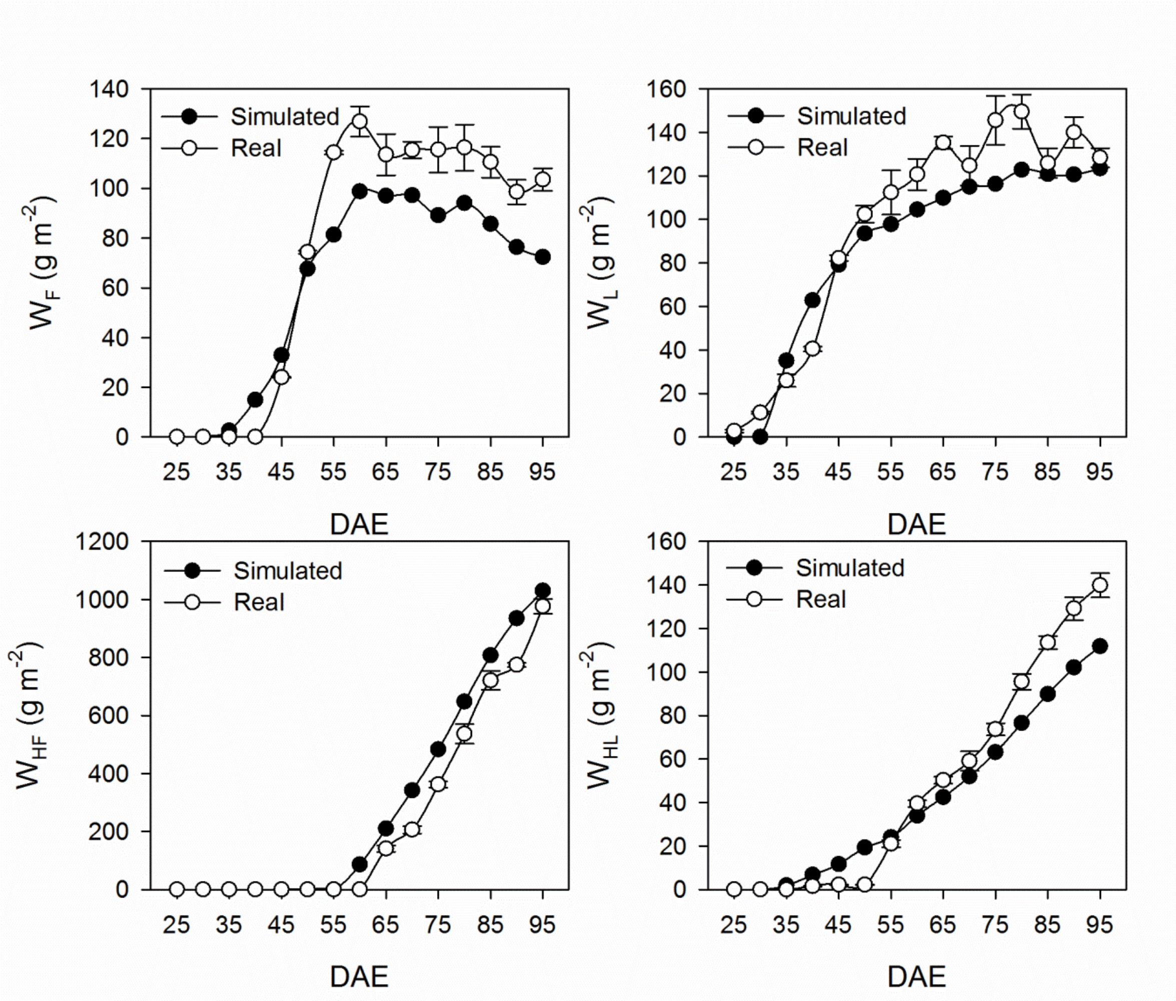

Figure 4. Validation graphs for the model outputs in the Luxell variety. The real data obtained from the 2016 cycle versus the simulated data are compared. DAE: Days after seed emergence.

3.2. *Mineral Uptake*

In Figure 5, the content of N, P and K in both Vitaly and Luxell varieties during the 2015 and 2016 cycle can be observed. The percentage of N for Vitaly variety remained between

2.2-3.9% and 2.6-3.4% during the 2015 and 2016 cycles respectively. Regarding the Luxell cv. the range remained between 2.3-4% and 2.7-4.2% during the 2015 cycles and 2016 respectively. The content of N in cucumber plants was decreasing as the growing time increasing, and the average was 3.5% for both varieties.

The range of phosphorus content was remained at 0.15-0.38% and 0.28-0.53% in Vitaly variety and 0.14-0.39% and 0.25-0.56% in Luxell varity during the 2015 and 2016 cycles respectively (Figure 5). The content of phosphorus don’t shows a clearly behavior throughout the growing time; however, it was maintained around of 0.3% for both varieties.

With respect to the percentage of K, were found ranges of 1.8- 2.7% and 1.3-2.7% in the Vitaly variety and 2-3.1% and 1.1-2.6% in the Luxel variety during the 2015 and 2016 cycles respectively (Figure 5). The content of potassium don’t shows a clearly behavior throughout the growing time; however, it was maintained around of 2.1% for both varieties.

When the correlation between total biomass and nutrient uptake (N, P and K) was made, a highly significant correlation (Pearson, $P < 0.01$) was observed for both cucumber varieties during the 2015 and 2016 cycles (Table 3). This result demonstrated that exist a linear relationship between biomass and nutrient uptake, therefore, to the greater accumulation of biomass corresponds to greater uptake of nutrients in the same proportion.

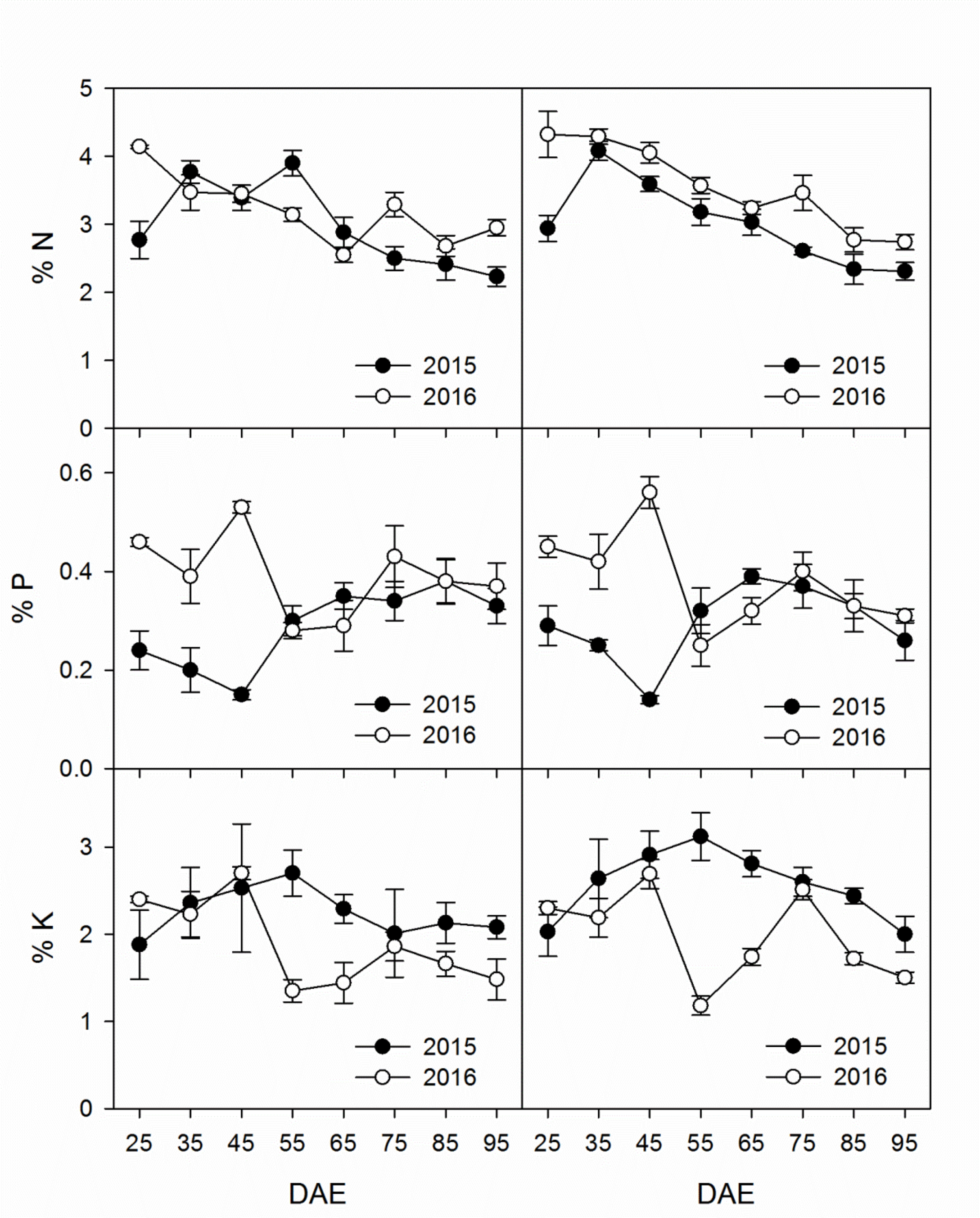

Figure 5. Content of N, P and K minerals expressed in percentage on dry matter base in cucumber plants throughout the time for both crop cycles (Vitaly in the left and Luxel in the right).

3.3. Modeling of minerals uptake in cucumber plants

Table 3 shows the *EF*, *Index* and RMSE obtained in the Vitaly and Luxell varieties when evaluating N, P and K. When assessing the calibration data, indices above 0.95 were observed in both varieties, however, during validation the indices were lower than those observed during the 2015 cycle. The lowest indices were observed in K, where Vitaly variety presented *EF* and *Index* of 0.903 and 0.905 respectively, while the Luxell variety presented values of 0.945 and 0.946 respectively. The RMSE of N, P y K simulations were from 0.35 to 9.70 in both varieties.

Figures 6 and 7 show the data of real and simulated N, P and K uptake by cucumber plants. Additionally, the applied amount by Steiner solution of these minerals for both varieties of cucumber crops (Vitaly and Luxell) was included. A good fit between the actual values obtained and those simulated by the model (Figures 6 a, c, e and 7 a, c, e) is clearly observed in model calibration for mineral extraction in both varieties. This was confirmed with the indices used (*EF* and *Index*) to evaluate the fit between real and simulated data, that show values better than 0.95. While in the validation process a good adjustment was also observed between real and simulated data (Figures 6 and 7 b, d and f) where both indices used were better than 0.90. According to the original model in tomato (Tap, 2000), the simulation process of the model starts at flowering, so that the validation of the model in cucumber Vitaly and Luxell varieties began 35 days after the emergence, 10 days after the calibration cycle (25 DAE).

On the other hand, it can be observed that in Luxel variety the model underestimated the N content, since this content found in plants at the end of the crop cycle was 21.7 % higher in experimental versus simulated data. In addition, this is corroborated by the reduction of the efficiency levels found in both the W_{HL} and N outputs for Luxel variety (Tables 3).

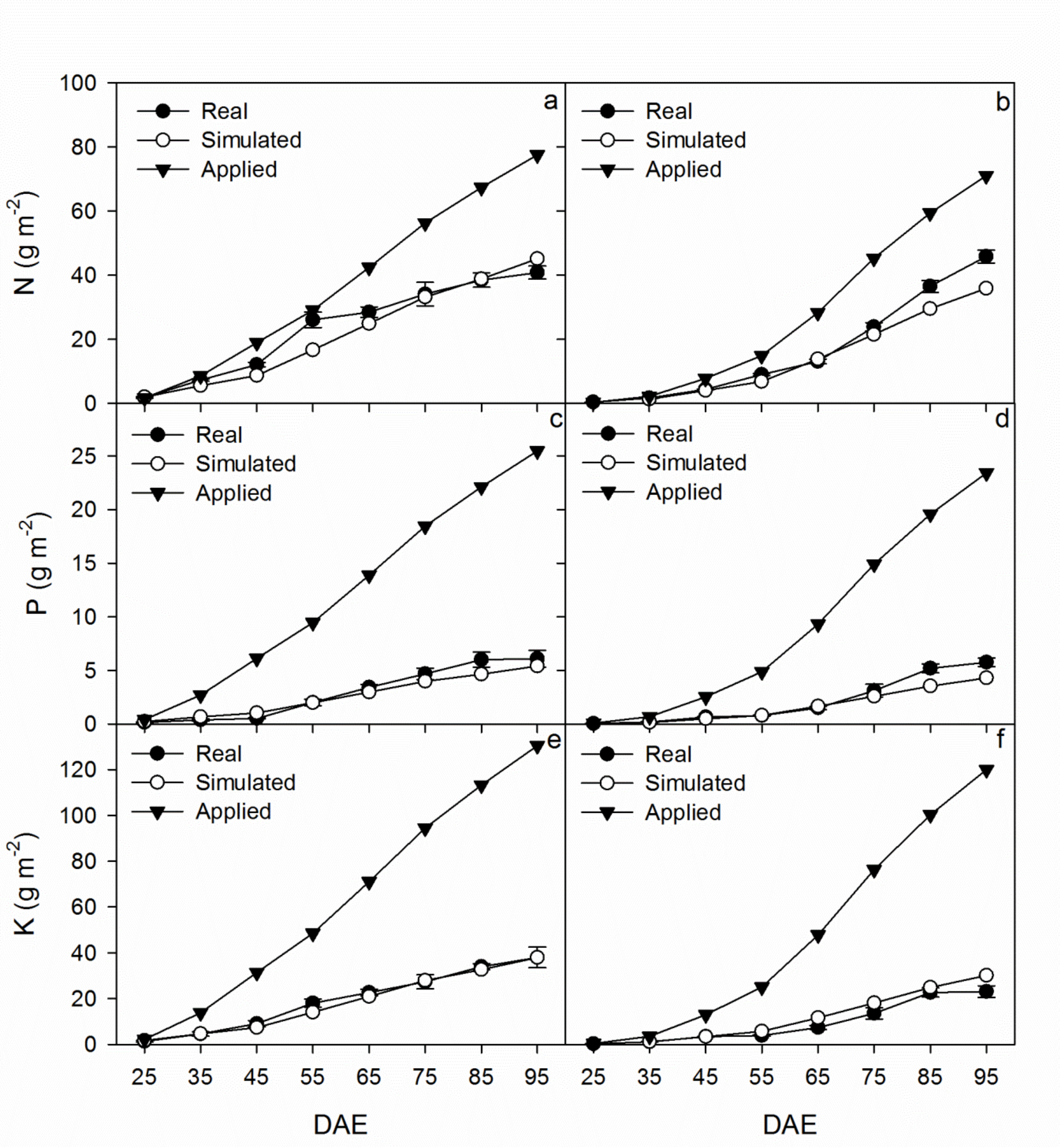

Figure 6. Calibration (a, c, e) and validation (b, d, f) of the nutrient uptake in cucumber for Vitaly variety. It also includes the amount of real minerals applied by the Steiner solution.

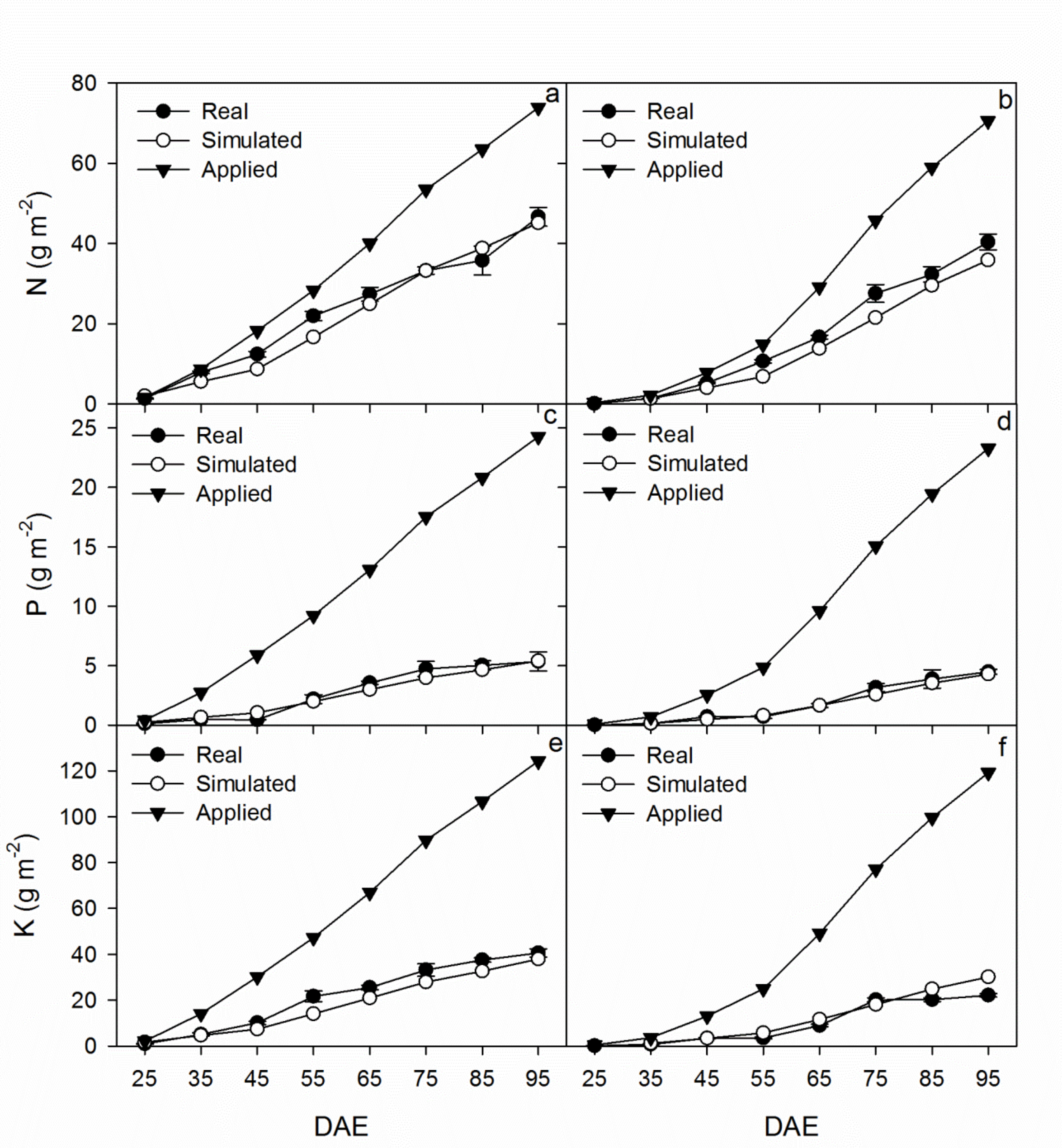

Figure 7. Calibration (a, c, e) and validation (b, d, f) of the mineral contents in cucumber for Luxell variety. It also includes the amount of real minerals applied by the Steiner solution.

4. Discussion

A model originally adapted for accumulation of biomass in tomato was presented, in which a good adjustment for the simulation of biomass accumulation in the cucumber crop. Biomass production depends on the photosynthetic activity of the leaves, and nutrients are directly necessary for leaf growth and are an integral part of the photosynthetic apparatus (Engels et al., 2012). On the other hand, the temperature is one of the environmental factors that directly influence the physical-chemical properties of the plants (Gruda, 2005)**.** The influence of these variables directly affects the growth of the plants, initiation of the flowering, as well as in the quality and growth of the fruits (Papadopoulos and Hao, 2000).

Each horticultural crop has its own specific nutrient needs, which arise from specific physiological responses controlled by environmental conditions (Pignata et al., 2017). According to the percentages of N observed in this work, the ranges found are low compared to that reported by Mills et al. (1996), since the authors mention that the range of N for the cucumber is of 3.5 to 6%. Contrary to what is observed in P, since the percentages found are within the range of phosphorus reported by Hopkins (2015), since the optimal ranges vary from 0.1% to 1%.

The optimal sufficiency ranges for K in cucumber vary from 3.5% to 4.5% (Maynard and Hochmuth, 2007), so according to the results obtained it can be mentioned that the levels are low.

The availability of nutrients is a factor that determines the growth and productivity of plants, therefore, with high availability, plants will perform the absorption of minerals according to their demand (Quilleré et al., 1994; Ruiz and Romero, 1999; Kiba and Krapp, 2016), In this scenario the nutrient uptake will remain constant according to the accumulation of biomass (Osvalde, 2011). The N, P and K contents on cucumber plants were lower than reported by other authors (Quilleré et al., 1994; Ruiz and Romero, 1999; Kiba and Krapp, 2016). However, during crop development symptoms of deficiency were not observed.

The modeling approach to evaluate the biomass accumulation and mineral uptake by crops can be a usefull tool to a better management of crops. Just as it has been proobed to optimization of water requirements by cucumber crop (Sun et al., 2012; Sun et al., 2013).

During the calibration process of the model, the number of modified parameters was higher than that reported by Juárez-Maldonado et al. (2014), since a total of 11 parameters were modified in tomato growth simulation. Changes in the parameters are mainly due to factors such as the region in which the experiment was carried out and the characteristics of the variety, as well as the species (Quesada-Roldán and Bertsch-Hernández, 2003).

Regarding the validation process, the model underestimated the dry weight of harvested leaf. The underestimation of the variable WH_L is due to the fact that the number of harvested leaves was reduced at the end of the cycle, since the development of the plant was slower than in the first cycle. During the 2016 cycle, the climate conditions were lower than those observed in the 2015 cycle, which was manifested in the decrease and delay of growth. This behavior was similar to that reported by Juárez-Maldonado et al. (2014), who also observed an underestimation in this output variable due to the management of prunings made during tomato crop growth.

For the evaluation of the simulation performed, the Index and EF mentioned by Nash and Sutcliffe (1970) y Willmott (1981) , the authors according a perfect efficiency is equal to 1, so from the values obtained can be mentioned that the efficiency of the simulation is very good. Similar results were reported by Gou et al. (2010), Sun et al. (2013), Gallardo et al. (2016) and Awais et al. (2017), to use in different simulation process the mentioned statistical indices used here. The efficiency indices observed are similar to those reported by Juárez-Maldonado et al. (2014), since the authors found an efficiency greater than 0.95 when evaluating the N, P, K and S extraction in tomato crop. Ma et al. (2012) mentioned that values of EF and Index > 0.75 are satisfactory to simulation process. Also, the values of RMSE observed here are satisfactory according to (Nangia et al., 2008; Guo et al., 2010; Sun et al., 2013).

In order to achieve perfect efficiency during the process of simulation of growth and mineral absorption in cucumber plants, it is necessary to control temperature, PAR and CO_2 content in the air, and to include during the simulation other factors such as vapor pressure deficit. This is based on the factors that determine the growth and development of plants (Li et al., 2007a, 2007b).

During the simulation of the absorption of N, P and K, a good fit was observed and this is corroborated with the indices used for the evaluation of the simulation. However, during the validation process of the model, the simulation of N, it was observed that the model underestimated the N content in Luxel variety. This behavior is related to the reduction of harvested leaves shown in the simulation (WH_L), since N is the most abundant element in plant tissue (Hawkesford et al., 2012). Proof of this, is the variety of studies worked around of N as main growth factor of the crops (Gou et al., 2010; Sun et al., 2013; Gallardo et al., 2016; Awais et al., 2017).

According to results, adjustments can be made in the mineral nutrition management of cucumber plants for both Vitaly and Luxell varieties under greenhouse conditions, based on the daily quantification of nutritional demand as proposed by (Bugarín-Montoya et al., 2002), avoiding a stress either by deficit or excess of minerals in cucumber plants.

5. Conclusions

The application of a dynamic model originally adapted for tomato crop in the simulation of growth and mineral uptake in Vitaly and Luxell varieties of slicer type cucumber adequately simulates plant growth and N, P and K absorption. Therefore, to use a static value of nutrient content in cucumber plants, can be more adequate to simulate the nutrient uptake as was observed here. This to allow perform analysis using mathematical models and simulations more easily.

According to the experimental and simulated data, both Vitaly and Luxell varieties behaved very similarly when evaluated by the same parameters, which makes it a more robust model and able to be applied to other cucumber varieties because both varieties showed practically the same N, P and K uptake and biomass accumulation during their production cycle.

The dynamic model calibrated and validated in this research can be a useful tool to generate different crop and nutritional management strategies for cucumbers under greenhouse conditions with very good precision. This allows efficient applications of fertilizers to cucumber crop under greenhouse conditions.

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Table 1. Description of model parameters. Nominal values were obtained from Tap (2000). Calibrated values were obtained from calibration process with data of crop cycle 2015.

Parameters	**Nominal value in tomato**	**Calibrated value in cucumber**	**Units**	**Description**
b1	2.7		$m^2\ g^{-1}$	Coefficient of the change buffer function
d1	2.13e-07	5.9332e-7	s^{-1}	Growth Rate Parameter
d2	2.47e-07	5.4664e-7	s^{-1}	Growth Rate Parameter
d3	20		°C	Growth Rate Parameter
d4	7.50e-11	3.46e-13	-	Growth Rate Parameter
f	1.2	1.5	-	Ratio of assimilated fruit requirements
f1	8.10e-07	6.1e-6	s^{-1}	Fruit growth rate coefficient
f2	4.63e-06		s^{-1}	Fruit growth rate coefficient
m	2.511		-	Correction-LAI function parameter
mF	1.157e-07	1.5e-6	s^{-1}	Breathing coefficient of maintenance of the fruit
mL	2.894e-07	2.89e-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	2.25e-03	2.6e-3	$g\ s^{-1}\ m^{-2}$	Maximum photosynthesis
QG	1		-	Temperature of the rate of growth of the fruit
QR	2		-	Respiration maintenance
t	86400		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
N	3.5		%	Average content of N on dry matter base
P	0.3		%	Average content of P on dry matter base
K	2.1		%	Average content of K on dry matter base

Table 2. Statistical indices to assess the simulation efficiency of dynamic model.

Variety	Process	Crop variables	RMSE	I	EF
Vitaly	Calibration	Fruit in plant	1.32	0.999	0.999
		Leaves in plant	24.97	0.998	0.998
		Harvested fruits	84.75	0.997	0.997
		Harvested leaves	20.34	0.996	0.996
		N	5.03	0.992	0.992
		P	0.81	0.987	0.987
		K	2.75	0.996	0.996
	Validation	Fruit in plant	16.36	0.989	0.989
		Leaves in plant	63.53	0.963	0.963
		Hardvested fruits	90.84	0.987	0.987
		Hardvested leaves	32.39	0.977	0.977
		N	7.57	0.966	0.965
		P	1.30	0.940	0.937
		K	7.06	0.905	0.903
Luxell	Calibration	Fruit in plant	0.79	0.996	0.996
		Leaves in plant	8.08	0.999	0.998
		Hardvested fruits	52.73	0.987	0.997
		Hardvested leaves	11.33	0.985	0.985
		N	4.12	0.994	0.994
		P	0.35	0.997	0.997
		K	9.70	0.967	0.967
	Validation	Fruit in plant	52.47	0.951	0.951
		Leaves in plant	37.64	0.989	0.989
		Hardvested fruits	211.81	0.948	0.948
		Hardvested leaves	23.87	0.979	0.979
		N	7.49	0.966	0.966
		P	0.43	0.991	0.990
		K	5.61	0.946	0.945

Table 3. Cucumber biomass and minerals correlation matrix

		Biomass		**N**		**P**		**K**	
		15	**16**	**15**	**16**	**15**	**16**	**15**	**16**
Biomass	**V**	1[†]	1	0.971	0.994	0.993	0.993	0.993	0.991
	L	1	1	0.987	0.991	0.962	0.987	0.973	0.956
N	**V**			1	1	0.961	0.994	0.988	0.988
	L			1	1	0.969	0.992	0.988	0.978
P	**V**					1	1	0.984	0.997
	L					1	1	0.984	0.988
K	**V**							1	1
	L							1	1

15: 2015 cycle. 16: 2016 cycle. [†]: Pearson Correlation Coefficient ($P<0.01$).

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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

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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

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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
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.

[redacted]

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.

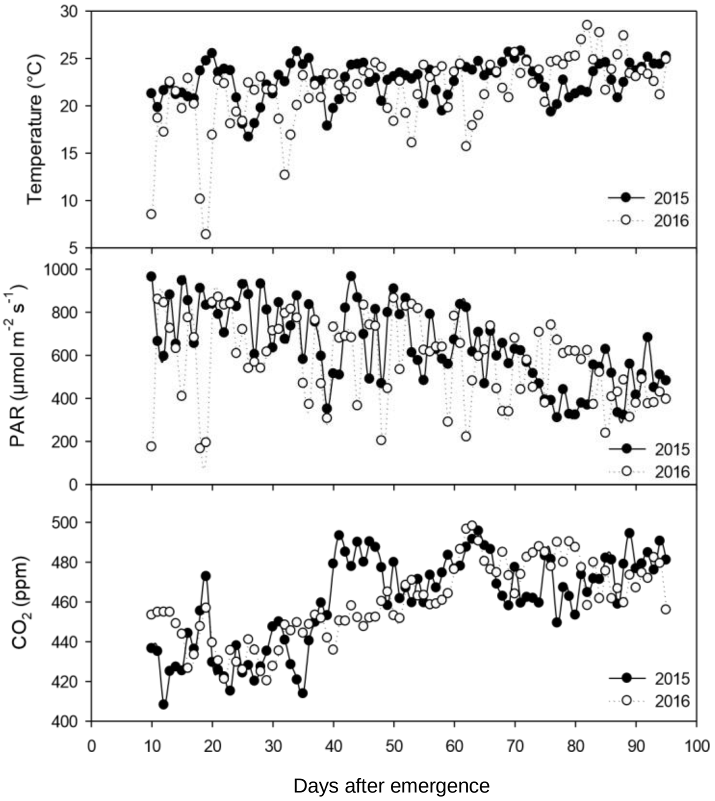

Figure 1. Climate data recorded during the development of tomato crops. The daily average is presented in the figure.

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.

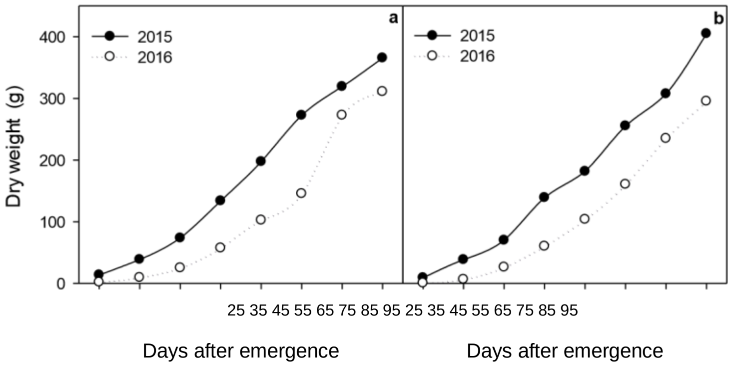

Figure 2. Accumulation of dry biomass recorded during the development of the cucumber crops Vitaly (**a**) and Luxell (**b**) varieties. The data are the average of four plants.

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.

cv	DAE	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)	
		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.

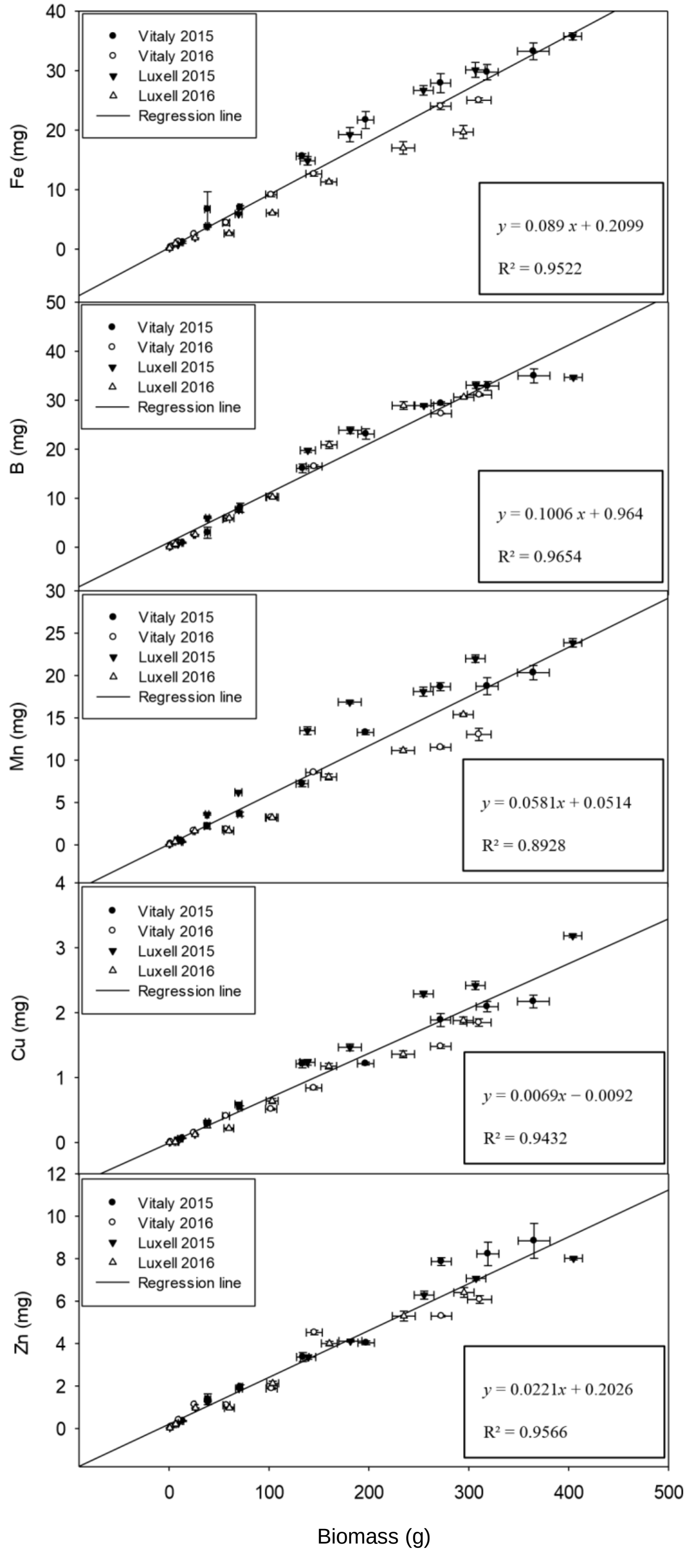
Fe (mg)
B (mg)
Mn (mg)
Cu (mg)
Zn (mg)
Biomass (g)
Vitaly 2015
Vitaly 2016
Luxell 2015
Luxell 2016
Regression line
y = 0.089 x + 0.2099
R² = 0.9522
y = 0.1006 x + 0.964
R² = 0.9654
y = 0.0581x + 0.0514
R² = 0.8928
y = 0.0069x − 0.0092
R² = 0.9432
y = 0.0221x + 0.2026
R² = 0.9566
0
100
200
300
400
500

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 L	1	1	0.99	0.99	0.99	0.99	0.99	0.98	0.98	0.99	0.99	0.97
		1	1	0.99	0.99	0.99	0.97	0.99	0.97	0.99	0.99	0.99	0.99
Fe	V L			1	1	0.99	0.99	0.99	0.98	0.99	0.99	0.98	0.97
				1	1	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99
B	V L					1	1	0.99	0.99	0.99	0.99	0.97	0.98
						1	1	0.98	0.99	0.98	0.98	0.99	0.98
Mn	V L							1	1	0.98	0.98	0.98	0.99
								1	1	0.99	0.98	0.99	0.98
Cu	V L									1	1	0.98	0.97
										1	1	0.99	0.99
Zn	V L											1	1
												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].

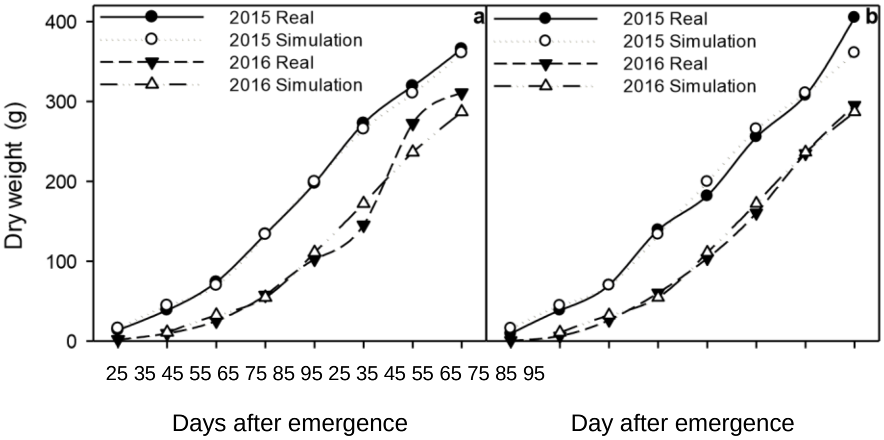

Figure 4. Comparison between the real and dynamically simulated data for the accumulation of dry biomass in cucumber plants for Vitaly (**a**) Luxell (**b**) varieties. The real data is the average of four replicates.

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.

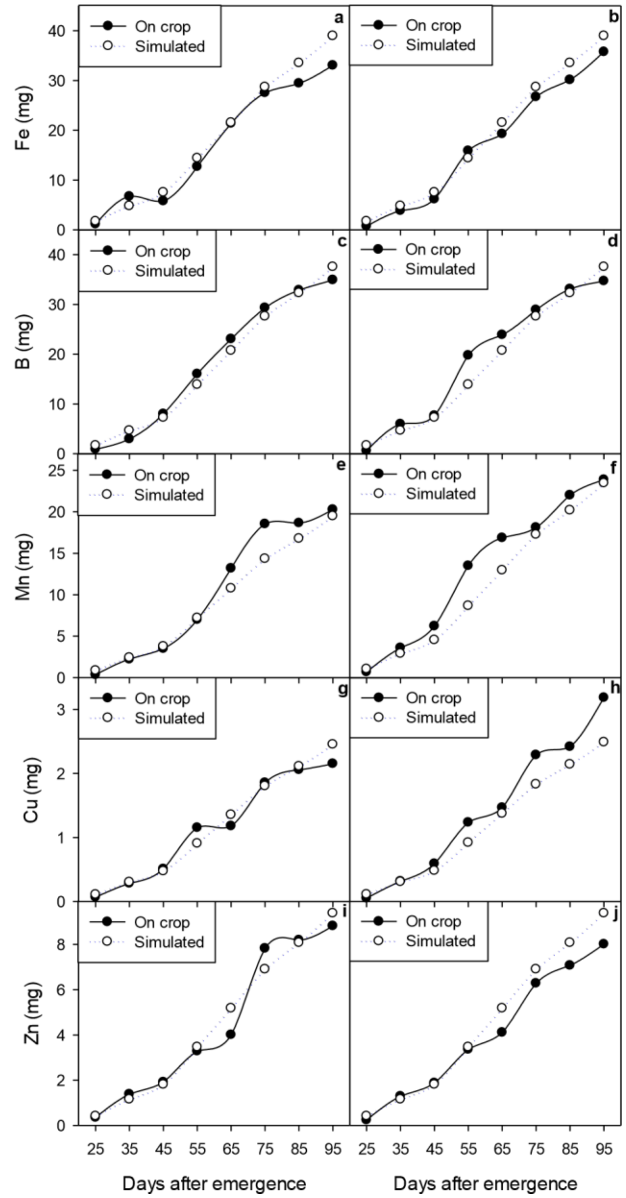

Figure 5. Comparison between the real and dynamically simulated data for micronutrient accumulation in the Vitaly (**a**,**c**,**e**,**g**,**i**) and Luxell (**b**,**d**,**f**,**h**,**j**) cucumber plant varieties. The data corresponding to the culture cycle used for the calibration are presented. The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

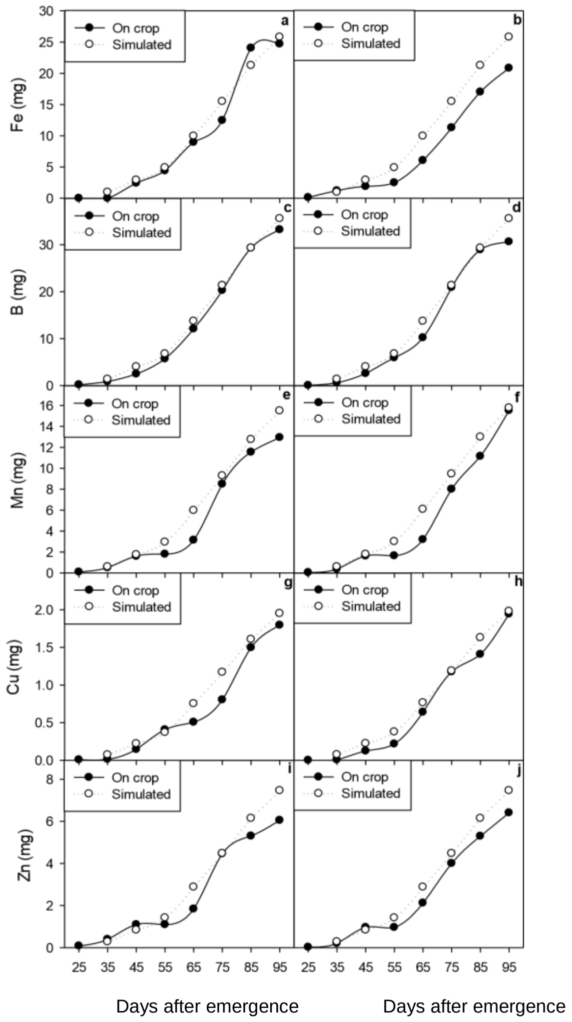

Figure 6. Comparison between the real and dynamically simulated data for micronutrient accumulation in the Vitaly (**a**,**c**,**e**,**g**,**i**) and Luxell (**b**,**d**,**f**,**h**,**j**) cucumber plant varieties. The data corresponding to the cultivation cycle used for the validation are presented.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

[redacted]

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):

$$TMA = CMO_{\mathrm{L}} + CMO_{\mathrm{S}} + CMO_{\mathrm{F}} + CMO_{\mathrm{R}} \tag{1}$$

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].

$$CMO = CM * D \tag{2}$$

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):

$$MCP = \frac{TMA}{DW} \tag{3}$$

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 ($y\mathrm{F}c$) 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 $y\mathrm{F}c$ 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)).

$$TAM = BT * ACM \quad (5)$$

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.

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

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

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].

[redacted] 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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CONCLUSIÓN GENERAL

La temperatura (transformada en unidades de calor), la radiación PAR y la transpiración son variables que influyeron significativamente en la tasa de acumulación de biomasa y en la absorción de minerales, consecuentemente en los rendimientos de pepino de las variedades Vitaly y Luxell.

A medida que la temperatura y la PAR disminuyen, la tasa de transpiración se redujo proporcionalmente, por lo que también disminuyeron las tasas de acumulación de biomasa y absorción de minerales (específicamente los menos móviles, Ca y S).

La aplicación del modelo de crecimiento validado originalmente por Tap (2000) para el cultivo de tomate, en la simulación de crecimiento y absorción de minerales en variedades Vitaly y Luxell de pepino tipo slicer simuló eficientemente el crecimiento de las plantas, así como la acumulación de N, P, K, Fe, B, Mn, Cu y Zn.

De acuerdo con los datos reales, las variedades de pepino Vitaly y Luxell mostraron un crecimiento similar, por lo tanto, al evaluarlas con los mismos parámetros, la simulación se manifestó el mismo comportamiento, lo que lo hace un modelo más robusto y se puede aplicar a otras variedades de pepino, porque ambas variedades mostraron concentraciones similares de los nutrientes evaluados, así como la acumulación de biomasa durante su ciclo de producción.

El modelo calibrado y validado en esta investigación puede ser útil para generar diferentes estrategias de manejo y nutrición para el cultivo de pepinos bajo condiciones de invernadero.

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