Project Number: NCERA-101
Project Title: Controlled Environment Technology and Use
Period Covered: 09-2020 to 11-2021
Date of This Report: December 2021
Annual Meeting Date: November 15-17, 2021

2021 NCERA-101 Annual Meeting
November 15-17, 2021
Hosted by Michigan State University (Erik Runkle, Roberto Lopez, and team)
Via Zoom Virtual Meeting

Participants:
Iris Adelakun (Conviron), Id Shamim Ahamed (UCDavis), Eva Birtell (Univ. Delaware), Mark Blonquist (Apogee Instruments), A.J. Both (Rutgers Univ.), Scott Bryson (Orbital Farm), Bruce Bugbee (Utah State Univ.), Doug Buhler (Michigan State Univ.), Justin Butcher ( ), Henry Carcamo (Syngenta), Bobby Clegg (Syngenta), Cristian Collado (North Carolina State Univ.), Joshua Craver (Colorado State Univ.), Stephanie Cruz (Univ. Florida), Jordan Dilicandro (Univ. of Guelph), Dinah Dimapilis (NASA), Rob Eddy (CEA Consultancy LLC), David Elliott (EGC), Taunya Ernst (80 Acres Farms), John Ertle (Ohio State Univ.), Ron Evans (NRC IRAP), Brendan Fatzinger (Utah State Univ.), Bruno Faucher (Capital Greenhouse), Rhuanito Ferrarezi (Univ. of Georgia), Dave Fleisher (USDA-ARS), Jonathan Frantz (Corteva Agriscience), Patrick Friesen (BioChambers), Gary Gardner (Univ. of Minnesota), Dan Gillespie (JR Peters), Ana Gomez (Univ. of Florida), Celina Gomez (Univ. of Florida), Thomas Graham (Univ. of Guelph), Yazan Hammad (Conviron), Joshua Harvey (Texas A&M Univ.), Riccardo Hernandez (North Carolina State Univ.), Jason Hollick (Ohio State Univ.), Alwin Hopf (Univ. of Florida), Doug Hopper (Achieving Solutions), Madeline Horvat (Ohio State Univ.), Brandon Huber (Ag Eye Technologies), Sara Humphrey (Univ. of Florida), Kale Ilchena (Conviron), David Imberti, Henry Imberti (Percival Scientific Inc.), TC Jayalath (Univ. of Georgia), Sangjun Jeong (Texas A&M Univ.), Fei Jia (Heliospectra), Dave Johnson (LiCor Biosciences), Murat Kacira (Univ. of Arizona), Luyang Kang (Eindhoven Univ. of Technology), Ramesh Kanwar (Iowa State Univ.), Meriam Karlsson (Univ. of Alaska), Nathan Kelly (Michigan State Univ.), Emily Kennebeck (Univ. of Delaware), Rob Kerslake (Kerslake & Associates), Dan Kiekhaefer (Percival Scientific Inc.), Changhyeon Kim (Univ. of Georgia), Hye-Ji Kim (Purdue Univ.), Rebecca Knight (Hawthorne Gardening), Kent Kobayashi (Univ. of Hawaii), Annika Elizabeth Kohler (Michigan State Univ.), Mary Jo Kopf (LI-COR Biosciences), Brian Krug (Corteva Agriscience), Chieri Kubota (Ohio State University), Paul Kusuma (Wageningen Univ.), Alex Ladroma (Conviron), Noah Langenfeld (Utah State Univ.), Stephen Lantin (Univ. of Florida), Emerick Larkin (Univ. of Florida), John Lea-Cox (Univ. of Maryland), Tanapol Leelertkij (Univ. of Florida), Mark Lefsrud (McGill Univ.), Daniel Leskovar (Texas A&M Univ.), Peter Ling (Ohio State Univ.), Jun Liu (Univ. of Georgia), David Llewellyn (Univ. of Guelph), Leo Lobato Kelly (Karma Verde Fresh), Roberto Lopez (Michigan State Univ.), Rod Madsen (LI-COR Biosciences), Gioia Massa (NASA - KSC), Jeff Mastin (TotalGrow Lights), Erico Mattos (GLASE, Cornell Univ.), Neil Mattson (Cornell Univ.), Qingwu Meng (Univ. of Delaware), Tim Mies (Univ. of Illinois),

Cary Mitchell (Purdue Univ.), Moein Moosavi-Nezhad (University of Tehran), Sun Nam (Univ. of Georgia), Most Tehera Naznin (York College of Pennsylvania), Genhua Niu (Texas A&M Univ.) Monique Oliveira (Unicamp), Yujin Park (Arizona State Univ.), Morgan Pattison (DOE), Robert Pauls (BioChambers Inc.), Catherine Peyotdes Gachons (Monell Chemical Senses Center), Brian Poel (Fluence Bioengineering), Jean Pompeo (Univ. of Florida), Federico Puksic (Grodan), Thais Queiroz Zorzeto Cesar (UNICAMP), Brad Rein (USDA National Institute of Food), Yan Ren-Butcher (80 Acres Farms), Meghan Roche (North Carolina State Univ.), Isadora Rodriguez (Syngenta), Mark Romer (McGill University), Erik Runkle (Michigan State Univ.), Carole Saravitz (North Carolina State Univ.), Noah Savastano (Univ. of Delaware), Diego Sepulveda (Syngenta), KC Shasteen (Univ. of Arizona), Tim Shelford (Cornell Univ.), Xiaonan Shi (North Carolina State Univ.), Jiyong Shin (Michigan State Univ.), Gregg Short (Greenhouse Design LLC), Todd Smith (Duke University), Elisa Solis (Univ. of Florida), Hans Spalholz (GE Current), Caleb Spall (Michigan State Univ.), Robert Spivock (GE Current), Eric Stallknecht (Michigan State Univ.), Gary Stutte (SyNRGE), Ronnie Sugden (Biochambers), Garry Taylor (UK CEUG), Daniel Terlizzese (Univ. of Guelph), Marc Theroux (BioChambers Inc.), Partin Thompson (North Carolina State Univ.), KC Ting (Univ. of Illinois), Victor Tishchenko (Univ. of Georgia), Marc van Iersel (Univ. of Georgia), Vera Velasco (Univ. of Toronto), Kahlin Wacker (Univ. of Georgia), Kellie Walters (Univ. of Tennessee), Colton Warren ( ), Nicole Waterland (West Virginia Univ.), Tharindu Weeraratne (WayBeyond Ltd), Ray Wheeler (NASA - KSC), John Wierzchowski (Environmental Growth Chambers), Rustin Wright (Biora), Bo-Sen Wu (McGill Univ.), Melanie Yelton (Plenty), Neil Yorio (Maui Greens), Azlan Zahid (Texas A&M Univ.), Paul Zankowski (USDA Office of the Chief Scientist), Yang Zhang (Conviron), Ying Zhang (Univ. of Florida), Shuyang Zhen (Texas A&M Univ.), Youbin Zheng (Univ. of Guelph), Wayne Zimmerman (Conviron).

To Dos

- Ramesh Kanwar encourages the NCERA-101 committee to re-apply for a Research Excellence award by the USDA
- Determine the location of the 2023 Annual Meeting
- Determine the award amount for the student talks

Brief Summary of the Minutes of the 2021 NCERA-101 Business Meeting

November 15, 2021
Start 1:00 pm

Attendance list from this conference (see above) – 146 attendees

Introduction of Executive Officers

Chair: Neil Yorio (Maui Greens Inc.), Vice-Chair: Murat Kacira (University of Arizona), Secretary: Marc Theroux (BioChambers), Past-Chair: Mark Lefsrud (McGill University)

Approval of Minutes

Minutes of meeting 2019 – Presented by Murat Kacira
Motion to Pass – Neil Yorio

Second – Gary Stutte
Passed unanimously

Other Conferences

- ISHS International Horticultural Congress (https://www.ihc2022.org/), Angers, France, August 14-20, 2022, Symposia S6 Innovative Technologies and Production Strategies for Sustainable Controlled Environment Horticulture and Symposia S8 Advances in Vertical Farming
- ASHS Annual Conference (https://ashs.org/page/GeneralConference), Chicago, Illinois, July 30 – August 3, 2022
- Indoor Ag Con (https://indoor.ag/), Las Vegas, Nevada, February 28 – March 1, 2022
- ASABE Annual International Meeting (https://www.asabemeetings.org/), Houston, Texas, July 17-20, 2022

Administration Advisors Report – Ramesh Kanwar

- Thanks members for participation with approximately 150 registered for the conference and 83 in attendance for the business meeting
- NCERA-101 project successfully renewed for an additional 5 years until 2026
- Station reports and meeting minutes to be submitted in the NIMSS system within 60 days after this meeting (due before January 14, 2022)
- Encouraged the group to pursue oversees meeting and to explore funding
- Encouraged the NCERA-101 committee to re-apply for a Research Excellence award by the USDA. In the application include that the committee started in 1972, has a growing membership, diversity of membership (USDA, NIFA, Universities, NASA, Industry, multi-Country membership), and highlight the projects which were funded at a multi-State and multi-University level.

USDA/NIFA Representative Report – Brad Rein

- Brad is the National Science Liaison for Sustainable Ag., Technology, Economics & Social Sciences
- Longest serving NIFA employee
- Present programs he is responsible for include Urban, Indoor & Emerging Ag. and 5 Hatch Multi-State (Micro-irrigation, Safety, Sustain. Systems Env. Hort.)
- Urban, Indoor, and Emerging Agriculture (UIE) is a new authorization from the farm bill and Brad is the lead to get the program started
- Mandatory funding of $10 million and authorized up to $10 million for each fiscal year FY19-FY23
- Working on getting ready for Request for Applications
- https://nifa.usda.gov/program/uie-ag
- Steven Thomson is the liaison for the NCERA-101

Website Report – Carole Saravitz

- Most visited website pages from Nov 2020 to 2021: Home page (28%), Growth Chamber Handbook page (14%), Meetings page (9%), Members page (5%), and Reporting Guidelines page (2%)

- Website visits by country: United States (39%), Canada (14%), China (9%), India (4%), Brazil (2%)
- Carole can post information and links on the website for research that is relevant to the group
- Gary Gardner recommended having a page on the website with information related to Vertical Farming and Carole responded that she could add a section on this topic and asked the group to forward her information for her to post

Membership Report – Mark Romer

- Mark collects/updates members information and works with Carole to update the members information on the website
- 46th Annual Meeting – First time in a large format Zoom meeting
- Grateful to Erik, Roberto, and team at MSU for having organized this years meeting
- Membership Summary (see appendix A)
    - 173 Members
    - 137 Total Institutions (53 Industry Institutions)
    - 33 U.S. States
    - 9 Countries
- Passing away of three members this past year including Don Krizek (founding father of this group and active participant since 1976), AO Rule (one of the first industry members), and Ed Harwood (member since 2008, established a successful indoor farming company)
- One of the earliest controlled environment facilities, the Biotron at the University of Wisconsin has closed to plant research. Started in 1967 and the home to a founding father of this group Ted Tibbitts. It was also the first place plants were grown with LED lights back in 1986.
- 20 Year membership awards presented to three members: Marc Theroux (member since 2001) presented by Mark Romer, Marc van Iersel (members since 2000) presented by Bruce Bugbee, and John Lea-Cox (member since 1997) presented by Marc van Iersel

Guidelines

- ASABE Standards efforts (Mark Lefsrud)
    - PAFS – 30 - X653 Recommended Practice for Heating, Ventilation and Air Conditioning (HVAC), and Lighting Systems Used for Indoor Plant Growth without sunlight. *It has been accepted, joint standard with ASABE and ASHRAE, session at ASABE annual meeting to present material, now published as ANSI/ASABE/ASHRAE EP653 Heating, Ventilating, and Air Conditioning (HVAC) for Indoor Plant Environments without Sunlight.*
    - ES-311 - X644 Performance Criteria for Optical Radiation Devices and Systems Installed for Plant Growth and Development. *On hold and is moving along.*
    - ES-311 - S642 Recommended Methods of Measurements and Testing for LED Radiation Products for Plant Growth and Development. *Published approximately 3 years ago.*

  - ES-311 - S640 Definition of Metrics of Radiation for Plant Growth (Controlled Environment Horticulture) Applications. *Up for renewal and new committee has been formed to potentially include the addition of ePAR*.
  - Bruno Faucher asked about X653 and a similar standard for greenhouses of which Mark Lefsrud indicated that there is a standard but that it is being archived as the greenhouse manufacturing society has it's own standard
- CEADS (Controlled Environment Agriculture Design Standards) (Gary Stutte)
  - Overall sustainability rating of facilities (https://ceads.ag)
  - Standard looks at crop quality, automation & labor, materials & waste, resource utilization, profitability, integrated pest management, equity & localness
  - Approximately 150 different criteria used for a point based system
  - Standards in development and undergoing prototyping with select number of industry participants before public release

<u>Instrument Package and Financials Report</u> – Bruce Bugbee

- $42,000 in the NCERA-101 "Travel" account
- Less money is being used for instruments and more towards student travel grants, student awards, and a buffer for hosting meetings
- Bruce is looking to see if the money could be placed in an interest bearing account with the University
- Consider investing more towards student awards and student travel grants

<u>Graduate Student Update</u> – Jonathan Frantz

- 11 speakers for student lightning talks (5 minutes each)
- Awards for 1st, 2nd, and 3rd place
- Bruce Bugbee mentioned that the money for the student travel awards are provided to the student's lab and that we should do the same for the student presentation awards as it is easier to process the payments from University to University versus a direct payment to the student, the lab could then re-imburse the students accordingly
- Neil Yorio suggested that after the meeting the executive committee discuss the amount that should be given for student presentation awards

<u>Future Meetings</u>

- 2022 University of Arizona (International Meeting), Murat Kacira's team hosting
  - Sept. 11-14, 2022
  - Marriott University Park Hotel, Tucson, Arizona, USA
  - 2.5 days of technical sessions, tour a commercial grower on afternoon of day 3
  - Hybrid meeting with in person attendance and also with remote attendance
  - Will have poster session and lighting talks for students
- 2023 Meeting
  - Shamim Ahamed from the University of California Davis expressed interest in hosting and Melanie Yelton from Plenty offered to help
  - Leo Lobato-Kelly from Karma Verde Fresh has also expressed interest in hosting a meeting in Mexico
  - The executive committee will meet to review the two options

- 2024 Iowa State University, Chris Currey's team hosting
- 2025 Meeting, host to be determined at a future date

Election of Secretary

- Motion to nominate Ricardo Hernandez (NC State University) by Neil Yorio
- Second Bruce Bugbee
- Passed unanimously, Congratulations to Ricardo

NCERA-101 Membership Growth – Bruce Bugbee

- As the group has grown there are some concerns with meetings losing their focus as an academic group as it is formally a multi-state working group from Ag Experiment Stations
- There have been previous discussions on separation of academic interests and commercial interests and this year the group provided 10 minutes for academic talks and 5 minutes for commercial talks
- Consider formalizing contributions to the group e.g. Gold, Silver, Bronze
- More time for academic talks and less time for commercial talks may reduce some of the insights gained from the commercial talks
- Neil Yorio discussed if presenters should submit abstracts and a committee would review the abstracts to determine if more time should be allocated
- Gary Stutte raised some concerns with having too much separation of the commercial group as they are a source for information on new innovations
- Gary Gardner mentioned that what makes the group unique is the blending of science from academia and commercial groups, consider distinguishing between new product versus scientific presentation from industry
- Erik Runkle has hesitation to abstract submissions as it can be a burden to the organizing committee and would prefer to leave the flexibility to the organizers and executive committee to determine the format which provides some variety to the yearly meetings
- Mark Romer commented that new industry members may need to be reminded that presentations are for a discussion on technology and not to promote products
- Neil Yorio indicated that this year we have three types of presentations: student lighting talks, academic presentations, and industry presentations
- Bruce Bugbee suggested that we leave it as it is and let the annual organizers determine the format but continue to be aware this issue
- Gary Gardner recommended that we further discuss this at next years meeting

New Business

- No new business items were brought forward for discussion

Passing of the Gavel

- Neil Yorio to Murat Kacira (now chair)

Adjourned 3:05pm (Neil Yorio)

Minutes respectfully submitted by Marc Theroux

Appendix A

NCERA-101 Membership Summary …… October 2021
Mark Romer, *Membership Secretary*

Membership Number ....March 2020 176
March 2021 173

- Additions 9
- Deletions.............................12
- Net Gain(Loss) ....(3)

Membership Composition	Institutions	Members
• Phytotrons & Controlled Environment Facilities	8	11
• University Departments, Agr. Exp. Stations	64	85
• Government Organizations & Contractors	12	11
• Industry Representatives	53	66
Total Number of Institutions / Members	**137**	**173**

Total Number of Countries 9
Total Number of US States 33

New Institutions:

University of Toronto Mississauga
Growth Facilities

University of Delaware
Plant and Soil Sciences

University of California, Davis
Biological and Agricultural Engineering

Texas A&M University
Department of Horticultural Sciences

Cornell University
Agricultural Experiment Station

- ELO Life Systems
- Greenhouse Design LLC
- Hawthorne Gardening Company
- Upward Farms

Appendix B

Accomplishments (19 Reports)
(The complete station reports are available on the NCERA-101 website https://www.controlledenvironments.org/station-reports/)

1. New Facilities and Equipment

Purdue

For the SCRI OPtimIA project, Phytofy LED arrays were replaced with ORBITEC/Sierra Space BPSE LED arrays for close-canopy lighting (CCL) experiments. Each BPSE unit is continuously variable in height, and red, green, and blue LEDs are distributed uniformly within the array, which is important for close lamp/crop separation distances. BPSE LEDs are dimmable by waveband, which also is important for control of spectral composition. Height is adjustable ranging from 15 cm as the closet vertical distance between lamp and crop surface to 45 cm, which is the control based on commercial settings.

For the AFRI Minitron III project, a CO_2 injection sub-system was added prior to the inlet port to the crop gas-exchange cuvette. A mass-flow valve (MFV) was installed within a stream of pure CO_2 prior to injection into a bulk air stream. MFV apertures are controlled from a computer keyboard. A CO_2 scrubbing sub-system was added to bulk airflow upstream of CO_2 injection for precise control of CO_2 concentration of cuvette inlet air. This was particularly useful for establishing CO_2 and light dose-response curves.

Kennedy Space Center

KSC continues to use Heliospectra RX30 LED lighting systems for many studies. The fixtures provide nine, selectively dimmable LED wavelengths -- 380, 400, 420, 450, 520, 630, 660, 735 nm, and white (~5700 K). KSC also uses four dimmable, 6500 K white LED arrays from BIOS Lighting (Melbourne, FL) and six red-green-blue BPSe arrays from SNC-ORBITEC (Madison, WI) mimicking the Veggie hardware. KSC have also purchased 90 OSRAM PHYOFY RL lights to outfit several of their growth chambers and plant growth rooms, with the intent of eventual replacing the Heliospectra RX30 lighting fixtures. The OSRAM Phytofy RL has selectively dimmable LED wavelengths at 385, 450, 521, 660, 730 nm and white (2700 K). KSC has installed a vertical wall growing system in one of their chambers that contains the 6 BPSe lights as well as 6 OSRAM PHYTOFY lights in 9 growth spaces for crop testing under environmental conditions relevant to the International Space Station.

Larry Koss of the KSC team completed fabrication and installation of six Environmental Test Chambers (ETC Chambers) that, when placed inside a walk-in chamber, allow for independent and precise control of a variety of environmental variables, to include CO_2, temperature, and humidity. The interior dimensions of the chambers are: interior is 16” w x 18” d x 19” h (40.6 cm x 45.7 cm x 48.3) with a volume of 89.7 L. These latest ETC Chambers are an upgrade to a previous generation, and feature SOA LED lighting systems, a larger growth area, and greater control capabilities.

The Ohio State University

- Construction of Controlled Environment Agriculture Research Complex (CEARC) began in January 2021. This state-of-the-art research greenhouse facility will provide a platform for interdisciplinary research at the nexus of horticulture/crop science, engineering, entomology, plant pathology, food science, computer science, and human nutrition/health. The $36 million project is located at Waterman Agricultural and Natural Resources Laboratory farm and will be completed by summer 2022.
- Old 1000-W MH lamps were replaced with LED lights (GAVITA CT 1930e LEDs, 780 W) in departmental research greenhouse compartments (a total of 7,000 sqft). While electric power consumption is saved by 20%, the PPFD over bench was increased to 3 times or greater level.
- Soil moisture sensors (Meter EC-5 and TEROS-12) were installed in the strawberry troughs filled with coco-coir substrate.
- UV lights were installed over tomato plants of genotypes sensitive to intumescence-inducing UV-deficient light environment. Operation time and target intensities were selected to provide a minimum UV-B dose (300-320 nm integral: 17 mmol m^{-2} d^{-1}) to prevent intumescence injury.
- LiDAR sensor was installed on a mobile irrigation boom to characterize plant canopy for precision variable rate liquid delivery.

Rutgers University New Jersey Agricultural Experiment Station

Rutgers conducted preliminary measurements within the canopy of a lean-and-lower tomato crop, comparing a LI-COR spherical quantum sensor (LI-193) with a combination of an upward and downward facing regular quantum sensors (LI-190R). Results showed that the spherical quantum sensor captures more radiation. The calculated DLIs were on average 1.55 higher when measured with the spherical quantum sensor compared to the DLI measured with an upward facing regular quantum sensor (n = 54, St. Dev. = 0.13). Rutgers plans to conduct additional experiments with the setup they designed.

University of Arizona

- Folium wireless environmental monitoring system from Autogrow Folium - Climate Monitoring Solution — Autogrow installed within a 107 m2 ETFE glazed greenhouse compartment is being evaluated in comparison to Campbell Scientific wired sensors for air temperature, PPFD, RH and leaf surface temperature in the production of truss tomato (Project PI Giacomelli).
- The University of Arizona received and installed 72 new LED lighting bars (Model HelioSPEC Izar, with Red, Green, Blue and FR spectrum) with drivers from Heliospectra within the vertical farm facility at CEAC (UAgFarm) as part of a collaboration within USDA-SCRI funded OptimIA project. A new controller (Hash Controller, Iluminar) was installed to control light intensity, DLIs and scheduling from the new LED lighting system. Iluminar Hash wireless sensor network measuring PPFD, air temperature, RH, VPD

(calculated), CO_2 was installed in their vertical farm facility to evaluate its performance and application in research activities, and as part of educational program (PI M. Kacira).

- Graduate student KC Shasteen (advisor M. Kacira) has developed and evaluated a computer vision system with predictive modeling to monitor and evaluate crop growth and yield.

Arizona State University

- The Arizona State University (ASU) Indoor Farming Lab was launched in April, 2021. The ASU Indoor Farming Lab consists of 10 deep water culture hydroponic growing racks, each with three tiers. Each growing rack is equipped with LED lamps, a quantum sensor (LI-190R, LI-COR), and a thermocouple (Type E, Omega Engineering). Two additional fan aspirated air temperature and relative humidity probes (EE08-SS, Apogee) are used to monitor the air temperature and relative humidity in the ASU Indoor Farming Lab. All environmental data is recorded by a datalogger (CR1000X, Campbell Scientific).
- Multiparameters pH/EC/DO/Temperature (HI98194, Hannah Instruments) were purchased to measure the dissolved oxygen concentration of the hydroponic nutrient solution.
- Fan aspirated thermistors (TS-110-SS, Apogee), pyranometers (LI-200R, LI-COR), quantum sensors (LI-190R, LI-COR), and a datalogger (CR1000X, Campbell Scientific) were installed in the research greenhouse.
- Two walk-in growth chambers are installed. The growth chambers will enable experiments to investigate the effects of different temperatures, light qualities, CO_2, and relative humidity on plant growth and development.

University of California Davis

The college of agricultural and environmental sciences (CAES) at the University of California, Davis (UC Davis), has 162 greenhouses facilities with about 155,00 sq. ft of spaces. A new shipping container-type facility has recently been added for teaching and research. The controlled environment engineering lab is currently working with the vendor to add a walk-in type indoor vertical farming facility to study the energy use efficiency for indoor growing spaces. CELPA is also working on designing a lab-scale autonomous vertical aquaponic growing system. This research facility would study the energy efficiency aspects and life-cycle assessment of vertical aquaponic systems for indoor application.

University of Delaware

The University of Delaware has completed the development of the Delaware Indoor Ag Lab (DIAL), which is housed in the Fischer Greenhouse Complex at the University of Delaware. This lab will serve as the main indoor agriculture research facility in Delaware with state-of-the-art LED technology and environmental control systems. It has three separate sections in the same room to allow for multiple simultaneous research projects:

- Two 3-tier shelving units are equipped with Osram Phytofy RL LED fixtures for indoor plant research on interactions among light quality, intensity, and duration. Each fixture has six independently programmable color channels, including ultraviolet-A, blue, green, red, far red, and warm white. The University of Arizona has installed vertical and horizontal fans to promote air movement and temperature and humidity sensors (Onset) to collect data on each shelf.

- Four 3-tier shelving units are equipped with arrays of Demegrow LED fixtures for indoor plant research on light intensity and duration. The warm-white LED fixtures are dimmable with adjustable timing through wireless smartphone control.
- Four reach-in plant growth chambers from Percival Scientific are dedicated to indoor plant research on environmental optimization. Each chamber has precise control of light, air temperature, relative humidity, and carbon dioxide concentration. Two tiers within each chamber have tunable LED arrays comprised of four independent color channels, including blue, green, red, and far red. All environmental parameters are adjustable and monitored through a touchscreen interface.

The University of Delaware has purchased a variety of instruments for plant data collection including: 1) a CIRAS-3 photosynthesis system (PP Systems); 2) a CI-202 leaf area meter (CID Bio-Science); 3) a CR-10 Plus color reader (Konica Minolta Sensing); 4) analytical and top-loading balances (A&D); 5) a Genesys 40 Vis spectrophotometer (Fisher Scientific); 6) quantum sensors and a field spectroradiometer (Apogee); 7) an MC-100 chlorophyll meter (Apogee); and 8) a forced-air drying oven (Shel Lab).

University of Georgia

Although not exactly a new facility or equipment, the University of Georgia's department of Horticulture is pleased to welcome Dr. Rhuanito Ferrarezi as a new faculty member with a research focus in CEA. Dr. Ferrarezi's research program will focus on CEA production systems and nutrient management. He will also teach a split-level course in greenhouse management and an undergraduate course in controlled environment agriculture.

Inspired by prior work with a commercial multi-spectral imaging system, the University of Georgia has developed a low-cost multi-spectral imaging system. The system uses a Raspberry Pi microcomputer and Arducam monochrome camera. The system takes images under red, green, blue, and infra-red light, as well as an image of chlorophyll fluorescence emitted by plants. Other colors can easily be added if desired. The Raspberry Pi automatically analyzes the images, applying a mask to separate plant from background and creates normalized difference vegetation index (NDVI) and anthocyanin content index (ACI) images. The spatial distribution of NDVI and ACI is automatically quantified. The system can be assembled for ~ $400.

Texas A&M University

- Texas A&M have installed a new shipping container with three compartments (equivalent to growth chambers) at Dallas Center.
- Texas A&M are establishing and equipping a new research laboratory in Controlled Environment Agriculture/Horticulture at College Station.

USDA-ARS (Beltsville, Maryland)

- A contract was awarded for 6 new Conviron PGC-FLEX growth chambers and 2 new walk-in BDW120 plant growth rooms to be installed in November, 2021 at the Controlled Environment Facility (CEF) located in Beltsville, Maryland. The CEF currently includes 21 actively managed growth chambers. These include 10 reach-in style EGC units equipped with HID lamps, 2 walk-in EGC units with fluorescent lamps, 7 Biochamber reach-in style units originally equipped with HID lamps, and two smaller Biochamber units with LED lamps. In response to an energy conservation push, USDA retrofitted the HID light canopies in the 7 Biochamber units with LED lamps. The new Conviron units will also be equipped with LED lamps of the same spectral quality. A set of six obsolete EGC reach-in units exceeded their life-cycle (purchased in the 1980s) and were removed from the facility. Moving forward into 2022, CEF will include 23 actively managed growth chamber units.
- Improvements related to outdoor chiller and cooling tower operations were implemented at the Soil-Plant-Atmosphere-Research (SPAR) facility. These included upgraded software systems to improve chiller control actions and new loop temperature and coolant flow sensors which together reduce energy consumption. A set 18 new LI-7000 CO_2/H_2O gas analyzers (LI-COR Biosciences) were installed to replace older style, obsolete, LI-6262 units. A new CO_2 scrubbing system was recently purchased to provide CO_2 free air to assist in maintaining desired set-points during the night-time in the SPAR chambers. The system will be integrated in 2022. In total, the SPAR facility includes 18 outdoor SPAR chamber units and six reach-in style Biochamber units with HID lamps.
- Two adjacent mini-greenhouse units which utilize forced air systems for heat were retrofit with CO_2 control along with data acquisition system and sensors for measurement of photosynthetically active radiation, relative humidity, air and soil temperature, and time-domain reflectometry (TDR) soil water content data. Climate data is logged at 30 second intervals while TDR data is recorded manually per end-user control.
- A new OctoFlox rugged multi-target SIF/hyperspectral reflectance spectrometer (JB – Hyperspectral) which will assist studies related to high throughput greenhouse phenotypic system related to measuring SIF (solar induced fluorescence) and reflectance. A Pika L hyperspectral camera (Resonon) was also purchased for this phenotyping work along with a RSE 600 (Fluke) thermal imaging camera.

Sierra Space

Sierra Space is in the process of testing the Astro Garden® test facility (Figure 1). The Astro Garden is a testbed for vegetable crop production in space habitations. The system has approximately 5.4 m^2 of growing area and most of the subsystems are designed to be gravity independent for operation. The testbed provides temperature, humidity, CO_2 control, and nutrient solution control. Root zones currently use aeroponics but are modular so alternative technologies can be tested. Lighting is provided by red, blue and white LEDs. Each module has individual control of light level, photoperiod and light quality. The system also has a mechanism for capturing transpired water. Astro Garden was configured to meet the NASA Exploration Life Support Salad Crop Diet production requirements.

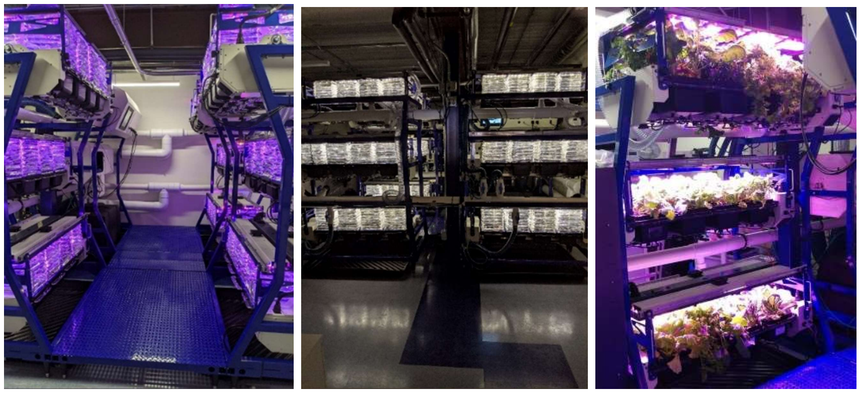

Figure 1. Astro Garden system with nine growing modules and three atmospheric control, fluid system, and electronics modules.

LI-COR BioSciences

LI-600

LI-6800

- The new LI-600 Porometer/Fluorometer is a lightweight, handheld porometer and optional fluorometer that simultaneously measures stomatal conductance and chlorophyll fluorescence of leaves while they are connected to the plant.
- The LI-6800 Portable Photosynthesis System characterizes gas exchange and fluorescence and numerous other parameters under controlled chamber conditions of light, temperature, humidity and CO_2.

Percival Scientific

With the help of USDA through the Rural Economic Development Loan and Grant Program, investment partners Minburn, CIPCO, the Iowa Area Development Group, City of Perry, and Perry Economic Development; Percival broke ground as part of a new expansion to the plant this year. This will add to the production space by over 60 percent, increase Percival's production capacity, and allow the company to focus on larger products while continuing to grow their traditional product lines.

Plenty

- In Compton, CA, Plenty is building a 95,000 ft^2 vertical farm with the world's highest leafy green production capacity.

- Plenty has attracted over $500M of investment so far.
- Plenty is collaborating with Driscoll's to grow strawberries vertically.

2. Unique Plant Responses

Purdue

Through gas-exchange analysis, baby-green and leafy-green crop stands followed the same pattern as they responded to various levels of CO_2 and light intensity in dose-response curves. Although the overall pattern was similar, leafy greens saturated at slightly higher concentration than did baby greens in CO_2 dose-response curves.

It is estimated that 68.4% of global population live in urban areas by 2050. The population growth demands regular supply of fresh, nutritious, and safe food in urban areas. One concept that has evolved recently is to produce food in urban areas using indoor vertical farming. These farms can be fitted with customized LED lights for producing leafy greens and other small-statured crops. Purdue is studying the effects of spectral composition of light ranging from 365 to 750 nm on phytochemical levels including beta-carotene (precursor to vitamin A), phylloquinone (precursor to vitamin K), and anthocyanins (anti-oxidants) in lettuce. The purpose is to understand the physiological mechanisms affected by light spectral composition that influence phytochemical levels in lettuce. Purdue's goal is to increase nutritional value of lettuce with minimal negative effect on plant growth and quality. Purdue has established a vertical production system where air temperature, light intensity, and spectral composition are tightly controlled. In addition, Purdue has established assays to measure phytochemical levels in plant tissue.

Although there has been a double-digit increase in the demand for organic produce during the last three decades, low crop yields have been a persistent problem in organic farming. This is attributed mainly to low nitrogen (N) availability to plants and lack of synchronization between crop growth and N release from organic fertilizers. Organic yields can be improved by optimizing plant N levels. However, this requires regular monitoring and optimal management of plant N status. Purdue is developing affordable and reliable IoT sensors for capturing and locally processing images, and estimating plant growth and N status. When developed, the sensors will effectively collaborate with each other and provide automated decision support on nutrient delivery to plants and managing optimal N status in plants. Currently, Purdue is manually studying different organic recipes for lettuce that result in crop yields which are comparable to conventional hydroponic production. Purdue will test the efficacy of the IoT sensor technology to automatically maintain high lettuce yields and optimize fertilizer use in organic hydroponic production using the developed organic fertilizer recipe.

Water scarcity, food insecurity, under-nourishment and unemployment are major issues faced by Egypt. With population growth expected to increase by 50 million in next 20 years, there is an increased risk of food insecurity in Egypt. Research has shown that hydroponic and aeroponic production systems can save 60 to 75 percent of irrigation water and produce yields similar or better than field based production. Hydroponic/aeroponic production under protected agriculture (e.g. greenhouse) can ensure year-round food production with less water requirement in Egypt. However, region-specific hydroponic production technologies need to be developed. The technology is medium to high in investment. To develop technologies that are feasible to small-scale growers in Egypt, it is critical that they are efficient and affordable. With support from USDA FAS, Purdue is conducting research on screening best hydroponic/aeroponic technologies for Egypt. Best technologies that reduce water-use and maximize crop yield and nutritional quality will be validated in Egypt. Sustainability of new technologies in Egypt will heavily rely on developing trained workforce. Purdue's approach is to conduct extension and outreach activities in Egypt to train producers (especially women and small-scale producers) by demonstrating the benefits of developed technology.

Kennedy Space Center

During the Veg-03I tech demo test on ISS in early 2021 the crew attempted to transplant an extra pak choi seedling into an empty plant pillow for the first time in Veggie. The extraction of the seedling did not go as intended, most of the roots were severed (Figure 2) and the ground team had little hope the seedling would reestablish itself in its new pillow and survive until final harvest. Much to the surprise of Kennedy Space Center researchers, the seedling survived and did quite well over the next few weeks and reached final harvest. A second transplant was attempted during Veg-03I with 'Red Russian' kale and a similar phenomenon was observed. The mechanisms are not clear right now, but microgravity appears to confer some benefit to transplanting in space.

Figure 2. *Left: Pak choi seedling transplanted 10 Days after initiation. Right: Comparison at Day 28 of an original and transplanted pak choi.*

McGill University

Chlorophyll's light-harvesting role in photosynthesis has not been challenged in over 40 years. Using light emitting diodes and a high-resolution monochromator, McGill University developed a method to measure at 1-nm increments a spectral photosynthesis curve determined in tomato plants with a 10-nm bandwidth light spectrum. Minimal photosynthetic rates (μmol CO_2 m^{-2} s^{-1} nm^{-1}) were recorded at spectra corresponding to peak chlorophyll absorbance (420 nm and 660 nm for chlorophyll *a*, and 450 and 640 nm for chlorophyll *b*), showing that extracted pigment absorbance peaks and photosynthesis are inversely correlated. Photosynthesis theory decrees that photosynthetic pigments drive photosynthesis, and that these pigments absorb and convert specific wavelengths of light energy into chemical energy. McGill Universities' finding implies that chlorophyll may carry out an additional regulatory function in photosynthesis that has not yet been identified.

The Ohio State University

- Low pH 4.0 of hydroponic nutrient solution can effectively suppress the severity of root rot caused by *P. aphanidermatum* initiated by zoospore inoculation without influencing basil plant growth. This could be a new, low-cost strategy for water-borne disease prevention in hydroponic basil production (Gillespie, 2019; Gillespie at al., 2020).
- While basil can tolerate low pH (upto 4.0), most crops exhibit growth reduction caused by reduced nutrient uptake at low pH. When tested at pH 4.5 spinach reduced the shoot fresh weight by almost 60% compared with that under a standard pH 5.5. By increasing the nutrient concentrations (3X), the shoot fresh weight was recovered but still ~25% lower than the standard pH 5.5 (Papio, 2021; Gillespie et al., 2021).
- Nine lettuce cultivars considered as relatively sensitive to tipburn were grown under tipburn inducive conditions to assess the different degrees of sensitivity among cultivar types (romaine, butterhead, and leaf), leaf color (red and green) and production systems originally targeted in breeding program (open-field and greenhouse). Greenhouse cultivars were found relatively less sensitive and exhibited lower tipburn incidences than did open-field cultivators when grown under tipburn inducive indoor growing conditions. Cultivar-type did not show a significant effect on tipburn sensitivity. (Ertle and Kubota, unpublished).
- Reciprocal grafts between two cultivars – 'Nufar' (NF), a vigorous and Fusarium wilt resistant cultivar, and 'Dolce Fresca' (DF) a compact & uniform type, were evaluated for impact of scion and rootstock on the plant growth and mineral nutrient uptake. While low vigor DF used as rootstock reduced the overall growth of NF, high vigor NF used as rootstock did not increase the overall growth. When NF was used as rootstock, plants developed relatively low biomass in roots suggesting a greater efficiency of nutrient and water uptake for NF. Basil is known to have low mineral nutrient requirement in hydroponics, which may be a reason why improved mineral nutrition did not induce greater vigor or biomass. Therefore, in addition to basil, similar studies were initiated for tomato cultivars and rootstocks in order to better understand underline mechanism of rootstock- or scion-specific mineral nutrition affecting grafting vigor in tomato (Hollick and Kubota, 2021).

University of Delaware

Undergraduate student Stefanie Severin and Qingwu Meng investigated how alternate light intensities at 12-h intervals influenced indoor tomato, lettuce, and arugula seedling growth. Experimental results indicated that the effects of the daily light integral depended on the allocation of light over time and crop type. Doubling the daily light integral increased shoot mass of arugula but did not affect that of lettuce.

University of Georgia

Chlorophyll Fluorescence Imaging: A Novel, Simple and Non-Destructive Method for Canopy Size Imaging

Non-destructive methods to quantify crop growth can provide a valuable tool in both research and production settings. Quantifying canopy size can be done using a variety of imaging techniques, with regular color (red/green/blue, RGB) imaging being the most common approach. However, separating canopy from background is not always easy using RGB imaging and different methods may be needed depending on the background in the image or the color of the leaves. To circumvent this issue, the University of Georgia developed an imaging approach that takes advantage to the fluorescence emitted by chlorophyll. The energy of about 1 to 3% of photons absorbed by leaves is re-emitted as photons in the range of ~690 to 740 nm. This fluorescence coming from plants is easy to photograph: plants are exposed to blue light and images are taken using a monochrome camera with a 680 nm long-pass filter (i.e., only photons with wavelengths > 680 nm can pass through the filter). This assures that the camera can only detect fluorescence from chlorophyll. One complication is that the chlorophyll in algae fluoresces similar to that in plants, so image processing may be needed to separate algae from leaves. This can be achieved by comparing images collected under both blue and white light: algae are more pronounced under blue than under white light. Alternatively, algicides have proven effective in suppressing algae without harmful effects on plants. Comparisons of leaf area measurements using the fluorescence imaging versus a leaf area meter indicate that the fluorescence imaging is almost perfectly correlated with standard leaf area measurements (R^2 = 0.998). Chlorophyll fluorescence imaging can also be used to monitor ripening of fruits that contain chlorophyll in their unripe state. The decrease in fruit chlorophyll levels during ripening is easily quantified using this approach. The hardware costs for a chlorophyll imaging system are ~$1,000 and the system is easy to assemble. Researchers: Mangalam Narayanan, Marc van Iersel, Mark Haidekker.

Light Intensity Affects Leaf-Level and Crop-Level Water Use Efficiency

The cost of dehumidification is a significant portion of the total production costs in indoor production systems. Minimizing this cost can be achieved by maximizing the water use efficiency of the plants, thus reducing the need for dehumidification. This study was performed to determine leaf- and crop-level water use efficiency of vegetative and flowering crops under various photosynthetic photon flux densities (*PPFD*). 'Purple Wave Classic' petunia and 'Green Salad Bowl' lettuce were grown in a walk-in growth chamber, under *PPFD*s ranging from 152 - 374 $\mu mol \cdot m^{-2} \cdot s^{-1}$, provided by white LED lighting. To achieve the same daily light integral (DLI) of 12 $mol \cdot m^{-2} \cdot d^{-1}$, photoperiods ranged from 21.6 to 9 h in the different treatments. The temperature in the growth chamber was 24 °C and CO_2 was maintained at 800 ppm. Leaf-level assimilation increased with increasing *PPFD* in petunias and lettuce. However, in petunias transpiration decreased with increasing *PPFD*, whereas in lettuce it increased. This led to an increase in leaf-level water use efficiency in petunias with increasing *PPFD*, whereas in lettuce, there was no correlation between water use efficiency and *PPFD.* For both lettuce and petunia, dry weight decreased with higher *PPFD*s provided over shorter photoperiods. Petunia biomass was 57.0% higher at 152 $\mu mol \cdot m^{-2} \cdot s^{-1}$ than at 374 $\mu mol \cdot m^{-2} \cdot s^{-1}$ and lettuce biomass was 33.9% higher at 152 $\mu mol \cdot m^{-2} \cdot s^{-1}$ than at 374 $\mu mol \cdot m^{-2} \cdot s^{-1}$, when plants were given the same DLI of 12 $mol \cdot m^{-2} \cdot d^{-1}$. In petunia, dry weight decreased more strongly with increasing *PPFD* than water use, and thus crop-level water use efficiency decreased with increasing *PPFD* ($p < 0.001$). For lettuce, crop-level water use efficiency also decreased with increasing *PPFD* ($p < 0.001$). In conclusion, leaf-level measurements and crop-level measurements of water use efficiency did not show the same trends; leaf level measurement may thus provide misleading information. Crop-level measurements of plants grown under varying *PPFD*, but with the same DLI showed that lower light intensities and longer photoperiods resulted in higher yields and higher water use efficiency in both lettuce and petunias. *Researchers: Laura Reese and Marc van Iersel.*

Supplemental Far-Red Light Increases Final Yield of Indoor Lettuce Production By Boosting Light Interception at the Seedling Stage

Understanding crop responses to light spectrum is critical for optimal indoor crop production. Far-red light is of special interest, because it can accelerate crop growth both physiologically and morphologically. Far-red can increase photosynthetic efficiency when combined with lights of shorter wavelength. It also can induce leaf expansion, possibly increasing light capture and growth. However, the optimal amount of supplemental far-red light for crop growth and yield in indoor lettuce production is yet to be quantified. Lettuce 'Cherokee', 'Green Salad Bowl', and 'Little Gem' were grown under 200 $\mu mol \cdot m^{-2} \cdot s^{-1}$ warm white LED light with 16 levels of additional far-red light, ranging from 0 to 76 $\mu mol \cdot m^{-2} \cdot s^{-1}$. Supplemental far-red light increased canopy light interception (a measure of canopy size) 6 days after far-red light treatment for 'Green Salad Bowl' and 'Little Gem' and after 8 days for 'Cherokee'. The enhancement in canopy size was no longer evident after 12 and 16 days of far-red treatment for 'Green Salad Bowl' and 'Little Gem', respectively. The length of the longest leaf of all three cultivars was increased linearly by far-red light, consistent with a shade acclimation response to far-red light. Final dry weight of 'Cherokee' and 'Little Gem' were increased linearly by far-red light when harvested 20 days after the start of far-red light treatment, but dry weight of 'Green Salad Bowl' was not affected. In conclusion, adding far-red light in indoor production gives lettuce seedlings a jumpstart at capturing light. Supplemental far-red light increases crop yield linearly up to 76 $\mu mol \cdot m^{-2} \cdot s^{-1}$ in two of the three cultivars tested. *Researchers: Jun Liu and Marc van Iersel.*

The Quantum Requirement for CO_2 Assimilation Increases with Increasing Photosynthetic Photon Flux Density and Leaf Anthocyanin Concentration in Lettuce

The quantum requirement for CO_2 fixation, or moles of photons required to fix one mole of CO_2, determines how efficiently plants can use light to produce carbohydrates. It is calculated as the amount of absorbed light (photosynthetic photon flux density (*PPFD*) × leaf absorptance) divided by gross photosynthesis. Due to the high lighting costs in controlled environment agriculture, a low quantum requirement may increase growth and profitability. Typical estimates of the quantum requirement (~10-12 $mol \cdot mol^{-1}$) are based on the initial slope of photosynthesis-light response curves and do not account for non-photosynthetic pigments or changes due to light intensity. Anthocyanins, typically located in epidermal cells, are not photosynthetically active and light absorbed or reflected by them cannot be used for CO_2 assimilation. Since anthocyanins reduce how much light reaches photosynthetic pigments, anthocyanin-rich lettuce cultivars may have a greater quantum requirement than green cultivars. Additionally, photosynthetic light-use-efficiency decreases with increasing *PPFD*. The University of Georgia hypothesized that both higher anthocyanin levels in lettuce and increasing *PPFD* would increase the quantum requirement and quantified this using six red and three green lettuce cultivars, having a wide range of anthocyanin concentrations. Lettuce was grown in a greenhouse without supplemental lighting. The environmental conditions were a temperature of 25.2 ± 3.2 °C, a vapor pressure deficit of 1.0 ± 0.5 kPa, and a daily light integral of 24.2 ± 6.3 $mol \cdot m^{-2} \cdot d^{-1}$ (mean ± SD). Leaf-level photosynthesis was measured at *PPFD*s of 0, 50, 100, 200, 400, 700, 1000, and 1500 $\mu mol \cdot m^{-2} \cdot s^{-1}$. An integrating sphere was used to measure leaf absorptance. Anthocyanin concentration of the lettuces ranged from 12 to 71 $mg \cdot m^{-2}$. Absorptance increased linearly from 0.77 to 0.87 with increasing anthocyanin levels ($R^2 = 0.72$, $P < 0.001$). Gross photosynthesis at a *PPFD* of 1500 $\mu mol \cdot m^{-2} \cdot s^{-1}$ was ~50% lower in leaves with the highest anthocyanin level (8.1 $\mu mol \cdot m^{-2} \cdot s^{-1}$) than that of those with the lowest anthocyanin level (16.2 $\mu mol \cdot m^{-2} \cdot s^{-1}$) ($R^2 =$ 0.32, $P = 0.004$). The quantum requirement for CO_2 assimilation at a *PPFD* of 1500 $\mu mol \cdot m^{-2} \cdot s^{-1}$ increased from 80 to 150 $mol \cdot mol^{-1}$ as the anthocyanin concentration increased ($R^2 = 0.32$, $P =$ 0.003). With *PPFD* increasing from 200 to 1500 $\mu mol \cdot m^{-2} \cdot s^{-1}$, the quantum requirement increased from 30 to 110 $mol \cdot mol^{-1}$ ($R^2 = 0.63$, $P < 0.001$). In summary, both anthocyanins and high *PPFD* increased the quantum requirement for CO_2 assimilation to levels far above those typically cited in the literature. *Researchers: Changhyeon Kim and Marc van Iersel.*

Only Extreme Fluctuations in Lights Levels Reduce Lettuce Growth

The cost of providing supplemental lighting in greenhouses or sole-source lighting in plant factories can be high. In the case of variable electricity prices, it may be desirable to provide most of the light when electricity prices are relatively low. However, it is not clear how plants respond to the resulting fluctuating light levels. The University of Georgia hypothesized that plants that receive a constant photosynthetic photon flux density (*PPFD*) would produce the more biomass than those grown under fluctuating light levels. To quantify growth reductions caused by fluctuating light levels. The University of Georgia quantified the effects of fluctuating *PPFD* on the photosynthetic physiology and growth of 'Little Gem' and 'Green Salad Bowl' lettuce. Plants were grown in a walk-in growth chamber outfitted with three shelving units, each divided into six growing compartments. Each compartment contained two dimmable, white LED bars, programmed to alternate between high and low *PPFD*s every 15 minute. The *PPFD*s in the different treatments were ~ 400/0, 360/40, 320/80, 280/120, 240/160, and 200/200 $\mu mol \cdot m^{-2} \cdot s^{-1}$, with a photoperiod of 16 hours and a DLI of ~11.5 $mol \cdot m^{-2} \cdot d^{-1}$ in all treatments. CO_2 was maintained at ~ 800 $\mu mol \cdot mol^{-1}$. Data was analyzed using linear and non-linear regression. At 400/0 $\mu mol \cdot m^{-2} \cdot s^{-1}$, 30-minute-integrated A_n (net photosynthesis integrated 15 minute at high and 15 minute at low *PPFD*) was ~65% lower than at a *PPFD* of 320/80 $\mu mol \cdot m^{-2} \cdot s^{-1}$ (or treatments with smaller *PPFD* fluctuations). 30-minute-integrated A_n in the four treatments with the smallest *PPFD* fluctuations (320/80 to 200/200 $\mu mol \cdot m^{-2} \cdot s^{-1}$) was similar. Plants grown at 400/0 $\mu mol \cdot m^{-2} \cdot s^{-1}$ also had fewer leaves and lower chlorophyll content compared to those in all other treatments. The four treatments with the smallest fluctuations in *PPFD* produced plants with similar numbers of leaves, chlorophyll content, specific leaf area, dry mass, and leaf area. Chlorophyll content, 30-minute-integrated A_n, and dry mass were positively correlated with each other. These results show that lettuce tolerates a wide range of fluctuating *PPFD* without negative effects on growth and development. However, when fluctuations in PPFD are extreme (400/0 or 360/40 $\mu mol \cdot m^{-2} \cdot s^{-1}$), chlorophyll levels are low, which can explain the low 30-minute-integrated A_n and poor growth in these two treatments. The ability of lettuce to tolerate a wide range of fluctuating light levels suggests that it may be possible to adjust the *PPFD* in response to variable pricing. *Researchers: Ruqayah Bhuiyan and Marc van Iersel.*

Chlorophyll Fluorescence Imaging: A Novel, Low-Cost Method for Early Stress Detection

Using non-destructive methods, like chlorophyll fluorescence imaging, to provide early stress detection in plants could augment growing methods and allow for corrective measures to minimize damage to the plants. While many chlorophyll fluorescence imaging techniques require expensive, sophisticated equipment while other techniques only take single-point measurements, the current study focuses on a scalable novel technique that provides whole plant digital images of the chlorophyll fluorescence (but not Φ_{PSII}) using blue excitation light, a monochrome camera, and a long-pass filter (> 690 nm). There are three fates of light once a photon has been absorbed by a plant: it can be used to drive photochemistry (electron transport), be converted to heat, or be reemitted as chlorophyll fluorescence. A decrease in photochemistry by stressors will typically lead to an increase in chlorophyll fluorescence and/or heat dissipation to prevent damage from excess light. Due to this relationship, chlorophyll fluorescence has been used to non-destructively diagnose the photosynthetic performance of plants, with the quantum yield of photosystem II (Φ_{PSII}) being a common indicator of photochemical efficiency. To test the performance of the system, a photosystem II-inhibiting herbicide was applied as a drench at standard field rates to lettuce (*Lactuca sativa*), impatiens (*Impatiens hawkeri*) and vinca (*Catharanthus roseus*). Chlorophyll fluorescence images were taken using the TopView Multispectral Digital Imaging System (Aris, Eindhoven, Netherlands), which also took regular RGB images. The combined reflectance and fluorescence from the leaf were measured using a spectrometer and Φ_{PSII} was measured using a chlorophyll fluorometer. These measurements were taken every 15 minutes for 8 hours. In between measurements, the plants were exposed to a photosynthetic photon flux density of 176 $\mu mol \cdot m^{-2} \cdot s^{-1}$ provided by white LEDs. The pixel intensity in the fluorescence image, a measure of chlorophyll fluorescence, was negatively correlated with Φ_{PSII} ($P < 0.01$) as measured using a fluorometer. The average reflectance in the spectral range of fluorescence (670 – 760 nm) was positively correlated with the pixel intensity ($P < 0.0001$) and negatively correlated with Φ_{PSII} ($P \leq 0.07$). The results suggest that the novel chlorophyll fluorescence imaging technique is a reliable way to inexpensively detect stress to photosystem II before visible damage occurs to the plant. *Researchers: Reeve Legendre and Marc van Iersel.*

Supplemental Far-Red Light Does Not Increase Growth of Greenhouse-Grown Lettuce

The positive effects of far-red (FR) light on growth of leafy greens have been well-documented for crops grown in plant factories. However, there is a lack of information on the effects of supplemental FR on greenhouse-grown leafy greens. Therefore, the University of Georgia conducted a study with two cultivars of lettuce (*Lactuca sativa*, 'Green Salad Bowl' and 'Cherokee') with five lighting treatments. The treatments were supplemental lighting with a photosynthetic photon flux density (*PPFD*) of 200 $\mu mol \cdot m^{-2} \cdot s^{-1}$, *PPFD* of 200 $\mu mol \cdot m^{-2} \cdot s^{-1}$ + 10 $\mu mol \cdot m^{-2} \cdot s^{-1}$ of FR light, *PPFD* of 200 $\mu mol \cdot m^{-2} \cdot s^{-1}$ + 20 $\mu mol \cdot m^{-2} \cdot s^{-1}$ of FR light, *PPFD* of 220

$\mu mol \cdot m^{-2} \cdot s^{-1}$, and sunlight only. Supplemental *PPFD* was provided with 75% red and 25% blue light for 4 hours before sunrise and 4 hours after sunset. The daily light integral (DLI) received from the sun averaged 7.5 $mol \cdot m^{-2} \cdot d^{-1}$ during the study period. The treatments with supplemental *PPFD*s of 200 and 220 $\mu mol \cdot m^{-2} \cdot s^{-1}$ averaged DLIs of 13.3 and DLI of 13.8 $mol \cdot m^{-2} \cdot d^{-1}$. The FR treatments with 10 and 20 $\mu mol \cdot m^{-2} \cdot s^{-1}$ received 0.29 and 0.58 $mol \cdot m^{-2} \cdot d^{-1}$ of supplemental FR light. All supplemental lighting treatments increased leaf area and plant dry weight compared to the treatment without supplemental lighting ($P < 0.0001$). However, the University of Georgia did not see any positive effects on crop growth by adding FR light. Similarly, the treatment with slightly higher PPFD level of 220 $\mu mol \cdot m^{-2} \cdot s^{-1}$ did not show a significant growth difference compared to the treatment with a supplemental PPFD of 200 $\mu mol \cdot m^{-2} \cdot s^{-1}$. These results do not provide any evidence for positive effects of supplemental FR light on greenhouse-grown lettuce. This may be due to the presence of high levels of FR light from the sun in the greenhouses. *Researchers: T.C. Jayalath and Marc van Iersel.*

Development and Implementation of a New Optimal Supplemental Lighting Control Strategy in Greenhouses

The use of supplemental lighting is an effective way for increasing greenhouse productivity. Recently, using light-emitting diodes (LEDs), capable of precise and quick dimmability, has increased in greenhouses. However, electricity cost of lighting can be significant, and hence, it is necessary to find optimal lighting strategies to minimize supplemental lighting costs. The University of Georgia has modeled supplemental lighting in a greenhouse equipped with LEDs as a constrained optimization problem, with the aim of minimizing electricity costs of artificial lighting. The University of Georgia considers not only plant daily light integral (DLI) need during its photoperiod but also sunlight prediction and variable electricity pricing in this model. The University of Georgia uses Markov chain to predict sunlight irradiance throughout the day. By considering sunlight prediction information, the system avoids supplying more light than plants require. Therefore, this lighting strategy supplies sufficient light for plant growth while minimizing electricity costs during the day. The University of Georgia propose an algorithm to find optimal supplemental lighting strategy and evaluate its performance through exhaustive simulation studies using a whole year data and compare it to a heuristic method, which aims to supply a fixed photosynthetic photon flux density (PPFD) to plants at each time-step during the day. The University of Georgia also implemented this proposed lighting strategy on Raspberry Pi using Python programming language. This prediction-based lighting approach shows (on average) about 40% electricity cost reduction compared to the heuristic method throughout the year. The University of Georgia will test this approach in their research greenhouse in the winter of 2020-2021. *Researchers: Sahand Mosharafian, Shirin Afzali, Javad Mohammadpour Velni, and Marc van Iersel*

USDA-ARS (Beltsville, Maryland)

- Grain chalk expression from a U.S. rice hybrid variety was observed to increase as much as 40% in response to short-term heat stress (+4 or +8°C above the 28/23°C setpoint thermoperiod) applied for 14 days during grain filling. Grain fill percentage declined as much as 50% as a result of the extreme heat event, which in turn was associated with substantial decline in grain yield. Growth under elevated CO_2 (740 ppm) slightly compensated for negative heat impacts on yield, but may have exacerbated chalk expression which negatively impacts grain quality. Research was conducted in six SPAR Daylit chambers.

- An experiment was conducted to evaluate the response of Parthenium, an invasive species, to CO_2 concentrations using two walk-in Biochamber growth cabinets. The weed was observed to grow faster and produce more parthenin (which reduces productivity of crop fields and pastures and is a cause of dermatitis in humans) with rising CO_2 levels as compared to a non-invasive biotype. This suggested that the current levels of CO_2 contributed to the plant's global invasiveness and toxicity. This information will allow for assessing better weed control strategies and provides ecological information on subspecies variation.

Sierra Space

Hybrid Life Support Systems- Plant Culture Units

Sierra Space is continuing work on the development of Exploration Life Support Salad Crop production as an early stage implementation of hybrid life support systems (combination of bioregenerative and physical-chemical life support technologies). Current efforts include development of aeroponic and nutrient film hydroponic (soilless) systems and variable plant spacing systems for use in the space environment. This continues efforts to develop advanced subsystems (e.g. LED lighting, porous interface transpiration recovery) that significantly reduce the mass, power, and volume of microgravity plant production.

Current efforts included a series of parabolic flights investigating aeroponic and nutrient film systems for use in microgravity, and a technology demonstration experiment for the ISS called the Exposed Roots On Orbit Test System (XROOTS) to look at these same parameters in long duration microgravity. Sierra Space is preparing the XROOTS payload for flight in early 2022.

Space Biology

Sierra Space continues to work with the Kennedy Space Center to support the two Veggie plant growth systems and the Mass Measurement Device (for support of animal and plant sciences) currently operating on the ISS (Figure 3).

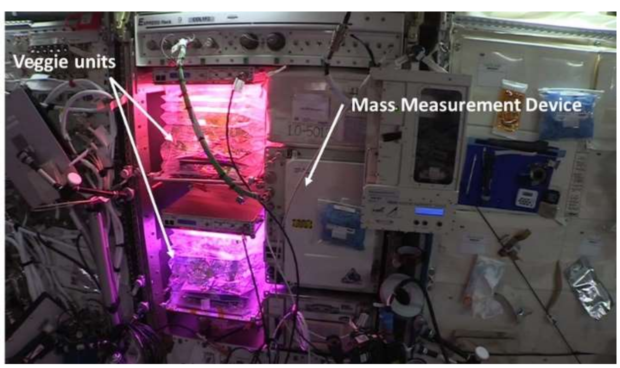

Figure 3. Image of the two Sierra Space Veggie plant growth units and the Sierra Space Mass Measurement Device on the ISS.

The Advanced Plant Habitat (APH) that Sierra Space fabricated for the Kennedy Space Center is operating on the ISS to support a wide range of microgravity plant research. This system is the largest plant growth system put in space to date. Sierra Space is currently providing engineering support to APH as it continues operations on the ISS (Figure 4).

Figure 4. Radish plants growing inside the Advanced Plant Habitat on ISS (NASA image ss064e013129 Dec. 20, 2020).

LIFE™ (Large Integrated Flexible Environment) Habitat

Sierra Space continues to work with commercial partners for development of human Life Support and Thermal Control systems for space habitats. Sierra Space has moved their full-scale mockup of its LIFE module (shown in Figure 5) to NASA Kennedy Space Center. This system is being designed to support a 1,100-day mission and is currently part of an effort to develop a large commercial space station (Figure 6).

Figure 5. Sierra Space LIFE module mockup. Left-view of inflatable structure. Center and Right-Interior views of habitat.

Figure 6. LIFE modules as part of commercial Orbital Reef Space Station development.

JR Peters

Through conversations and experience working with ornamental and cannabis growers, anecdotal reports indicate that plants grown under LED lights benefit by increasing fertilizer application rates by 25-50% compared to plants grown under HPS and MH (indoor and greenhouse).

3. Accomplishment Summaries:

Purdue

For the OptimIA project, CCL tended to capture more photons that otherwise would be lost by typical 120 to 130 degree beam spread outside the cropping area below LED fixtures. Use of white curtains helped to reflect back some photons that otherwise would be would be lost. Combining CCL and reflective curtains kept or retrieved the most light, and plants either grew more or saved more energy for lighting, depending on the CCL strategy being tested.

For Minitron III, crop gas-exchange measurements indicated that photosynthesis of baby and leafy greens saturates at CO_2 levels about half of what commercial growers use, and the low light level growers use likely is why they do not get more response to their elevated CO_2.

Kennedy Space Center

A series of Veggie tech demo tests were completed in early 2021 that introduced varying amounts of crew autonomy to plant care operations. Veg-03I grew a variety of leafy greens (Red Russian kale, Dragoon lettuce, Wasabi mustard, Extra Dwarf pak choi, and Outredgeous red romaine lettuce) alongside Veg-03J (Outredgeous romaine lettuce), the first on-orbit test of a seed film technology developed at KSC that enables astronauts to plant seeds on-orbit. Veg-03K (Amara mustard first flight) and Veg-03L (Extra Wwarf pak choi) occurred immediately following Veg-03I/J, and featured the first example of fully autonomous crew growing of crops in space; the crew decided watering amounts and frequency, harvest dates, and other horticultural considerations independent of the ground team.

A technical demonstration in the Advanced Plant Habitat (APH) on ISS will end in November 2021 that is growing cv. Espanola Improved chile (chili) peppers for a period of 137 days. This test will assess the capabilities of APH to conduct long-duration plant growth operations and the nutritional and microbiological differences that arise in chile peppers grown in microgravity. The crew will consume a portion of the fruit and perform behavioral health surveys to assess the impacts of growing crops in space. The first pepper harvest was conducted on Day 109 and received considerable media attention. This project is being conducted by Matt Romeyn, LaShelle Spencer, Oscar Monje, Jacob Torres, Jeff Richards, Lucie Poulet, Ray Wheeler, and Nicole Dufour.

Gioia Massa continues work on 3-yr NASA grant to grow dwarf tomato in Veggie for the first time. Ray Wheeler, Mary Hummerick, Matt Romeyn, LaShelle Spencer, and Jess Bunchek at KSC, Bob Morrow at Sierra Nevada, and Cary Mitchell at Purdue are Co-Is on the grant along with several Co-Is from Johnson Space Center focusing on food and behavioral health. The focus of this research is to assess fertilizer and light quality impacts on crop growth, nutrient content, and organoleptic appeal. KSC has worked closely with Florikan Inc. to assess different controlled release (CR) fertilizer combinations. Two sets of mizuna were grown in Veggie plant pillows, one for 35 days and the second for 60 days with repetitive harvesting under both red-rich (ratio of 9:1:1 Red: Blue: Green) and blue-rich (ratio of 5:5:1 Red: Blue: Green) LED light.

The team at KSC continues work in partnership with Moon Kim and his team at USDA ARS-Beltsville on advanced plant imaging technologies for use in spaceflight. The focus of this work has been on developing hyperspectral imaging technologies and a database of plant responses relevant to spaceflight, such as drought, over-watering, and pathogenic fungus. The goal is to create a monitoring system able to recognize stressors early enough to take swift corrective action, and eventually, being the eyes of an autonomous plant growth system.

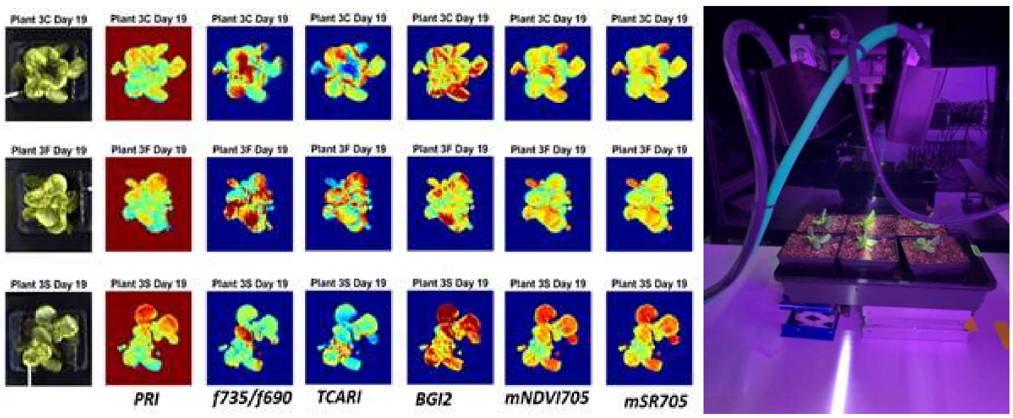

Figure 7. *Left: Development of vegetation indices for integration with AI. Right: Hyperspectral camera scanning plants at Kennedy Space Center.*

Gioia Massa was awarded a 3-yr NASA grant to study the impacts of watering on the plant microbiome in microgravity using the Advanced Plant Habitat (APH) on ISS. Plants will be grown under four different substrate moisture scenarios to assess impacts to plant growth of chronic and intermittent substrate moisture conditions. The microbiomes of the different treatments will be cataloged and assessed for impacts on food safety and other impacts of interest.

A one-year legume screening study was completed, with 26 cultivars of multiple pea and bean (others?) being screened and 8 promising candidates down-selected for further growth studies, and nutritional and organoleptic analysis, and possible inclusion in future growth demonstrations on ISS.

Multiple areas of new research and technology into microgreens are occurring at KSC. A one-year investigation to assess the food safety metrics of microgreens is ongoing, this is a necessary step to clear the way for microgreens testing and consumption on ISS. A study into novel microgreens is also underway to identify microgreen types that are sources of calories, fats, protein, and thiamine; some of the cultivars in this investigation include cantaloupe, sunflower, quinoa, and many types of legumes. NASA Postdoctoral Fellow Lucie Poulet received a one-year award to conduct parabolic flight testing of different microgreen techniques and technologies to enable harvesting of microgreens in microgravity.

Studies on herbs and herb microgreens continued to determine herb varieties that will grow well in a space environment to supplement packaged diets in space flight. Sixteen herb varieties (how many species?) were tested initially in spring of 2020, and down selection of these continued based on growth, and nutrient content. In 2021, 12 varieties of full-sized herbs and 14 varieties of herb microgreens were cultivated under spaceflight-relevant conditions and analyses of these are ongoing, with microbial and nutritional analysis underway. Additionally, novel leafy crops such as Malabar spinach, dandelion and golden purslane have been tested, with more crops to be studied in the coming year.

Lucie Poulet is a NASA Postdoctoral Fellow working on a project entitled "Modeling plant growth and gas exchanges in various ventilation and gravity levels." Lucie has been using the LI-6800 to study plant leaf responses to different ventilation levels and has designed a custom chamber for the LI-6800, which will allow similar studies of entire crop plants and canopies of microgreens. Data collected will be used to calibrate and validate a plant gas exchange model in reduced gravity environments. Lucie is also a collaborator for the PH-04 technical demonstration of chile peppers on ISS.

Christina Johnson is a NASA Postdoctoral Fellow at KSC assessing the differences between microgreens grown in unit gravity versus those grown in simulated microgravity using clinostats and random positioning machines (3-dimensional clinostats). She is working with a team to design a microgreens growth and imaging platform that will be used on a random positioning machine and enable testing of microgreens growth responses to different simulated gravity levels, including lunar and Martian gravity. Christina leads monthly Microgreen Chats where she brings together contacts from NASA, USDA, academia, and the private sector with interest in microgreens. Christina has also authored and co-authored multiple white papers for the "Decadal Survey" taking place right now, where NASA solicits inputs for future research areas.

Michigan State University

- Michigan State University coordinated several outreach programs that delivered unbiased, research-based information on producing plants in controlled environments, including the Michigan Greenhouse Growers Expo and the Floriculture Research Alliance annual meeting.
- Michigan State University updated the MSU Extension Floriculture & Greenhouse Crop Production website that includes MSU-authored resources on the production of plants in controlled environments.
- Research technician Annika Kohler and Roberto Lopez quantified the effects of various rates of uniconazole on stem elongation under low (2.0 $mol \cdot m^{-2} \cdot d^{-1}$) and high (16.3 $mol \cdot m^{-2} \cdot d^{-1}$) daily light integrals of five succulent genera over time. Using at least 1 $mg \cdot L^{-1}$ of uniconazole was enough to suppress stem elongation in most succulents studied after 10 or 15 weeks but 2 $mg \cdot L^{-1}$ can be used for all succulents.
- M.S. student Caleb Spall and Roberto Lopez investigated the influence of supplemental light (SL) quality on time to harvest and finished quality of several long-day specialty cut flowers. Time to harvest under SL containing blue, red, and far-red radiation, or 100% blue radiation, was hastened compared to plants grown under high-pressure sodium or broad-spectrum LED SL. Additionally, time to harvest was delayed under 100% red SL.

- M.S. student Caleb Spall and Roberto Lopez investigated the influence of young- and finished-plant photoperiod on time to harvest and quality of several cut flowers. Marigold ‘Xochi’ seedlings grown under 11- to 24-h photoperiods or a 4-h night interruption and finished under 10- to 12-h days were marketable, and of comparable finished quality.
- M.S. student Sean Tarr and Roberto Lopez quantified the influence of day and night air temperatures (72/59, 77/64, 82/70 °F) and light intensities (150 to 300 $\mu mol \cdot m^{-2} \cdot s^{-1}$) on growth of red oakleaf and green butterhead lettuces ‘Rouxaï’ and ‘Rex’. Fresh mass was greatest for both cultivars under 300 $\mu mol \cdot m^{-2} \cdot s^{-1}$ of light and at day/night temperatures of 77/64 or 82/70 °F for ‘Rouxaï’ and 82/70 °f for ‘Rex’. However, incidence of tip burn was greater under the higher light intensity.
- M.S. student Sean Tarr and Roberto Lopez investigated how air temperature and CO_2 concentration (500, 800, and 1200 $\mu mol \cdot mol^{-1}$) influenced growth of ‘Rouxaï’ and ‘Rex’ at a light intensity of 300 $\mu mol \cdot m^{-2} \cdot s^{-1}$. Fresh mass was greatest for both cultivars at day/night temperatures of 82/70 °F and CO_2 concentrations of 800 $\mu mol \cdot mol^{-1}$ for ‘Rouxaï’ and both 800 and 1200 $\mu mol \cdot mol^{-1}$ for ‘Rex’.
- M.S. student Sean Tarr and Roberto Lopez modelled the response of kale and red oakleaf and green butterhead lettuces at day and night temperatures of 52/41 to 97/86 °F. The greatest leaf unfolding of ‘Rouxaï’ and ‘Rex’ occurred at 79/70 °F. However, fresh mass of ‘Rouxaï’ and ‘Rex’ was greatest at 88/77 °F and 79/68 °F, respectively. Kale had the greatest fresh mass at 70/59 °F, but had the greatest leaf number at 97/86 °F.
- Ph.D. student Eric Stallknecht and Erik Runkle studied the effect of an experimental red-fluorescent greenhouse film that converts some of the blue and most of the green light into red light on greenhouse- and indoor-grown lettuce. On average, the experimental film decreased the average light transmission by 25% compared to an un-pigmented control film. Despite lower light transmission, lettuce yield per plant increased by 5% to 20%, depending on cultivar. Butterhead lettuce had the greatest yield increase under the experimental red-fluorescent film.
- Ph.D. student Nathan Kelly and Erik Runkle quantified the interaction between day length and light intensity on the yield of two lettuce cultivars grown in an indoor vertical farm. The research results indicated that, at the same high daily light integral, a longer day length paired with a lower light intensity led to higher yields than a shorter day length and higher light intensity.
- Visiting scholar Viktorija Vaštakaitė-Kairienė, Ph.D. student Nathan Kelly, and Erik Runkle quantified the effects of light quality on lettuce yield, nutritional quality, and post-harvest quality preservation. Experimental results revealed that the color of light added to a white light background had varying effects on lettuce growth and nutritional quality. In general, white light plus blue or red light increased the concentration of nutritional metabolites before and after storage.

McGill University

The Biomass Production Laboratory at Macdonald Campus of McGill University is investigating the relationship between pigment absorbance and supplemental lighting for crop production. McGill has shown that the maximum photosynthetic activity in tomato plants does not correlate with extracted pigment absorbance peaks. It is widely accepted that major pigments play an important role in harvesting light energy at specific wavelengths, according to their spectral absorbance (blue and red light. This knowledge has led to the widespread application of blue/red LEDs for plant growth. Yet, with decades of research, the optimal light ratio of these two wavelengths remains elusive. More importantly, this purplish light should theoretically outperform any other lighting system in the market, but purplish lighting configurations do not increase plant growth rates or result in better plant yields when compared to conventional lighting systems in controlled environment agriculture (i.e. amber-light-abundant high-pressure sodium lamps. Nearly five decades ago, photobiologists reported optimal lighting configurations based on spectral photosynthesis curves. Although comparisons between spectral peaks of photosynthetic activity and extracted pigment absorbance were not attempted at the time, reported spectral photosynthesis peaks do not correlate with extracted pigment absorbance peaks.

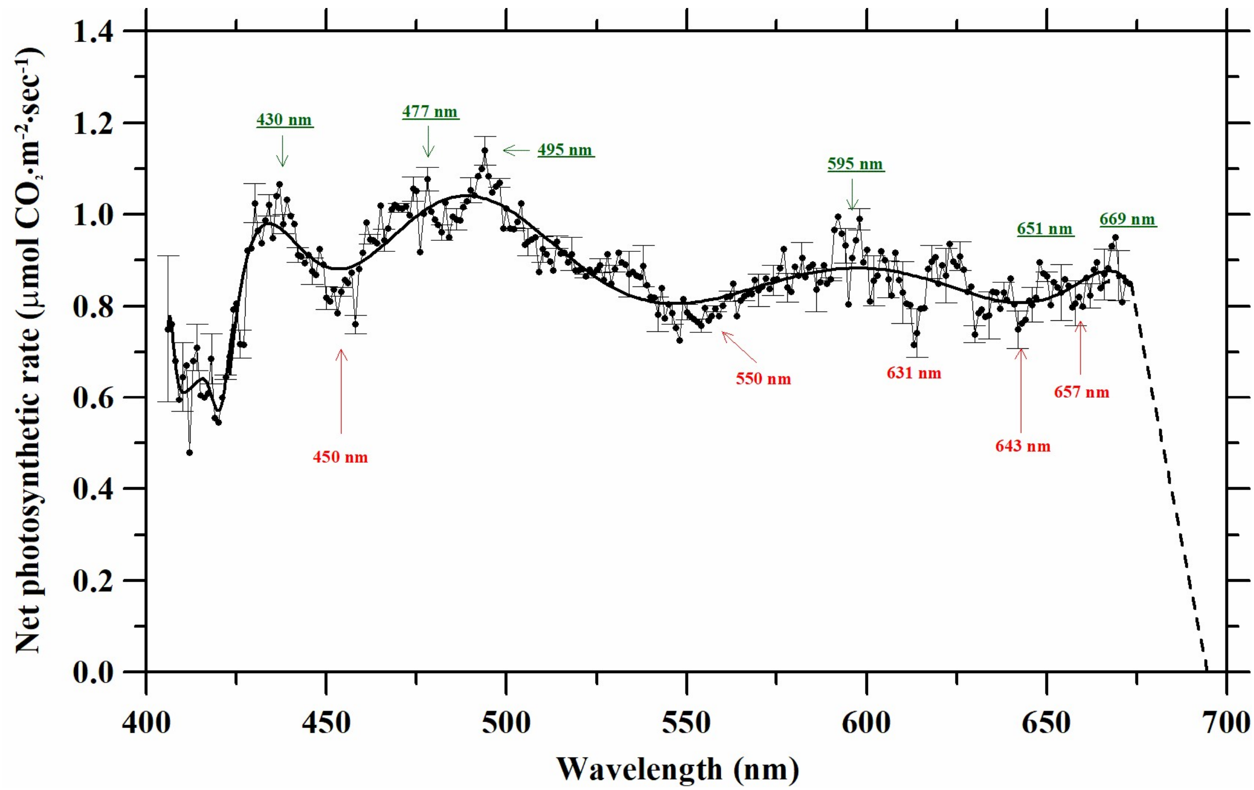

Figure 8. *The 1-nm increment spectral photosynthesis curves plotted with high resolution data acquired from the spectral responses of young tomato (S. lycopersicum) (405 nm to 670 nm). Error bars through data points represent standard error. Wavelengths indicated in green and in red refer to peaks and valleys, respectively.*

The Ohio State University

- The Ohio State University founded Ohio Controlled Environment Agriculture Center (OHCEAC) with 18 inaugural faculty members covering Horticulture, Engineering, Plant Pathology, Microbiology, Entomology, Workforce training, and Food Safety.

- The 2021 Greenhouse Management Workshop (January 27-29, 2021) was organized by Peter Ling and Chieri Kubota with 164 participants. This year's focus was 'Improving Production via Listening to Plants'.
- The Strawberry School (March 26, 2021) was organized by Chieri Kubota and Mark Kroggel with 120 participants.

Rutgers University New Jersey Agricultural Experiment Station

Rutgers continues to evaluate a variety of lamp fixtures for light output, light distribution and power consumption using a 2-meter integrating sphere and a small darkroom. Rutgers is continuing to work on a comprehensive evaluation of ventilation strategies for high tunnel crop production (David Lewus). Rutgers is continuing work using life cycle assessment tools to assess the environmental impacts of switching from high-pressure sodium lighting to LED lighting (Farzana Afrose Lubna).

University of Arizona

- Graduate student Joseph Alcorn (advisor, G. Giacomelli) successfully produced quality vegetable crops in high solar radiation, high air temperature (>30 oC) and modest VPD (<2.0 kPa) conditions to determine the effect on harvest quality and yield compared to standard, optimal conditions (25°C). Tomato (truss and cherry), cantaloupe and cucumber were grown within a recirculating topdrip hydroponic nutrient delivery system. Basil and lettuce were also produced within a deepwater culture, floating raft hydroponic system. All crops and both nutrient delivery systems were within a single-bay, gutter-connected, glass-covered greenhouse compartment of 7.5 x 15.1 m. The work was supported by sub-contract to UC-Merced from an INFEWS-T2 NSF grant, whose primary goal was to develop a solar-energized greenhouse for the purification of the salt-laden drainage water from field production agriculture in the Central Valley of California. It will further produce edible vegetable crops while operating at its excessive air temperatures required for desalinization.
- Graduate student, Michael Blum (advisor, G. Giacomelli) has outfitted a recirculating top-drip nutrient delivery system within a single-bay, gutter-connected, ETFE-covered greenhouse compartment of 7.5 x 15.1 m for evaluating the wavelength altering properties of quantum dots in plastic films for the improvement of tomato plant production supported by a NASA-STTR grant with UbiQD company, Los Alamos, NM, and collaborators Matt Bergren and Charles Parrish.
- Kacira is co-PI (UArizona), with Runkle (PI, Michigan State University), Lopez and Valde de Souza (co-PI, Michigan State), Kubota (Ohio State), and Mitchell (Purdue), and Boldt (USDA-ARS) in a fouryear project supported by the USDA Specialty Crops Research Initiative entitled "Improving the profitability and sustainability of indoor leafy-greens production."
- Kacira Lab, in collaboration with Sadler Machine Co., SynerGy LLC., Thales Alenia Space, German Space Agency, Italian National Research Council, University of Naples Federico II, continued to work on designing and evaluation of a water and nutrient delivery system for crop production in microgravity environments with project funded by NASA.
- Chiara Amitrano, visiting PhD Student in Kacira Lab, from University of Naples Federico II,

evaluated the effects of VPD and CO2 during a short term exposures of EC (as stress treatment) on green and red-leaf 'salanova' lettuce grown in recirculating DWC based hydroponics system within LED lighted indoor vertical farm (UAg Farm) at the UA-CEAC. The study is evaluating the Energy Cascade Model (MEC) predictions of crop biomass and photosynthesis and to be a model as decision support system.

- PhD student Rebekah Waller and Murat Kacira (advisor), through Binational Agriculture Research Development funds (BARD) project in collaboration with Volcani Research Center and Triangle Research Center, evaluated the effects the effects of wavelength selective organic photovoltaic film deployed as greenhouse roof covering on growth and yield of tomato crop. Results indicated that for the OPV arrays evaluated in the research decreased the shortwave radiation transmittance by approximately 40% and photosynthetically active radiation (PAR) by approximately 37% to the growing area. During the hottest months of the measurement period (May–July), the OPV shade provided a suitable climate for tomato crop production, stabilizing canopy temperature during the times of day with the highest solar radiation intensities. In doing so, the OPV performed the function of a conventional shade screen method. A much greater light utilization efficiency was determined, based on the cumulative yield obtained per cumulative PAR radiation received by the crop canopy, with crops under the OPV covering compared to those under polyethylene cover in the Control section. The overall power conversion efficiency, the ratio of energy output from the solar cell to input energy from the sun, for the OPV arrays evaluated was 1.82%, with lower PCE in the afternoon periods compared to morning and midday periods. Compared to the unshaded Control crop, the OPV-shaded plants achieved higher weekly yields during the hot and high-light periods. Comparable yields were seen between the OPV-shaded plant and the plants grown under a conventional shade net. Overall, results indicated the potential of using OPV as a shade element while also being able to generate electrical energy within the same greenhouse footprint.
- Graduate student KC Shasteen (advisor Murat Kacira) developed and evaluated a computer vision system to monitor crop health and growth in a vertical farm setting. The research evaluated computer vision-based crop monitoring and modeling-based crop fresh and dry biomass prediction approach (speaking plant based approach) to be used for decision making and environmental control application in vertical farming system and evaluated various what-if scenarios for cooptimization of environmental variables (air temperature, humidity, DLI, CO2) leading to resource savings. Furthermore, the model developed was used to identify and evaluate most optimal planting densities for the maximum crop yield outcome under specific environmental conditions.
- Tilak Mahato (hydroponic specialist), Neal Barto (Engineer) and Murat Kacira continued to provide technical support for crop production and greenhouse systems controls and collaborations with Todd Millay (Director of UArizona Student Union Affairs) for the rooftop greenhouse facility which provides education and training for students, community outreach, and fresh produce access for food challenged students through campus pantry.
- Kacira (co-PI), in collaboration with K. Chief (PI) et al., within NSF-NRT funded project titled "Indigenous Food, Energy, and Water Security and Sovereignty" continued to educate a cohort graduate students on novel and sustainable off-grid production of safe drinking water, brine management operations, and controlled environment agriculture systems to

provide technical solutions for communities, currently with Navajo Nation, challenged to have access to fresh produce and safe drinking water. The project collaboration included educational and training programs for technical staff members and intern students, on controlled environment agriculture (CEA) systems, hydroponic crop production, sensors and controls in CEA, offered during 2021 Tribal Universities and Colleges Internship Program, and within UA-CEAC annual virtual greenhouse crop production and engineering short course and intensive workshop.

- UA-CEAC continued to provide educational opportunities on CEA for new farmers through its 19th Annual Greenhouse Engineering and Crop production Short Course (virtual program in 2021), UACEAC Intensive Workshops on education of growers producing tomato crop hydroponically (Dr. Stacy Tollefson, Instructor) and within aquaponic systems (Dr. Mathew "Rex" Recsetar).
- Cuello has been directing the Arizona Green Box, a modular vertical farming project using a shipping container in which students grow crops hydroponically using artificial lighting. Cuello and his students designed an original cultivation system, the V-Hive Green Box, that is intended to achieve maximum crop productivity per unit volume.

Arizona State University

- *ASU Indoor Farming Certificate Program:* Yujin Park and Zhihao Chen are launching a new Arizona State University certificate program 'Indoor Farming Certificate' from the 2022 Fall semester. As a part of the certificate program, Zhihao Chen launched the ABS 394 Future of Agriculture: Vertical Farming course in the 2021 Spring semester, and he will launch ABS 369 Hydroponic Food Crop Production course in the Fall 2022 semester.
- *Indoor Strawberries:* The influence of sole-source lighting was investigated on plant growth, flowering, and fruit development in ever-bearing strawberry 'Albion' in the vertical farm. Increasing photosynthetic photon flux density (PPFD) from 200 to 450 $\mu mol \cdot m^{-2} \cdot s^{-1}$ and photoperiod from 12 to 16 hours increased plant growth while extending photoperiod was more effective at accelerating flower and fruit development and increasing fruit yields than increasing PPFD.
- *Sustainable Fertilizers for Vertical Farming:* In collaboration with Homer Farms Inc., the effects of organic fertilizer derived from food waste were evaluated on indoor hydroponic leafy green production. At the same electrical conductivity (EC), food waste fertilizer provided 60% less total nitrogen than chemical fertilizer, and most nitrogen in the food waste fertilizer was in the form of ammonium (63%) and organic nitrogen (37%) while 80% of nitrogen in the chemical fertilizer was nitrate. Arugula and two lettuce cultivars were successfully grown with food waste fertilizer, but the arugula and lettuce plants grown with food waste fertilizer had 85-98% lower shoot fresh weight than those grown with chemical fertilizer. Other organic fertilizers, including fish products, are being tested for optimal plant growth in the Indoor Farming Lab as well.
- *Luminescent Greenhouse Film Applications:* In collaboration with UbiGro, the effects of using quantum dot luminescent greenhouse films were evaluated on greenhouse strawberry production. The spectral conversion using luminescent greenhouse films improved the

strawberry fruit yield and quality under lower daily light integral conditions compared to transparent greenhouse film.

- *Greenhouse Industrial Hemp Transplants*: In collaboration with SMH Organic Family Farms, the effects of soil types and nutrient concentrations were investigated on the greenhouse industrial hemps transplant production. In three industrial hemp cultivars 'Frost Lime', 'RN13', and 'Serenity', the germination rate increased with silt loam than with sandy loam, and increasing EC of fertilizer up to 2.0 $mS \cdot cm^{-1}$ enhanced industrial hemp seedling growth regardless of soil types.

University of California Davis

The following are the summary of the accomplishments related to the research in controlled environment agriculture (CEA) at UC Davis:

- A new research laboratory named Controlled Environment Engineering Lab (Dr. Ahamed) was initiated at UC Davis for studying the energy-efficient design and optimization and integration of renewable energy for the operation of HVAC systems for CEA.
- The senior undergraduate students work on the energy-efficient greenhouse shape and orientation design for three different locations (Bridgeport, Santa Rosa, Imperial) in California. The study used the GREENHEAT model with the integration of a ventilation sub-model to analyze the heating and cooling costs for six different greenhouse shapes and the orientation at 15° intervals. The results indicate the quonset shape is more energy efficient for the freestanding greenhouses, but the modified arch shape is energy efficient for the gutter-connected multi-span option for all three selected study locations. The lab also collaborates with experts in CEA to review the opportunities for implementing solar energy technologies in agricultural greenhouses. UC Davis also analyzed the heating cost for Chinese-style solar greenhouses in cold regions and their energy efficiency compared with conventional greenhouses.
- A new course named Controlled Environment for Plants and Animal was offered for the first time in fall 2021 at UC Davis.
- Plant AI and Biophysics Lab (Dr. Earles) worked on a non-destructive plant biomass monitoring system and a prediction technique of the plant traits using machine learning algorithms.
- UC Davis is currently participating in the third urban greenhouse competition, and the autonomous greenhouse challenges 3rd edition. These two competitions are organized by the University of Wageningen from the Netherlands. UC Davis team placed 2nd in Part B of the 3rd autonomous greenhouse challenge.

University of Delaware

- Qingwu Meng designed, developed, and constructed the Delaware Indoor Ag Lab (DIAL) at the University of Delaware. In addition, Qingwu Meng led the construction of photoperiodic lighting structures in a research greenhouse.

- Qingwu Meng created and taught a new course, Hydroponic Food Production, in which 28 students learned about hydroponic techniques in controlled environments. A new hands-on lab section allowed students to build, test, and manage various hydroponic systems and grow leafy greens and culinary herbs in a greenhouse environment.
- Qingwu Meng published a series of three articles with Erik Runkle (Michigan State University) in the Produce Grower magazine. These articles summarized their latest research on LED lighting in indoor hydroponic lettuce production for professionals in the controlled-environment agriculture industry.

University of Georgia

In collaboration with electrical engineers, the University of Georgia has developed optimal control algorithms for supplemental lighting in greenhouses. These algorithms can be used for control of dimmable LED lights, HPS lights with a few discrete power levels, or non-dimmable lights. The algorithm can also predict sun light levels, and accounts for plant physiological responses to light. In the case of variable electricity prices, the algorithms can also minimize the cost of the electricity required for supplemental lighting. Simulations suggest that this may reduce lighting costs by up to 40%. The algorithms have been tested in a small testbed, using a Raspberry Pi for implementation and will soon be trialed on a larger scale in a greenhouse.

Texas A&M University

- Organic hydroponic research briefing: Texas A&M conducted organic hydroponic research in two systems (NFT and deep-water culture system, DWC). In the NFT system, Texas A&M used a Pre-Empt liquid organic fertilizer and a bacteria-based microbial product called TerraBella, a total of three treatments with three replications. For propagation, Texas A&M used several organic several plugs: closed bottom organic plug (organic coco coir), Ellepot (peat-based plug) Jiffy plug, and control (Rockwool plug). Among them, Jiffy plug performed the best. Results indicate that lettuce organic treatments with microbial product have the potential to achieve similar yield as the control. For longer term production (reusing the organic solution for multiple cycles), additional potassium fertilizer may be needed. In the DWC systems, Texas A&M used an organic fertilizer from JHB with or without TerraBella with three treatments and repeated three times. Texas A&M found that organically grown lettuce yield was slightly lower than the control and TerraBella did not make any difference in this organic fertilizer. Similarly, leaf tissue potassium level was lower than that in the control.
- Research on light spectrum and temperature interactions: Texas A&M conducted the first of a series of studies to examine the interactive effects among environmental factors, especially between light spectra and temperature, on crop growth and physiology in controlled environment production. In this first study Texas A&M characterized how red/far-red ratios interacted with temperature (constant and dynamic day/night gradients) to control photo- and thermo-morphogenesis in lettuce and basil. Texas A&M found that the light spectral effects on yield and morphology of lettuce and basil were dependent on the temperature regimes, and vice versa. Results indicate that interactions among environmental factors should be better characterized and taken into consideration in production system optimization.

- Texas A&M AgriLife Research collaborated with AgriLife Extension organized the second conference in urban controlled environment agriculture (virtual) attended by more than 100 participants in December 2020.

USDA-ARS (Beltsville, Maryland)

- An artificial intelligence algorithm and an improved corn model, MAIZSIM, were constructed that more accurately predict effects of decaying cover-crop mulch residue, and effects of tillage, on soil characteristics. These tools can predict crop biomass and changes in soil nitrogen and water content through both cover- and cash- crop growing seasons and permit more realistic assessment of multi-year cropping rotations. Soil, environment, plant genetics, and climate change effects on cover crop performance can be evaluated for specific locations. This work is being used collaboratively with scientists at USDA-ARS, University of Maryland, and North Carolina State University to develop a set of best cover crop management guidelines.
- The U.S. is the fifth largest rice exporter in the world. Negative effects on grain yield and quality due to warming temperatures are occurring, and future projections indicate temperatures are likely to increase by several degrees. Simulations from a newly developed rice model showed declines in yield up to 20% based on 2040 climate predictions. These yield variations were correlated with rising temperatures and negative impacts on grain were slightly offset by elevated CO_2. Location specific adaptation strategies can be developed by growers, including adjusting planting dates to avoid heat during anthesis and cultivar selection. These simulations are of interest to the U.S. rice breeders and farmers and can be used for identifying phenotypic traits ideal for location specific cultivar breeding.

NASA Ames, Moffet Field, California

- Completion of the joint NASA, USDA, State of California, University of California project, "Delta Region Areawide Aquatic Weed Project" (DRAAWP). The DRAAWP provided for development, gap-filling science, and demonstration of how science and remote sensing-based tools regarding plant ecosystem responses to climate change can be fused to support adaptive management decisions in a complex aquatic ecosystem with a wide range of stakeholder pressures and regulatory oversight.
- Environmental response and economic models, derived using controlled environments, and satellite-based, remote sensing mapping tools in use and impacting natural resource management practices.
- Awards from scientific society for outstanding technical contributions, Federal Lab Consortium (FLC) for interagency collaboration, and NASA Ames Research Center for Technology Transfer.
- Initiation of Space Act Agreement involving NASA Ames Research Center and the State of California "Utilizing Adaptive Management Methods for Invasive Aquatic Plant Management".

JR Peters

- Collaborated with The Ohio State University to develop a pre-mix fertilizer formulated for soilless strawberries.
- Actively working on solutions to improve nutrient management in recirculating fertigation systems.
- Actively collaborating with industry partners to determine optimum phosphorus application rates for cannabis grown in controlled environments.

LI-COR BioSciences

LI-600 Porometer/Fluorometer

The LI-600 makes its measurements in 5-15 seconds, allowing you to sweep through your entire greenhouse to make measurements in a very short time. A barcode reader is also built into the device to allow you to scan plants and/or tables that might be coded for quick documentation and metadata of your measurements. The LI-600 also includes computer software for flexible configuration set-up and data streaming. The newest version coming in 2022 facilitates leaf angle and GPS measurements to supplement the dataset.

LI-6800 Portable Photosynthesis System

The LI-6800 is the only photosynthesis system capable of measuring combined gas exchange and fluorescence from leaves and aquatic samples in a controlled environment. With gas analyzers, temperature response, and the flow path split all located near the chamber, measurements are faster and more precise than ever before.

Percival Scientific

Percival-Scientific developed new algorithms, including machine learning and optimizations using quantum computers, to improve lighting performance. Care was taken to properly define a non-trivial optimization criterion according to how quality assurance is performed in house as well as in the field. In the case of machine learning applications to this problem, difficulties cropped up in computational complexity. Many of these issues were addressed in reformulating this problem per an Ising formulation so that the problem could be ran in an annealing quantum computer (specifically, a Pegasus architecture D-Wave quantum computer). In the process, many numerical issues resulting from coherence issues had to be addressed as well. Based on this, a platform increasing lighting uniformity and reducing spectral banding was developed.

Plenty

- Plenty re-branded its products using rich, eye-catching colors and attractive fonts.
- Plenty ranked number one on Forward Fooding's FoodTech 500 list.
- Plenty developed and released two new mixed leafy green products.

- Plenty consistently supplies nutritious food to consumers no matter the season or climate, and despite supply chain limitations. While other producers were unable to adequately stock grocery store shelves during the COVID-19 crisis, Plenty more than doubled the amount of produce delivered to customers, non-profits, and food banks.

4. Impact Statements:

Purdue

The goal of both OptimIA and Minitron projects is to save energy and resources for growing leafy-greens indoors. The overall approach combines close-canopy lighting, targeted lighting, and phasic optimization, utilizing timing and degree of CO_2 enrichment in combination with spectral and intensity optimization at different stages of baby and leafy greens production.

Kennedy Space Center

The Advanced Plant Habitat (APH) is a quad locker ("oven") sized plant research chamber installed on the International Space Station (ISS) in November 2018. APH is environmentally closed from the ISS cabin air and has a suite of advanced sensor and control systems, to include automated watering and complete control and command capabilities from the ground. *Arabidopsis* and 'Apogee' dwarf wheat were grown as part of the hardware validation test, followed by experiment PH-01 that also grew *Arabidopsis*. In December 2020 'Cherry Belle' radishes were grown as part of experiment PH-02. In addition to the valuable science gathered during PH-02, the crew were also able to consume nine of the nineteen radishes harvested. Experiment PH-04, a technical demonstration growing 'Espanola Improved' chile peppers began in July 2021 and will conclude in late November 2021. Using chile peppers from the first harvest, the crew made space tacos that received a considerable amount media coverage.

Figure 9. *Left: Radishes grown during PH-02. Right: Crew on ISS with chile peppers from first harvest of PH-04 test with the Advanced Plant Habitat.*

KSC's space crop production research group has developed a list of gaps that has been vetted and approved with different NASA stakeholders. To enable partnership and collaboration on the challenges in controlled environment crop production KSC has been sharing its gaps list and having discussions with other government agencies, members of academia, and relevant industry professionals. The challenges that KSC face, while unique, have many intersections or areas of synergy with various sectors including agriculture automation and robotics, industrial sanitization, vertical farming, fluid and gas handling, modelling, sustainability and circular economy research, and greenhouse agriculture.

Michigan State University

- Michigan State University learned more about cultivar-specific responses to CO_2 concentrations, day and night temperatures, and light intensities for indoor farming of lettuce. This sets up for future studies to refine the growing parameters with a focus on crop quality within the environmental conditions that brought forth the greatest yield.
- Michigan State University has generated models that predict the base, optimum, and maximum temperatures of leafy greens that will help growers determine production temperature setpoints and conduct cost-benefit analyses.
- Advanced greenhouse glazing materials can change the transmission spectrum or absorb solar energy not useful for photosynthesis to generate electricity. In a single case study with a red-fluorescent film, Michigan State University learned that the paradigm of increased light increases crop yield does not account for changes to the light spectrum. Thus, it is essential to continue research on how photoselective greenhouse materials influence crop growth and quality, while also considering potential impacts during light-limited times of the year.
- Michigan State University published a review paper on how changing the indoor lighting environment impacts quality attributes of leafy greens such as nutritional quality, taste, and leaf coloration. This paper provides an easily digestible, comprehensive review of recent research that industry professionals can use to develop lighting strategies to optimize production.
- The Michigan Greenhouse Growers Expo and Floriculture Research Alliance meeting delivered unbiased, research-based information to over 400 greenhouse growers, plus additional growers and marketers of vegetable and fruit crops.

McGill University

The Biomass Production Laboratory at McGill University has an alternative theory of photosynthesis. The present interpretation of photosynthesis is such that major light-capturing pigments drive photosynthesis by funneling and transferring specific wavelengths of light energy, ultimately converting this energy into chemical energy for photosynthesis. These pigments are the main components of photosystems I and II, in addition to the antenna complex. The importance and essential functions of these photosynthetic pigments have not been questioned since their absorbance properties were first characterized. Likewise, the basic theory of photosynthesis is based on the absorbance characteristics of these pigments. McGill's laboratory findings do not conform to these existing theories. The spectral photosynthesis curve reported in the laboratory shows that an alternate function for photosynthetic pigments may exist, rather than solely absorbing and utilizing the light at specific wavelengths based on their absorbance spectra. With this, McGill suggests that a new theory is required to better understand the role that pigments play in photosynthesis.

The Ohio State University

The Ohio State University continues offering an online monthly forum 'Indoor Ag Science Café' to serve as a non-competitive communications platform for indoor farmers and relevant stakeholders. The listserve currently has ~1,000 members, serving as a very effective engagement method with industry stakeholders. During the reporting period, the forums reached a total of 1,373 stakeholders. Cumulative number of views (YouTube) of recorded presentations was 4,167.

Rutgers University New Jersey Agricultural Experiment Station

Nationwide, Extension and NRCS personnel and commercial greenhouse growers have been exposed to research and outreach efforts through various presentations and publications. It is estimated that this information has led to proper designs of controlled environment plant production facilities and to updated operational strategies that saved an average sized (1-acre) business a total of $25,000 in operating and maintenance costs annually. Crop lighting presentations and written materials on controlled environment crop production techniques have been prepared and delivered to local and regional audiences. Greenhouse growers who implemented the information resulting from this research and outreach materials have been able to realize energy savings between 5 and 30%.

University of Arizona

- Gene Giacomelli, using the controlled environment changed the future procedures/practices in the development of new varieties of field corn for animal feed. The Marana, AZ 7.5 greenhouse and laboratory facility represents a highly automated greenhouse hydroponic crop production system for the continuous yearly production of seed corn for breeding new varieties. Future benefits to the farmer include new breeding lines, developed up to 3 years faster (7 rather than 10 years), that ultimately create new corn varieties with attributes farmers will need, such as drought or salt tolerance to meet the effects of climate change. Given that the Bayer (Monsanto) Company supplies 70% of the world's feed corn production this science and engineering technology will be affecting billions of dollars of the global agricultural economy. This new system recycles all its irrigation water and nutrients for seed corn production, and it requires only 20% of the total amount that is used in field production. Furthermore, with recycling, there is no discharge to the environment of wastewater or plant nutrients. The closed environment of the greenhouse makes IPM [Integrated Pest Management] highly effective for control of pests and diseases, effectively eliminating the need for chemical pesticides. Stefanie Boe, Monsanto Company's Community Relations/Site Enablement Lead stated that: "The UA-CEAC has been an instrumental partner (G. Giacomelli, PI) in developing the necessary technology and capacity to conceive and build the new $100M Marana, Arizona Greenhouse Complex, creating 40 - 60 new local jobs which range from HVAC engineers to plant biologists, and access for others within the company."
- UA-CEAC organized the 20th Greenhouse Crop Production and Engineering Design Short Course (March 2021, virtually) with ~200 participants, with technical program providing unbiased research outcomes and information. UA-CEAC Intensive workshops helped to

educated about 70+ participants, mostly new/beginner CEA growers, on hydroponic tomato crop production and aquaponic systems.

- Total of 7 graduate students (2 supervised by Giacomelli and five by Kacira), and 17 undergraduate students [10 Giacomelli and 7 Kacira] were hired, educated, and advised through grant funded projects to be competent in CEA hydroponic crop production systems design and operations.
- In UA-CEAC research with experiments and modeling based, consideration of various DLI and CO_2 concentration injection combinations evaluated, co-optimization of variables evaluated, and strategies developed, can help achieving energy savings, and the CFD models developed in this research can help improving environmental uniformity with alternative air distribution system hardware and designs and environmental control strategies in indoor vertical farm-based operations.
- The outcomes and information generated by the research programs at UA-CEAC with the wavelength selective organic photovoltaics based, and quantum dots-based film technologies can lead to innovation and new frontiers for greenhouse covering material alternatives.

Arizona State University

- There are growing interests in vertical farming, urban farming, and greenhouse production in the Phoenix metropolitan area. For students and working professionals interested in controlled environment agriculture, the new Arizona State University Indoor Farming certificate program will provide specific indoor crop production and management training. Students will gain marketable knowledge and skills that will enable them to prepare and advance their careers in the greenhouse and indoor vertical farming industry.
- The Arizona State University Indoor Farming Lab is working with strategic partners from both private sectors (e.g., Homer Farms Inc.) and public sectors (e.g., Swette Center for Sustainable Food Systems) to build a more resilient food system in Arizona when Arizona is under Tier 1 Water Shortage.
- The effects of sole-source lighting were mostly studied in leafy vegetables and ornamental plants. Arizona State University demonstrated the value of optimizing sole-source lighting conditions for enhancing indoor strawberry fruit yields.
- Arizona State University demonstrated the possibility of using anaerobic digestate derived from food waste as sustainable alternatives to synthetic chemical fertilizer for growing leafy vegetables in the vertical farm to create a circular economy from food waste to food.
- Using a luminescent greenhouse film is a way to use sunlight more efficiently for crop production. Arizona State University demonstrated the spectral changes by a luminescent greenhouse film can benefit greenhouse strawberry production under low light conditions.
- While industrial hemp is a high-value crop with many uses, including fiber, fuel, and food, Arizona growers face many challenges of growing industrial hemp, including poor seed germination and seedling establishment. Arizona State University identified better soil and nutrient conditions to improve the germination and seedling establishment for local industrial hemp growers.

University of California Davis

Energy requirements for a greenhouse with different shapes and orientations could be significantly different depending on the location. A recent study from the controlled environment engineering lab shows that the energy demand for the uneven span is about 18.5% higher than the quonset shape greenhouse in California. The energy demand for the even span shape and modified arch shapes is about 16% and 11.0% higher than the quonset shape, but no significant effect for changing the orientation. Regarding location, the total energy demand in Imperial (hot) is about 1.5 times higher than the greenhouse located in Bridgeport (relatively cold).

Dr. Gross lab at UC Davis produced 3 YouTube videos on Aquaponic plant production:

1) What is the difference between coupled and decoupled aquaponics (https://youtu.be/JkeMIQXRLis)
2) Aquaponics USDA Speciality Crops (https://youtu.be/_iZ0YmMLVbY)
3) Top Aquaponic Systems, and Hydroponics (https://youtu.be/xrpHNurpVIw)

University of Delaware

- The development and establishment of the Delaware Indoor Ag Lab (DIAL) have enabled controlled-environment research to optimize lighting and environmental variables for a wide range of specialty crops. The University of Delaware will use this research facility to help indoor growers determine efficient lighting and environment management strategies.
- Qingwu Meng was a featured speaker at the TEDxUniversityofDelaware event on October 1, 2021. His talk was entitled "How Do We Grow Food Anywhere, Without Soil?" This in-person event was livestreamed, attracting 283 participants (172 in-person and 111 virtual). It was the largest in-person event ever held by the TEDxUniversityofDelaware.
- Qingwu Meng created a YouTube channel, Grow Anywhere, to publish educational videos that teach the public to 1) understand plant responses to environmental variables in controlled environments; and 2) build hydroponic setups to grow food crops at home, in a greenhouse, or in an indoor facility. This channel has amassed 435 subscribers in a year. Two recent videos have gained 7,065 and 4,144 views.

University of Georgia

Most past research on lighting requirements for CEA crops has focused on providing the same daily light integral (DLI). The University of Georgia has shown that lettuce does not require the same DLI and is actually quite tolerant of fluctuations in DLI. Following a day with a higher than 'required' or 'optimal' DLI, the target DLI can be lowered for one or more days. As long as the DLI fluctuations are not more than ~ 10 $mol \cdot m^{-2} \cdot d^{-1}$, and the average DLI is unchanged, fluctuating DLI levels have little or no negative impact on growth. Based on simulations, taking advantage of this 'carry-over' DLI can save greenhouses ~ \$6,000 – 9,000/acre/year.

Texas A&M University

The book “Plant Factory – Indoor Vertical Farming System for Efficient Quality Food Production” (published in 2019) was well received and positively impacted the indoor farming industry and scientific community.

Texas A&M’s second controlled environment conference held virtually in December 2020 also was well received and attended by the industry.

USDA-ARS (Beltsville, Maryland)

Process-based models for rice (RICESIM), soybean (GLYCIM), and cotton (GOSSYM) were improved using experimental data generated at USDA. A new interface tool, Crop Land and Soil SIMulator (CLASSIM), was developed and integrated with these models. CLASSIM is used by national and international collaborators at USDA-ARS, University of Nebraska, University of Maryland, North Carolina State University and Taiwan for evaluating G x E x M strategies that influence crop sustainability at various field locations.

Sierra Space

- Sierra Space is working toward development of hybrid life support systems for space applications, integrating biological and physical/chemical technologies.
- Sierra Space is advancing the technology of controlled environment systems to meet the performance and quality needs of long duration space applications. Some of this technology may be transferable and scalable to terrestrial protected agriculture systems.
- Sierra Space continues to develop LED lighting configurations and control strategies for plant and human habitat lighting applications to provide increased lighting system utility for aerospace and gravitational biology applications.
- Sierra Space continues to use its space biology controlled environment work and human life support work to spark interest in high school and college students in controlled environment technology and STEM.

JR Peters

- Recirculating fertigation systems offer a sustainable alternative to drain to waste systems and it is possible these systems may be mandated in the future. One of the biggest challenges in recirculating systems is nutrient management. In collaboration with university and industries partners, JR Peters is actively working to identify trends in nutrient uptake by plants grown in recirculating systems and how this differs between species and growing environments to offer more sustainable and effective management strategies for recirculating systems.
- In agricultural and horticultural production, phosphorus is often overapplied which can lead to run-off into the environment causing algae blooms and eutrophication. In recent years, the legalization of commercial medical and recreational cannabis production in many states has led to the development of large-scale commercial production facilities. Most facilities

employ intensive forms of production where large amounts of nutrients are applied and excess leachate solution is drained to waste. With little peer-reviewed research on optimum nutrient application rates for cannabis, growers often target P application rates much higher than that of other cultivated flowering crops. JR Peters is actively working with an industry partner to determine optimum phosphorus application rates in an attempt to minimize phosphorus run-off into the environment.

LI-COR BioSciences

When used together, the two instruments provide highly complementary data. For example, the LI-600 can be used to screen a large population and the LI-6800 can be used to measure selected individuals from that population in greater detail.

LI-600 Porometer/Fluorometer

- Rapidly Screen up to 200 samples per hour to identify candidates for detailed measurements.
- Measures in ambient conditions.
- Easy to use, basic configuration options.
- Chlorophyll *a* fluorescence in ambient light.

LI-6800 Portable Photosynthesis System

- Measure detailed physiological and photosynthetic parameters, including light response curves and A/Ci curves.
- Measurements in controlled conditions; capable of multiple independent controls, including light, CO_2, H_2O, and temperature
- Sophisticated configuration options in an intuitive graphical interface.
- Chlorophyll *a* fluorescence with controlled light, capable of induction kinetics measurements.

Controlling the inputs/drivers in a system can have significant affects, positive or negative, on plant growth. Measuring the plant's response to these influences is key. Besides plant disease, other indicators of stress arise from lack of water or overheating.

Percival Scientific

Developments in lighting architecture at Percival have enabled us to achieve coefficients of variation of the light intensity in 4+ multispectral LED platforms at less than 0.08 at 15cm and less than 0.05 at 30cm in their standard 41 series chambers. Percival has also used this knowledge to choose monochromatic LED illumination ideal for insects as well.

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