Project No and Title: NCERA-101 Controlled Environment Technology and Use
Period Covered: 04-2019 to 09-2020
Date Reporting: 09/09/2020
Annual Meeting: 2020 Annual meeting postponed due to COVID-19

<u>Minutes of the 2020 NCERA-101 Business Meeting</u>
September 9th, 2020
Via Zoom Virtual Meeting

Executive Officers:
Chair: Neil Yorio (NKOM Scientific Corporation), Vice-Chair: Murat Kacira (University of Arizona), Secretary: Marc Theroux (BioChambers), Past-Chair: Mark Lefsrud (McGill University)

Attendance:
Ramesh Kanwar, Neil Yorio, Murat Kacira, Marc Theroux, Carole Saravitz, Mark Romer, Mark Lefsrud.

Agenda Items:
1. NCERA-101 project renewal proposal for 2021-2026 term, the process, tasks, deadlines for submission
2. NCERA-101 project summary report for 2016-2021 project period
3. 6th International Meeting CEA Conference, postponed 2020 NCERA-101 Meeting

Minutes:

NCERA-101 Committee annual meeting that was officially authorized to be conducted in in 2020 inTucson, Arizona could not be conducted due to COVID-19. However, NCERA-101 Executive Committee met virtually via Zoom on September 9, 2020 from 8:30am to 9:30am (EST) and discussed some of the urgent items listed in the agenda above.

1. The Executive committee discussed the requirements for the NCERA-101 project renewal proposal for 2021-2026 term, the process, tasks, and deadlines for submission.
    a. Proposal renewal procedure, required for proposal template and tasks, were discussed. Murat Kacira (The University of Arizona) will lead the renewal proposal preparation and submission, with the active participation and support from Executive Committee members, Administrative Advisor, and several NCERA-101 Committee Members.
    b. Following deadlines are identified for proposal submission:
        i. September 15: Submit request to write a proposal in NIMSS and upload the Issues and Justifications section.

ii. October 15: Upload the Objectives section in NIMSS. Once this was completed, the NIMMS/NCRA office will send out the request for participation.
iii. November 15: Ideally, all participants and their AES offices should have submitted completed Appendix E forms into NIMSS.
iv. December 1: Submit the proposal to NIMSS in its entirely.

2. NCERA-101 project summary report for 2016-2021 period will be prepared next year as a summary and termination report of five-year activity of the ongoing project.
3. Following the trends and situation with the ongoing pandemic and its effects, NCERA-101 Executive Committee and Organizing Committee (M. Kacira, G. Giacomelli, and J. Cuello) of 6th International CEA Conference will follow during January and February 2021 to discuss the potential dates to hold the postponed International Conference and Meeting and the format of the Meeting (Onsite, Virtual, or hybrid). Then, the NCERA 101 Committee Members will be informed about the decisions made.

Appendix A:

NCERA-101 Membership Summary …… March 2020
Mark Romer, *Membership Secretary*

Membership Number	March 2019	171
	March 2020	176

- Additions 13
- Deletions...............................8
- Net Gain(Loss) 5

Membership Composition	Institutions	Members
• Phytotrons & Controlled Environment Facilities	9	11
• University Departments, Agr. Exp. Stations	60	85
• Government Organizations & Contractors	12	11
• Industry Representatives	51	69
Total Number of Institutions / Members	**132**	**176**

Total Number of Countries 9
Total Number of US States 33

New Institutions:

Arizona State University
College of Integrative Sciences and Arts

University of New Mexico
Department of Biology

Texas A&M University
Texas AgriLife Research & Extension, The Dallas Center

University of California, Davis
Department of Plant Sciences

USDA Agricultural Research Service
Greenhouse Production Research Group

- CURRENT powered by GE
- Hettich Benelux
- JR Peters Inc.
- Karma Verde Fresh (Mexico)
- Koidra Tech LLC
- Plenty Unlimited
- SyNRGE LLC Space Life Science lab

Appendix B:

Accomplishments (15 Reports)
(The complete station reports are available on the NCERA -101 website:
https://www.controlledenvironments.org/station-reports/

1. <u>New Facilities and Equipment</u>

Purdue University

The Minitron III system for hydroponic growth, LED lighting, CO_2 control, and gas-exchange monitoring of crop-stand dynamics within a growth area of 0.41 m^2 was brought online in the C.A. Mitchell lab at Purdue University after an extended period of design, fabrication, testing, calibration, and upgrades. Progress during the past reporting period was sponsored by an AFRI project. Minitron III utilizes an open system of gas exchange, beginning with a high-capacity blower that delivers air at controlled flow rates through or around a humidification column and into the adjustable volume of a crop-growth/cuvette space sealed on the bottom against a hydroponic cropping surface and on the top against an overhead LED array. The sidewalls of the cuvette are of an accordion design that accommodates changes in separation distance between the mobile LED array and stationary crop stand, and therefore accommodates adjustable cuvette volume as well. Gas-flow options include scrubbing of CO_2 from air prior to the inlet port on the cuvette, injection of pure CO_2 through a mass-flow control valve (MFV) into the inlet air stream, scrubbed or unscrubbed, and controlled airflow rate of humidified or non-humidified air through the inlet port into the cuvette headspace through a larger MFV. Inlet air is delivered via an L-shaped distribution manifold into the cuvette space where two adjustable-angle fans mix inlet air turbulently with cuvette air being processed photosynthetically by plants in the light. An outlet port on the opposite side of the cuvette space vents excess, mixed cuvette air into a well-ventilated growth room housing Minitron III while a separate outlet draws representative air at a low controlled flow rate out of the cuvette space through a gas-routing board (GRB) and ultimately through an infrared gas analyzer (IRGA, Li-Cor 7000). A slipstream of pre-inlet air bypasses the cuvette and goes directly to the GRB and IRGA as a reference stream to determine photosynthetic drawdown of CO_2 by the contained, growing crop stand. CO_2 uptake by plants is corrected for mole-fraction differences in water vapor between sample and reference air streams.

The LED array sealed to the top of the cuvette side walls is an OSRAM creation custom-designed to their needs and requirements. It has four channels of red, blue, green, and far-red LEDs independently dimmable by waveband, as well as being on/off switchable by individual engine. It self-monitors electrical power (kW) and energy (kWh) consumption by two fixture fans and 48 LED engines when energized. Light engines on the array have been positioned directly above each plant-holder space on the hydroponics lid, and each light engine has removable secondary-optic lenses that can be used during targeted-lighting studies, or not used during complete-coverage-lighting studies. An RGB video camera mounted in the middle of the overhead array (instead of a central light engine) provides real-time overhead images of crop stands at all stages of growth and canopy closure, and daily screen-shot images are used as a living growth curve to monitor the progress of crop development and canopy closure. The OSRAM-developed LED array has been dubbed YETI, which stands for "Yield-Enhancement Technical Instrumentation".

Lining the cropping surface between hydroponic plant holders is copper tubing through which water flows from and back to a temperature-controlled water bath located exterior to the walk-in growth chamber housing Minitron III. The copper tubing serves as a heat-exchange surface to maintain desired cuvette temperature in the light and prevent greenhouse-effect heating when YETI is energized. Three light-shielded thermocouples (TCs) and an Apogee PAR-FR sensor are mounted at crop level in the cuvette space. The PAR-FR sensor is periodically re-calibrated with a spectroradiometer to ensure accuracy of YETI photosynthetic photon flux density (PPFD), total photon flux density (TPFD), and spectral composition for each new light treatment applied. Another RGB video camera with pan-&-tilt adjustment capabilities is mounted in one corner of the cuvette that gives an image of the crop stand from the side, including height of the stand, which cannot be determined from overhead images in the closed cuvette.

Sensor outputs are directed through signal conditioners, as required, to a central command & control (C&C) computer located exterior but adjacent to the walk-in growth chamber housing Minitron III. Signal outputs from the TCs, PAR-FR, IRGA, MFVs, and YETI are directed to the C&C computer. YETI operational software also has been loaded onto the C&C computer, and YETI lighting parameters are controlled from that computer. Original control of inputs and monitoring of outputs was established using the $C^{\#}$ programming language. However, the programming language was recently translated into the Python language for robustness of programming and stability of program running. Presently, the C&C computer reports 11 output or performance parameters including one data point per parameter every second over the course of an entire cropping cycle, which is 28-30 days for leaf lettuce. These parameters include CO_2 and H_2O*v* concentrations in both bypass and sample lines, as well as the differential CO_2 and H_2O*v* concentration between bypass and sample lines, temperature readings of three thermocouples, inlet flow rate, and IRGA barometric pressure. Gas-exchange differentials not only are tabulated digitally in streaming format, but also are presented graphically over a running 24-hour time span to facilitate near-term planning regarding changes to environmental treatments such as inlet CO_2 concentration, inlet flow rate, PPFD and/or TPFD, spectrum, or temperature in the light. During dark periods, the external water bath automatically switches off and thermal controls of the walk-in growth room housing Minitron III are programmed to control dark-temperature treatments within the cuvette.

As part of an SCRI project, an EGC high-bay walk-in growth room installed in 2006 received a C-6 control-system upgrade during the reporting period. The upgrade included touch-screen controls for all major environmental parameters, the most important of which for the near-term include day/night temperature, humidity, and CO_2 concentration. This growth chamber is equipped with a WMA-5 CO_2 gas analyzer to accommodate CO_2 concentration control and monitoring.

Within the refurbished high-bay growth chamber, four adjustable-height aluminum shelving frameworks were constructed with four vertically movable OSRAM Phytofy LED arrays, each consisting of three fixtures mounted above each stationary shelf holding four standard 20” x 10” plastic plant-growth trays. Computer controls for each daisy-chained lighting unit are located outside the growth chamber, and power/energy meters are connected to each set of three LED arrays above a given shelf. Up to 16 plant trays are being grown simultaneously comparing four different close-canopy lighting treatments, with or without fixture dimming, and/or testing different species or cultivars of greens crops with simultaneous energy measurements. One crop type will be tested at a time, focusing on determination of optimum separation lamp/tray-separation distance with minimal energy expenditure.

University of Guelph

Five PS1000 growth chambers located in their satellite laboratory in Napanee, Ontario, and previously equipped with seven channel Intravision multispectral LED arrays, had analytical balances installed to improve the resolution of transpiration measurements. The chambers are currently investigating the effect of light recipes on cannabis growth, development and biochemistry.

Electrical, control and lighting upgrades were completed in two Constant Temperature walk-in growth chambers, adding 480 amps of additional equipment support, Argus control and multi-spectral LED lighting systems capable of wavelengths from 365 UV through far red.

They purchased a LI-COR 180 spectrometer to take some of the lighter work away from their busy Ocean Optics USB2000+ unit.

New Argus Control systems were bought to replace existing systems in four walk-in growth chambers and four incubator/shakers.

Kennedy Space Center

Kennedy Space Center continues to use Heliospectra RX30 LED lighting systems for many of their studies. The fixtures provide nine, selectively dimmable LED wavelengths -- 380, 400, 420, 450, 520, 630, 660, 735 nm, and white (~5700 K). They also use 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. They also have purchased 50 OSRAM PHYOFY RL lights to outfit several of their growth chambers and plant growth rooms, with the intent of eventually replacing the Heliospectra RX30 lighting fixtures. The OSRAM Phytofy RL has selectively dimmable LED wavelengths at 385, 450, 521, 660, 730 nm and white (2700K). They have 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.

Michigan State University

Michigan State University received 18 new Phytofy RL fixtures (each with 6 independently controlled LED channels) from Osram/Fluence, which are used to light 6 growing canopies inside the Controlled-Environment Lighting Laboratory. These fixtures replace 25% of the prototype fixtures delivered in early 2017.

They purchased a CID Bio-Science CI-340 Handheld Infrared Gas Analyzer to analyze leaf photosynthesis, respiration, transpiration, stomatal conductance, and internal CO_2, a CID

Bio-Science CI-110 Plant Canopy Analyzer to capture 150° images of plant canopies and estimate canopy leaf area index, a Felix-750 Near-Infrared Spectrometer to measure crop color (anthocyanins), and a Li-Cor LI-180 Spectroradiometer to measure light intensity and quality.

The Ohio State University

LIDAR based plant sensing systems have been developed for characterizing plant canopy in controlled environments. The sensor mounted on an irrigation boom, and a drone have been used to detect plants and to estimate canopy density.

A new LED lighting system (Philips GrowWise Control LEDs) was acquired as part of USDA SCRI OptimIA project for leafy greens in indoor farming (www.scri-optimia.org). This system can create custom LED light recipes to optimize the light quality and intensity.

Rutgers University

Rutgers University New Jersey Agricultural Station purchased a handheld Gigahetrz-Optik spectroradiometer model BTS256-EF that can measure illuminance (photopic, scotopic, melanopic), PAR, spectrum, light color, color rendering index, and flicker (range: 360 nm to 830 nm). They also purchased a neutral density filter attachment for their integrating sphere that allows them to measure higher intensity lighting fixtures.

University of Georgia

The University of Georgia has acquired and build several new imaging system for the detection of plant size and health. The TopView system (Aris, Eindhoven, the Netherlands) takes top-down images of plants under seven different colors of LEDs, including fluorescence images (plants are excited using blue light and a longpass filter in front the of the camera lens assures that the camera only captures fluorescence coming from chlorophyll. Data collection is quick and easy and allows for subsequent multi-spectral image analysis (not so quick and easy).

They have since designed and assembled three scaled down systems to only capture fluorescence images. This method allows for rapid and quick assessment of canopy size and can detect certain stresses that affect photosystem II well before any visible symptoms are present. A recording of how this works can be found at:

https://ashs.confex.com/ashs/2019/meetingapp.cgi/Paper/30905.

Texas A&M University

They installed 18 units of OSRAM LED Research Lights PHYTOFY RL. The AgriLife Research at Dallas Center currently has two repurposed shipping containers for plant science research in controlled environment. A new three-compartment shipping container with independent climate control will be built by the end of 2020. Several NFT systems and deep-water culture systems for hydroponic research and an Agilent LCMS were purchased and installed recently at the Dallas Center.

Heliospectra

In 2019, Heliospectra continued to develop helioCORE™ and new features for the light control system software. They also improved a vertical farming system in a research facility at headquarters in Göteborg, Sweden.

2019 also brought new construction of the unique EDEN ISS growth facility on Antarctica as an active partner on the EDEN ISS European project team. The structure is equipped with custom, water-cooled Heliospectra lighting system was opened in summer 2019 and welcomes interested researchers. More information: https://eden-iss.net/

Heliospectra introduced the MITRA series of LED fixtures to the research and commercial food production markets. This new generation of highly efficient dimmable 600Watt or 300Watt top lights was designed for crops with high light and intensity requirements including vine crops and medicinal plants. Commercial trials with Neame Lea Nursery in United Kingdom demonstrated advantages in greenhouse herbs production.

Hort Americas

A greenhouse dedicated to providing South Dallas communities with fresh produce while testing and proving agricultural equipment/technoloiges is located on the state fairgrounds just feet from the historic Cotton Bowl. The hydroponic production systems in this greenhouse include: (2) floating rafts systems, (1) organic raised bed, (2) nutrient film technique (NFT) systems, multiple multilayered ebb-n-flow growing systems, (2) separate dutch bucket systems and new for 2020 are (2) additional grow racks, a new dutch bucket system and a new grow bag/gutter system for vine crops.

Agritechnove

Agritechnove worked on the new Plant Growth Environments Facility for the University of California / Riverside. They're almost done with the new Science Initiative Building Research Greenhouse, for UW in Laramie, WY and with the new Plant Science Building at NCSU in Raleigh. Both projects are entirely air conditioned and the Laramie greenhouse has complete CO_2 management, including injection and scrubbing. The NCSU project also has BSL-2 and BSL-3 compartments.

Licor BioSciences

New LI-180 Firmware (new features and benefits)

For measuring the spectral quality of the light in your greenhouse, the portable LI-180 Spectrometer captures intensity and composition of the five major wavebands at the single-nanometer level. With this information, supplemental lighting can be optimized through the different stages of growth. Matching light sources (and wavelengths of light) to one of twelve pigmentations in the leaves (pre-programmed into the device and plotted against light source) can identify peaks where growers can adjust light recipes for more desirable outcomes.

New LI-600 Porometer/Fluorometer

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. Stomatal conductance to water (g_{sw}), which responds to light, CO_2, temperature, and humidity, amongst others, is a measure of the degree of stomatal openness and the number of stomata. It is an indicator of a plant's genetic makeup and physiological response to environmental conditions. Measurements of chlorophyll *a* fluorescence can provide information about the leaf's quantum efficiency, electron transport rate (ETR), non-photochemical quenching (NPQ), as well as an assortment of reactions that collectively protect a leaf when it absorbs excessive light energy. This hand-held device can be carried throughout the greenhouse, making multiple measurement per plant, as well as multiple plants throughout the greenhouse.

Plenty

Over the past fiscal year Plenty grew to over 300 employees. A large part of this growth represented targeted hires in the R&D branches of both Plant Science and Engineering. Promoting a culture of cutting-edge interdisciplinary innovation remains their priority.

Over the past fiscal year Plenty officially began commercial production at scale on its first fully automated farming platform - Tigris.

Iterative learning and a drive for constant improvement is a cultural pillar of their institution, as such they have confirmed plans to build the next generation of their farming platform in Compton, CA with an expected launch date in 2020. This next farm will incorporate learnings from Tigris, allowing them to build a larger and more efficient production platform.

2. Unique Plant Responses

Purdue University

Preliminary to the close-canopy lighting studies ongoing in the refurbished high-bay plant-growth chamber, fiber mats were investigated as a potential double-tray-based cultivation system with bottom fertigation for baby greens production based upon similar success with micro-greens. Commercial mats made from bamboo and/or hemp fiber were tested for growth of lettuce, arugula, kale, and mizuna in a standardized climate-control room. Preliminary findings were that baby-green crop stands of the above test species were labor-intensive for fertigation with non-uniform seedling growth, evaporative chilling from the wet mat surface, and non-toxic but unsightly algal growth on mats, possibly competing with plants for nutrients. Mizuna actually did the best of species tested followed by lettuce. Arugula and kale did not perform well in mat culture taken to the baby-green level of maturity (first set of true leaves expanding). Non-uniformity of hemp matting from one commercial source to another also appeared to be a cause for seedling non-uniformity of growth. Pelleted seed, which is the only available form for some greens species, did not respond well to the mat-growing system. Investigation of fiber mats as a growth medium for baby greens has been suspended in favor of a soilless-medium-based method of tray cultivation with bottom fertigation.

Kennedy Space Center

Kennedy Space Center completed a series of tests to grow different leafy crops in controlled environments with or without supplemental far-red lighting. These included chard, wasabi mustard, amara mustard, shungiku (an edible crysanthemum), several radicchio spp., several escaroles, sorrel, pak choi, red mustard, kale, red Russian kale, as well as lettuce. In general, species with distinct stems and internodes showed more elongation with supplemental FR (as expected), while heading plants (lettuce, escarole, radicchios) showed greater leaf expansion with FR. The Pak Choi cv. Extra Dwarf showed no difference.

Michigan State University

Former Ph.D. student Qingwu Meng and Erik Runkle studied the effects of green and blue light on plant morphology and quality attributes of red-leaf lettuce. The research results indicate that growth attributes were primarily controlled by blue light, and green light maintained or suppressed lettuce growth, depending on the intensity of blue light.

Former post-doctoral research associate Yujin Park and Erik Runkle investigated how substituting green with red radiation influenced plant growth with and without far-red radiation in an indoor environment. The results showed the utility of including far red in an indoor radiation spectrum, but there was little to no value of including green radiation.

M.S. student Annika Kohler and Roberto Lopez quantified how air and root-zone temperature influence rooting and morphology of cold-tolerant, cold-intermediate, and cold-sensitive bedding plants and herbs. The results indicate that un-rooted cutting responses to air and root-zone temperature are species-dependent. Most cold-tolerant species can be propagated with air average daily temperatures and root-zone temperatures of 16 °C and 21 to 24 °C, respectively, without sacrificing plant quality or delaying rooting.

M.S. student Anthony Soster and Roberto Lopez investigated if supplemental lighting containing a moderate amount of blue light ($\geq$15 $\mu mol \cdot m^{-2} \cdot s^{-1}$) was as effective as low intensity photoperiodic or high-pressure sodium (HPS) lamps at inducing long day perennials into flower. The results indicate that providing 30 $\mu mol \cdot m^{-2} \cdot s^{-1}$ of blue light is as effective as low-intensity photoperiodic and HPS lamps. Additionally, plants finished under 50 to 90 $\mu mol \cdot m^{-2} \cdot s^{-1}$ of supplemental light are generally of higher quality than those finished under photoperiodic lighting.

Ph.D. candidate Kellie Walters and Roberto Lopez quantified the influence of daily light integral and CO_2 concentration on growth and development of dill, parsley, and sage transplants produced indoors. The results indicate that increasing the light intensity from 100 $\mu mol \cdot m^{-2} \cdot s^{-1}$ to 400 or 600 $\mu mol \cdot m^{-2} \cdot s^{-1}$ results in increased mass at transplant and increased subsequent yields while elevating CO_2 concentration during the seedling stage has minimal to no affect.

The Ohio State University

New pH response charts of nutrient availability specific to liquid culture hydroponic conditions were proposed for spinach and basil plants (fig. 1; Gillespie, 2019), based on nutrient concentrations of the leaf tissue. Compared with charts commonly referenced for soil- or substrate- based conditions, the responses of these charts are species-specific and unique to hydroponic liquid culture conditions. For example, availability of micronutrients that are known to increase in soil and soilless substrates at low pH were shown to decrease in hydroponics under low pH.

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).

Watermelon seedlings generally exhibit a chilling damage when grown at temperatures lower than 15°C. However, the seedlings could tolerate to a short-term (<48 hours) chilling as low as 3°C (Ertle et al., 2020). The tolerance to 1°C was depending on growing conditions of the young seedlings before the exposure to the chilling (Ertle and Kubota, unpublished).

Freezing tolerance of watermelon and interspecific hybrid squash rootstock was examined. Watermelon seedlings have lower leaf osmotic potential and some plants (40%) survived at a freezing temperature of -3°C, where interspecific hybrid squash seedlings could not survive. The freezing point of watermelon seedlings was also reduced to below -4°C when plants were acclimatized to a low temperature (10°C) under dim light for 7 days prior to freezing but plants were quickly deacclimatized for one day at an ambient temperature (Maeda and Kubota, unpublished).

Rutgers University

Yuan Li observed increased frost protection for basil plants grown in a floating hydroponic system and supplied with a Si amended nutrient solution.

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*. They 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. They 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. They 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 minutes. 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 μmol·m^{-2}·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 μmol·m^{-2}·s^{-1}) was similar. Plants grown at 400/0 μmol·m^{-2}·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. Their 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 μmol·m^{-2}·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, this 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 μmol·m^{-2}·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, they 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, they 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 $\mu mol \cdot m^{-2} \cdot s^{-1}$. Their 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. They have modeled supplemental lighting in a greenhouse equipped with LEDs as a constrained optimization problem, and they aim at minimizing electricity costs of artificial lighting. They consider not only plant daily light integral (DLI) need during its photoperiod but also sunlight prediction and variable electricity pricing in their model. They use Markov chain to predict sunlight irradiance throughout the day. By taking sunlight prediction information into account, they avoid supplying more light than plants require. Therefore, their lighting strategy prepares sufficient light for plant growth while minimizing electricity costs during the day. They 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. They also implement their proposed lighting strategy on Raspberry Pi using Python programming language. Their prediction-based lighting approach shows (on average) about 40% electricity cost reduction compared to the heuristic method throughout the year. They 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

Heliospectra

Heliospectra research team continues to work on application of Far Red enriched spectrum on increased productivity of greenhouse crops – herbs, lettuces and other leafy greens together with commercial partners. Presence of FR in growth spectrum has a significant effect on plant productivity even in a greenhouse environment with a presence of sunlight.

Pulsed light (PVM) was shown to have both positive and negative effect on basil development; therefore, PWM dimming must be used with caution in research facilities and when planning light settings. Increasing DC from 50 to 80%, DC has a positive effect on basil growth.

Green light percentage has a significant influence on morphology and light availability inside the canopy and consequently affects quality of tomatoes grown under a LED sole source light. Heliospectra's research team collaborated on earlier greenhouse studies (Kaiser et al. 2019) showing a positive effect of growth spectrum with a high green light proportion on tomato. ***The results will be presented during IX International Symposium on Light in Horticulture in June 2020 – now postponed to 2021.***

AeroFarms

AeroFarms is entering the third and final year of the Foundation for Food and Agriculture Research, Seeding Solutions in Urban Food Systems Program (# 534680) grant. The grant allows them to examine how to use their control of the growth environment to demonstrate the phenotypic plasticity of cultivars. In the first year of the project four leafy green varieties were chosen and exposed to six abiotic stressors, including light and nutrient conditions. Using their own internal analysis and that of Rutgers University labs (Dr. James Simon's biochemistry lab and Dr. Beverley Tepper's sensory lab) they have been able to document methods to alter color, taste, texture, and phytochemicals.

In their second year, they narrowed the stressor field and started combining them. Spectrum, intensity, and timing of light were altered in various combinations representing 10 unique growth cycles that included: combined red, blue, green and far red; light intensity x spectrum; far red start x blue finish; and nitrogen x light. The greens produced in these experiments were again measured by AeroFarms and analyzed by Simon and Tepper labs. They then focused on 4 varieties, and grew those plants under 3 stressors at 5 levels. These experiments included: blue light finishing treatment, added on different days of the growth cycle in five different trials; combined spectrum experiment comparing plants exposed to at least five different red to blue light ratios; and light intensity experiments testing 5 different light levels with one spectrum.

In their third and final year they will expand their knowledge of control range and will combine multiple stressors towards creating bespoke growth algorithms that can make their produce more attractive, nutritious or tasty. They will also produce journal publications.

Two outcomes of the project worthy of note stem from work of PhD candidate Regina O'Brien in Dr. Tepper's lab. Regina obtained a North East – Sustainable Agriculture Research & Education (NE-SARE) pre-doctoral grant (GNE19-212-33243) entitled, "Increasing Consumer Acceptance of Baby Leafy Greens Grown in a Controlled Environment" and gave a presentation at the 2019 NY Produce show entitled, "Controlled Environment Agriculture: A Tool to

Understand Flavor Profiles and Consumer Demand for Baby Leafy Greens." She will present at the Institute of Food Technologists Annual Meeting, Chicago, IL, in July 2020 "Development of a lexicon to describe *Brassicaceae* and non-*Brassicaceae* baby leafy greens grown with Controlled Environment Agriculture with links to chemical composition." The introduction reads, **"**Baby leafy greens are increasingly popular with consumers and Controlled Environment Agriculture allows rapid, consistent growth, and high-quality production of these plants. While published lexicons exist for adult plants, descriptive language for baby leafy greens is lacking. This study developed a lexicon for *Brassicaceae* and non-*Brassicaceae* varieties of baby leafy greens grown indoors, and linked the sensory profiles of these plants to their phytochemical composition.

3. <u>Accomplishment Summaries:</u>

Purdue University

Two research technical capabilities have been brought online during the reporting period, and both are expected to greatly enhance future capability to gather data for controlled-environment crop responses to different energy-saving treatments, including close-canopy lighting, targeted lighting, and those, in turn will open up unique opportunities for phasic optimization involving those lighting approaches. The Minitron III plant-growth/gas-analysis system will allow investigators to make real-time informed decisions regarding next-steps in growth-environment adjustment that will affect crop responsiveness to lighting, CO_2, and/or temperature conditions affecting energy-use efficiency. The refurbished-chamber close-canopy-lighting system is expected to greatly expand capability to simultaneously test effects of different light/crop separation distances on crop response with or without energy or PPFD standardization, and expand capability to compare responses of a variety of species and cultivars. Phasic-optimization treatment comparisons also can be greatly expanded using both systems. A cadre of undergraduate student helpers from the Purdue Polytechnic institute working together with students from the schools of Science and Agriculture have received valuable experience and training in multi-disciplinary controlled-environment-agriculture engineering and research during the reporting period. These experiences will influence their future professional choices for occupations.

University of Guelph

Collaboration and technology transfer with Intravision Lighting and Elevate Farms resulted in the construction of a vertical farm facility with 4000 square metres of growing space for leafy green production located in Welland, Ontario.

Tomatosphere, a free science outreach program available throughout North America, is now in its 21st year, and has engaged over 3 million students since its inception.

Kennedy Space Center

Ye Zhang and Matt Romeyn continued to oversee some of the "validation" testing with Veggie plant growth systems on the International Space Station (ISS), which mixed crop tests with two types of lettuce and mizuna, continuous production in two veggie units, and the addition of new crops, Red Russian Kale, Dragoon lettuce, Wasabi mustard, Amara mustard and Extra Dwarf pak choi. Additionally, a seed film delivery technology will be tested in the upcoming Veg-03J technical demonstration test.

A technical demonstration in the Advanced Plant Habitat (APH) on ISS is slated to launch in early 2021 that will grow cv. Espanola Improved chili peppers for a period of 120 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 chili peppers grown in microgravity. This project is being conducted by Matt Romeyn, LaShelle Spencer, Oscar Monje, Jacob Torres, Jeff Richards, and Nicole Dufour.

Gioia Massa has a 3-yr NASA grant to conduct the first official plant testing using Veggie (with leafy greens in 2019 and dwarf tomato in 2022). 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. They have worked closed 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. Tomatoes will be grown in the Veggie using the Passive Orbital Nutrient Delivery (PONDS) growing system under the same lighting conditions to complete the project. A modified version of the PONDS hardware will be tested on ISS soon.

Mary Hummerick and LaShelle Spencer along with super undergraduate and graduate interns, conducted several tests with lettuce, mizuna, radish, dwarf tomato and dwarf peppers to assess their microbial counts, and compared these to similar vegetables purchases in local grocery stores. The intent of these studies was to establish some baseline or “norm” for acceptable microbial counts and food safety for space crops. In general, plants grown in the controlled environment chambers were lower in microbial counts than similar crops purchased at grocery stores, and in all cases, the levels of microbes could be reduced by treating the leaves or fruits with ProSan, a citrate based sanitizing agent. Colleagues at Johnson Space Center have used the data to develop a risk assessment for fresh produce grown in space.

LaShelle Spencer, Matt Romeyn, Ray Wheeler and some super interns completed a set of studies where leaf vegetables were grown at 400, 1500, 3000, and 6000 ppm CO_2 to study growth and development, and stomatal conductance across a range of CO_2. For the first tests at 400, it became very difficult to hold the set point due to CO_2 pollution in the surrounding room and humans coming and going in the chamber. They later added CO_2 scrubbing systems from Percival, which contain multiple trays with color-indicating NaOH coated pellets. This worked quite well for holding 400, even with one person in the chamber. But you need to be sure the pellets are changed when they are exhausted. Larry Koss of the KSC group put a clear acrylic “window” on the scrubbing box to allow easy viewing of the pellets.

A two year tomato and pepper screening study was completed, with over 40 cultivars being screened and promising candidates down-selected for further growth studies and nutritional and organoleptic analysis.

A one year study to screen microgreen cultivars was finished in 2020. This is the first of several projects aimed at identifying promising microgreen species / cultivars for use in space and assessing nutritional impact and food safety. KSC has brought on a new postdoc and partnered with USDA ARS in Beltsville, MD to develop microgreens as a future crop for spaceflight.

Studies on herbs were initiated to consider what herb varieties might be best for supplementation of packaged diets in space flight. Sixteen herb varieties were tested initially in spring of 2020, and this work will continue with down selection based on growth, and nutrient content. Additionally, upcoming studies will focus on herbs that will grow well as microgreens.

Lucie Poulet was selected as a NASA Postdoctoral Fellow and began working at KSC in January, 2019, 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.

Christina Johnson was selected as a NASA Postdoctoral Fellow and began working at KSC in August 2019 with a focus on microgreens. She has been assessing the differences between microgreens grown in unit gravity versus those grown in simulated microgravity via clinostats and random positioning machines. 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.

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 (https://www.canr.msu.edu/floriculture/expo) and the Floriculture Research Alliance (http://floriculturealliance.org) annual meeting.

Developed a new page on the MSU Extension Floriculture & Greenhouse Crop Production website (https://www.canr.msu.edu/floriculture/resources) that includes MSU-authored resources on the production of plants in controlled environments, with categories such as “greenhouse temperature management” and “light management in greenhouses & controlled environments”.

Runkle is project director and Lopez is a principal investigator in a new, four-year project supported by the USDA Specialty Crops Research Initiative entitled “Improving the profitability and sustainability of indoor leafy-greens production” (http://www.scri-optimia.org), in collaboration with colleagues at Arizona, Michigan State, Purdue, Ohio State, and the USDA-ARS.

The Ohio State University

Precision variable-rate spraying technology has been developed to improve application efficiency for controlled environment plant production in greenhouses. The variable-rate control system reduced spray volume by 29-51% compared with conventional constant-rate spraying.

The 2020 Greenhouse Management Workshop (January 16-17, 2020) was organized by Peter Ling and Chieri Kubota with 106 participants (including 16 online). This year’s focus was ‘Sustainable & Safe Crop Production’ covering both ornamental and food crops.

Rutgers University

Rutgers University continues to evaluate a variety of lamps for light output, light distribution and power consumption using their 2-meter integrating sphere and a small darkroom.

They evaluated the spectral output of a variety of lamp technologies and compared various waveband ratios with sunlight. They are continuing work on a comprehensive evaluation of ventilation strategies for high tunnel crop production. They started work on life cycle assessments of supplemental lighting systems. A variety of outreach presentations on the engineering aspects of high tunnels, greenhouse production, and energy consumption have been delivered at local and out-of-state venues.

University of Georgia

In collaboration with electrical engineers, they have developed optimal control algorithms for supplemental lighting in greenhouses. These algorithms can be used from 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

Texas A&M AgriLife Research continued research on optimizing indoor sole-source light environment on the growth and nutritional quality of sweet basil and leafy greens. Most recent completed research on supplemental ultraviolet-B (UV-B) radiation before harvest increased phytochemical concentrations up to 169% in green basil leaves but decreased plant yield, while lower UV-B radiation doses increased antioxidant capacity in *Brassica* species without yield reduction. Results showed that UV radiation has a potential to increase the concentration of bioactive compounds in leafy greens and herbs and its impact depends on dosage, timing and method of delivery the UV radiation, and species and cultivars.

Texas A&M AgriLife Research started research on organic hydroponics in NFT and deep-water culture systems. Organic CEA production methods are still in their infancy and there is extremely limited research-based information. The major challenge of organic hydroponics is lower yield due to slower plant growth compared to conventional farming. They have been conducting several experiments on comparing conventional vs. organic hydroponic lettuce production with or without microbial root inoculant using various propagation plug types. Preliminary results indicated that crop yield is lower in organic fertilizer treatment but crop quality is enhanced.

Texas A&M AgriLife Research collaborated with AgriLife Extension on organizing their first conference in urban controlled environment agriculture and attracted 60 participants in 2019.

Texas A&M University, Department of Horticultural Science on main campus, hired Dr. Shuyang Zhen who started August 2020. Dr. Zhen will teach and conduct research on controlled environment horticulture.

University of Maryland

A primary focus of their current research is to better relate substrate volumetric water content (VWC) to plant-available water (matric potential, MP), so CE growers can better establish irrigation thresholds, increase the precision of irrigation applications, and maintain growth rates by avoiding water stress.

A primary focus of research activities during 2019 was finalizing deficit irrigation with greenhouse-grown strawberry and a series of urban vegetable crop production in green roof substrates. Incorporation of biochar had no significant effect on water-holding capacity in these substrates. Incorporation of 5% aluminum oxide significantly reduced soluble phosphate but not nitrogen leaching from compost amendments, without affecting the growth of three successive vegetable crop cycles.

A comparison of irrigation-water containment methods and management strategies between two ornamental production systems to minimize water security threats journal article was published.

A book chapter entitled "Advances in Irrigation Practices and Technology in Ornamental Cultivation" in the book entitled "Achieving Sustainable Cultivation of Ornamental Plants."

Heliospectra

Heliospectra hosted Plant and Light Workshops in Europe and United States to foster community and share of knowledge with commercial growers. Discussions focused on photobiology, validation of light spectra for transplant, rooting and produce finish and appearance, and resource efficiencies achieved with LED technology and controls for medicinal plants, tomatoes, leafy greens and herbs.

Heliospectra continues R&I work related to bio sensors, light control systems and biofeedback control, initiating a new research project with academic partners to evaluate biotic stress detection with optical sensing.

Hort Americas

Hort Americas has continued to partner with Big Tex Urban Farms and the State Fair of Texas. Their joint efforts continue to include:

1. Continue to strive to be a thought leader in the development of urban agriculture in hot and humid climates.
2. Testing and proving equipment in medium-tech greenhouses located in a hot and humid environment.
3. Providing residents of South Dallas communities, which have been designated USDA food deserts, with access to fresh produce through a variety of local charities (partners).

Their project is only 1½ years old and they have already provided more than 400,000 servings of fresh locally-grown produce to the residents of South Dallas.

Licor BioSciences

New LI-180 Firmware

With the LI-180 Spectrometer, you can now configure custom wavebands to measure only the light intensity for the wavebands in which you have an interest. Similarly, you can set up your own custom ratios to compare fractions of light between various wavebands.

New 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 period. 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.

4. Impact Statements:

Kennedy Space Center

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 they have been sharing their gaps list and having discussions with other government agencies, members of academia, and relevant industry professionals. The challenges that they 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

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.

They learned more about the advantages and disadvantages of including green light in an indoor lighting spectrum. This information helps indoor (vertical) farm growers determine what lighting spectrum to deliver to their crops.

Due to increased plant densities during seedling production, fewer inputs per plant are required, creating the potential to increase production efficiency. Faster growth rates can result in reduced production time and increased yields. By understanding and modeling the effect of daily light integral and CO_2 concentration on culinary herbs, growers can conduct cost-benefit analysis to increase profitability and group plants with similar daily light integral and CO_2 responses in a common environment.

The Ohio State University

They continue 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 340 members, serving as a very effective engagement method with industry stakeholders.

Rutgers University

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 improved 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. Greenhouse growers who implemented the information resulting from their research and outreach materials have been able to realize energy savings of between 5 and 30%.

University of Georgia

Electricity costs for supplemental lighting can be a major cost for greenhouses. By combining plant physiological information, light measurements, and predictive modeling, they have developed optimized lighting control strategies that can reduce the cost of supplemental lighting by up to 40%.

Texas A&M University

The second edition of the book "Plant Factory – Indoor Vertical Farming System for Efficient Quality Food Production" (edited and co-authored) has received positive feedback from indoor farming industry and scientific community, which is why Texas A&M were asked to work on the second edition. The first edition book was published in 2015.

Evaluation summaries of the first annual 'controlled environment conference' are: 92% of participants indicated gain in knowledge; 70% anticipate economic benefits as a direct result of what they learned; and 97% would recommend this activity to others.

University of Maryland

Assist the controlled-environment industry to efficiently and successfully utilize available primary and secondary (recycled) water sources.

Examine disease risk factors associated with deficit irrigation strategies, to overcome real and perceived barriers to adoption of deficit irrigation techniques, particularly when using recycled water.

Evaluate the efficacy of recycled water remediation strategies in reducing / eliminating cryptic oomycete pathogens.

Evaluate the efficacy of slow sand filtration in reducing paclobutrazol (a widely-used plant growth regulator) concentrations in recycled irrigation water.

Reduce the N and P loading potential of organic substrates used in urban rooftop vegetable production to local rivers and streams.

Heliospectra

Heliospectra continues work with Dr. Brande Wulff at John Innes Research Centre, Dr. Lee Hickey at University of Queensland, and Amir Sharon of ICCI at University of Tel Aviv to support technology transfer of speed breeding research protocols and rapid seed to seed generation of cereals and grains. University of Queensland recently extended their program focus with a trial installation in Ethiopia with the aim to improve seed applications and secure future food supply in arid climates.

Heliospectra is participating as industrial partner in the *LEDs make it resilient project* at Wageningen University, which started in 2019. To support technology advancement, the project team and three PhD candidates are investigating the effects of different light quality and temperature conditions on crop production and resilience with findings to be published over upcoming years.

Heliospectra continued support of the Wageningen University Autonomous Greenhouse Challenge 2019-2020 with teams using the ELIXIA adjustable spectrum LEDs and helioCORE™ light control platform.

In response to COVID-19 and cancellation of vital educational and industry conferences, Heliospectra launched a *By Growers for Growers webinar series* in April 2020 with 14+ online sessions to date, featuring presenters from Cornell University, Michigan State University, Colorado State University, Wageningen University, and Swedish University of Agricultural Sciences to continue to engage and share CEA and cultivation knowledge with growers and partners across the globe.

Licor BioSciences

What you can do with new LI-180 software

For light quality, knowing and controlling the spectrum of the light source can have significant effects on your plant. For example, you can affect the following: morphology with blue light, growth and yield with red light, plant heath and chemical content with UV light, and transition from vegetative to flowering with FR light. In addition, you can apply different light spectrums at different growth stages. Light source selection should be dependent on the stage of growth and the goal during that stage. Knowing the light source's spectrum, or using an LED 'recipe,' equips growers with the ability to make confident decisions on which light sources to use and when to use them.

What you can do with new LI-600 Porometer/Fluorometer

Controlling the inputs/drivers described above can have significant affects, positive or negative, on plant growth. Measuring the plant's response to these influences is key.

Besides plant disease, one of the other indicators of health is plant stress, typically from lack of water or overheating. To help identify plant stress, measurements can be made on leaves to measure transpiration rates in the form of stomatal conductance. When these measurements are out of range, this can be used as an early indicator of plant stress, even before visible signs are present. This also plays a role in affecting leaf temperature, water requirements, and the greenhouse microclimate, including water loss from the soil or substrates and plant surfaces. A good value of stomatal conductance can inform you that your plant is growing as expected and is reacting to the source of light being applied and the VPD/RH levels in the greenhouse.

Plenty

They are making strides in AI-enabled adaptive management for lighting and irrigation.
They are actively developing a robust breeding program.
Their Plant Science team has tested over 700 varieties across different crops.
They continue to work towards improved flavor and production techniques for indoor-grown strawberries, with an eye towards launching commercial production soon.

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