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## 2.1: Research Track

# ENGAGING BUSY SCIENTISTS, ENGINEERS, AND DESIGN FACULTY IN INTEGRATIVE STUDIES OF LIVING ROOF ECOSYSTEMS

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## Abstract

We know that interdisciplinary research and design are essential in our efforts to create resilient and more regenerative regions, cities, neighborhoods, buildings, and landscape systems. Question: How does a landscape architect and green infrastructure designer who teaches at the college level bring a wide range of busy university researchers to the table to study living roof ecosystems? Answer: Focus on issues that make a real difference to science and society—including stormwater harvesting and runoff attenuation, plant-substrate-water relations and climate science, urban pollinator and wildlife habitat as stepping stones, creating places of refuge for people and other creatures, plant health and biomass production for thermal cooling, microbiology and carbon sequestration, ecological design and engineering, use of aerial imagery, rooftop photography, and various sensors to observe changing patterns and dynamics, and long-term monitoring and maintenance strategies. Botanists, biologists, entomologists, plant and soil scientists, climatologists, ecologists, engineers, and others are intrigued by the possibilities that place-based mixed-species green roofs and green infrastructure can make cities more livable for people and larger ecological systems. This paper reflects on the reasons and ways that scientists, statisticians, and engineers at a land-grant university in the USA have been actively engaged with designers to explore the workings of living roof ecosystems. Focused and meaningful research questions, adequate funding for student and faculty researchers, acquisition of needed equipment and sensors, collaboratively preparing publications, and developing long-term cooperative learning, outreach, and scholarly partnerships that address practical, applied problems important to society are deemed to be very important.

## Introduction

In his *Ecoregional Green Roofs* afterword, Bruce Dvorak (2021, 604-605) discusses the future outlook and research gaps for green roofs designed and implemented in cities west of Indiana, USA (including parts of southern Canada and northern Mexico). This geographic area can experience periods of very hot and/or dry weather—which is being made more challenging due to warming air and ocean temperatures across much of the world. As noted by Dvorak, research on a wide range of green roof related issues, including ecosystem dynamics on living roofs, be they dormant or vibrantly growing, is greatly needed.

In *Green Roof Ecosystems*, edited by Richard Sutton (2015), the call is for much more research (both short- and long-term studies) and dissemination of research findings and discussion of the implications for design, implementation, and management. The question is—given time, budgetary constraints, and many other pressing research priorities related to larger landscapes and urban ecosystems (as just one example see the work being done by Columbia University's Center for Resilient Cities and Landscapes: https://crcl.columbia.edu/)—how do we effectively facilitate and support the types of interdisciplinary green roof research that are needed?

Much has been written about the need for interdisciplinary research and the ways to make it more effective in tackling complex challenges (NAS et al. 2005; NRC 2014; NRC 2015) Due to the complexity of coupled human and natural systems we know that interdisciplinary research effectively integrating ecology and design are essential in our efforts to create resilient and regenerative regions and cities (McPhearson et al., 2016), neighborhoods and buildings, and landscape systems at multiple scales (which include green roofs and other living infrastructure).

As with any complex area of study related to urban ecology and sustainable design, one discipline cannot (and should not try to) address all important issues related to green roof design, implementation, and management. Thus, integration of design and research are vital (Felson et al. 2013). As clearly articulated by Dunster and Coffman (2015), Dvorak and Skabelund (2021), Lundholm and Williams (2015), Rowe (2015), Skabelund et al. (2015), Sutton and Lambrinos (2015), and others contributing to Sutton (2015) and Dvorak (2021), the perspectives of engineers, designers, scientists, material suppliers, irrigation specialists, facility and landscape maintenance staff, and other practitioners are important to building a meaningful, robust body of research that improves where and how green roofs are created and maintained.

This paper reflects on the reasons and ways that leading and emerging scientists, statisticians, and engineers at a land-grant university in the USA (Kansas State University in Manhattan, Kansas) have been actively engaged with designers to explore the workings of living roof ecosystems. It also synthesizes the thoughts of 18 faculty members at 10 institutions as they responded to the question of how to bring busy researchers together to study green roofs.

### Reflecting on Interdisciplinary Living Roof Projects at Kansas State University

Four major living roof design and subsequent green roof research projects have been undertaken at Kansas State University since 2008 (two 300-350 square-foot green roofs in close proximity to each other at Seaton Hall, home of the departments of Landscape Architecture and Regional and Community Planning and Biological and Agricultural Engineering; one at the historic Memorial Stadium, where two steep-slope green roofs were

designed and implemented by professional landscape architects and designers working with other professionals on the former stadium bleachers/concrete steps; and the Experimental Green Roof, co-designed by professional designers and engineers on the College of Architecture, Planning and Design's new building).

Each project was proceeded by conceptual green roof design work that I (Lee Skabelund) was involved with. I served as the lead green roof designer for each of the two small (approximately 300-350 square foot) Seaton Hall projects; the Upper Green Roof was constructed by faculty and students in 2009, and the Lower Green Roof by faculty, staff, and students in 2012. I also led the work on the design and implementation of a 300-gallon cistern to be used to irrigate the Lower Green Roof (implemented in 2014). For the Memorial Stadium project, I prepared a concept design for the East Memorial Stadium Green Roof, which was used by the dean of our college to encourage the Alumni Association and university administrators to move forward with final design and construction documents (prepared by Jeffrey L. Bruce and Company). Implementation of these two steeply-sloped living roofs at Memorial Stadium took place in 2015 and 2016.

For the APDesign Experimental Green Roof (APD-EGR), I prepared a three-bed green roof concept that included drawings and text showing desired data-logger locations and a way to monitor stormwater runoff. Due to budget constraints it was determined that the proposed stormwater monitoring setup could not be implemented. However, the new building construction contract included an 800-gallon cistern, a water pump, several spigots and electrical outlets, and replicate plots—all to be created as part of authentic green roof beds so that our research team could monitor three different plant mixes and two substrate types, each repeated four times in randomized blocks at three different depths. The idea to have 72 roughly one-meter-square plots (24 plots at three different depths) was implemented in the fall of 2017 and spring of 2018. Our research team replaced many dead plugs on the APD-EGR during late spring and early summer 2018 so that we could formally initiate our monitoring and research work.

Sensors and data-loggers for monitoring soil moisture and/or temperature and other variables were installed for each of the five green roofs for these four project locations on campus. A weather station was added to the Seaton Hall Upper Green Roof (UGR) in 2009, and detailed abiotic (precipitation, air temperature, relative humidity, wind direction and speed, surface and subsurface temperatures, and soil moisture), and biotic (plant survival and growth) data was collected for more than five years on the UGR. In 2018, a new and more robust weather station was added to the APD-EGR (along with sub-surface soil moisture and temperature sensors in the all-native plant plots). In both instances the expertise of Mary Knapp, a climatologist who works closely with the National Weather Service, played a critical role in setup of our monitoring systems and in the collection and interpretation of data. Several faculty members from the Bio-Ag Engineering, Agronomy, Plant Pathology, and other departments at K-State have also played vital roles in helping develop research questions, think through research design, submit grant applications, secure monitoring equipment and sensors via purchase and on-loan, collect and analyze data, review student theses and dissertation work, and help prepare publications and conference abstracts and presentations.

Other faculty members became interested as I led the effort to secure funds to implement the two small Seaton Hall green roofs and receive many donations to support the design-build and

monitoring efforts. Carol (Blocksome) Baldwin, who had expertise in collecting vegetation data in prairie ecosystems, helped developed plant monitoring protocols used on the UGR between 2009 and 2014. Collection and analysis of soil samples on the UGR was supported by Rhonda Janke (soil scientist) while Tim Todd (plant pathologist) became involved because of his interest in these novel ecosystems and his willingness to share his knowledge of statistical analysis with our growing team. A number of other K-State staff, students, and faculty (including doctors Trisha Moore, Tim Keane, Deon Van der Merwe, Ajay Sharda, David Haukos, Mary Beth Kirkham, Gerard Kluitenberg, and Charles Rice) got involved as time passed, with many faculty being invited by me to work on conference and journal papers, and others invited by students—namely Priyasha Shrestha, Pamela Blackmore, Allyssa Decker, and Lekhon Alam—to serve as committee members for their thesis and dissertation research.

Some of us prepared our proceedings papers for CitiesAlive in 2014 (Skabelund et al., 2014) and 2017 (Skabelund et al., 2017; Van der Merwe et al., 2017), while others worked on our first international publication (Liu et al., 2019), led by a visiting scholar who was invited by me to join our research team in Manhattan, Kansas for one year (spring 2018 to spring 2019). Six research posters were also prepared for local and international conferences and research symposia (including the Kansas Water Conference, CitiesAlive 2017, and K-State undergraduate research symposia). As a result, one or two posters were created for each of our four green roof projects. In September 2021 LAF (the Landscape Architecture Foundation) published a case study of the Memorial Stadium Green Roofs project as part of their Landscape Performance Series (Skabelund and Alam, 2021).

In addition to these research efforts, active vegetation management (including ongoing weeding of invasive and nuisance plants) of each of the five living roofs and provision of supplemental irrigation on these green roofs has been led or coordinated by Lee Skabelund and his graduate students. These management efforts sometimes required us to manage nearby weeds (in adjacent green roofs and on-the-ground rain-gardens and campus landscapes) so that weed seeds would not be so readily transferred to the green roofs we were managing and studying. As a result, we have had less time than desired to focus on writing papers and disseminating research findings.

I have viewed the successful establishment of each of these green roofs at Kansas State University (including the management of invasive and nuisance species such as pigweeds, ragweed, marestail, wild sweet clover, and a range of woody plants) to be a very important part of our monitoring and research, teaching and education, and service and outreach efforts.

Disciplines involved in our living roof research between 2009-2021 include: landscape architecture (lead discipline), environmental planning/design, architecture, bio-ag engineering, climate science, soil science, agronomy/plant science, plant pathology, wildlife biology, botany, entomology, horticulture, landscape ecology, civil engineering, and agriculture (see Appendix A: Involvement in Living Roof Projects and Green Roof Research by Kansas State University Faculty and by Emerging Professionals, Practitioners, and Suppliers).

### Learning from Other Colleagues at Kansas State University and Beyond

While I have dedicated more than a decade to the design, implementation, management, and study of green roofs many questions have arisen. One of the most important and pressing can

be simply framed as: Given their modest size (even large ones), are green roofs worth the time, expense, and risks? This question inevitably leads to other questions such as who needs to be involved in addressing this big-picture concern and hundreds of other related and unrelated questions. Along with landscape architects, planners and architects, botanists and entomologists, plant and soil scientists, climatologists, biologists and ecologists, engineers, and others are intrigued by the possibilities that green roofs and green infrastructure can make cities more livable for people and larger ecological systems. However, to determine the appropriateness and sustainability of specific green roof applications (including the type, size, and location of these designed and engineered ecosystems) interdisciplinary and transdisciplinary scientific research and long-term observations are needed.

Thus the question: How to bring a wide range of busy university researchers to the table to study living roof ecosystems? My initial answer, placed in my Cities Alive 21 abstract submission, follows: “One-by-one, focusing on one roof at a time, and on issues that make a real difference to science and society—including stormwater harvesting and runoff attenuation, plant-substrate-water relations and climate science, urban pollinator and wildlife habitat as stepping stones, creating places of refuge for people and other creatures, plant health and biomass production for thermal cooling, microbiology and carbon sequestration, ecological design and engineering, use of aerial photography, photography, and various sensors to observe changing patterns and dynamics, and long-term monitoring and maintenance activities.”

Yes, but “what am I missing?” I asked. The input of others was deemed to be essential.

## Informal Survey Methodology

Without time or resources to complete a full-blown scientific study I decided that I must try learn what I could from respected colleagues in less than a week. I subsequently selected 26 (two baker’s dozen) scientists, designers, engineers, and green roof researchers to send the following question: **“How does a landscape architect and green infrastructure designer [like myself, who teaches and does research] bring busy university researchers to the table to study living roof ecosystems?”** 18 of my 26 contacts (10 of these from Kansas State University) were able to respond and share some of their thoughts with me within a week of my initial email prompt (which was sent to each person individually with a personalized message). Each respondent indicated that I could share their thoughts and cite them by name (see Appendix B for their comments—responses that in some instances were edited by me for greater clarity).

### Informal Survey Findings Reported as a Synthesis of Thoughts Shared

Here is a synthesis (with my interpretations and ample “reading between the lines”):

We need to change what we value and how we think about the ways we address critical issues. If we are to address the pressing concerns related to climate change, loss and degradation of essential ecosystem functions and services, increasing impacts related to drought and severe storms (including fire and flooding), human disconnection from places, and disavowal of the precautionary principle, we must better recognize that built environments, interacting with natural patterns, processes, and forces, bring harms and opportunities.

Dilemmas and challenges associated with how we build cities, neighborhoods, landscapes, buildings, and other infrastructure can be effectively addressed by wise planning and design informed by fair-minded and collaborative science and engineering (including green roof and green infrastructure work).

We need the perspectives of others and the willingness broaden and deepen our understanding and develop collaborations that address root concerns and help explore challenges, limitations, and opportunities—especially those related to life-cycle assessments of green infrastructure and living roof dynamics over long-periods of time.

We need to address problems and issues meaningfully and well-considered research can help. The knowledge that practitioners (planners and designers) *and* green roof suppliers and contractors provide can complement the knowledge of interdisciplinary and transdisciplinary university research teams. Understanding the research (the green roof literature and implemented living roofs that serve as precedents) is deepened and improved as we bring in the perspectives of different, relevant disciplines. No one discipline can address the complexity of issues associated with green roof ecosystems. Designers need to learn from ecologists and biologists who seek to develop a compelling hypothesis that relates to a broader issue, employ a rigorous experimental design that involves statistical analysis, and produce results that can be generalizable to other ecosystems, places, or contexts.

The challenges associated with scientists and designers working together can be difficult to surmount; we both need one another but we may not have the time and/or funding to support these important collaborations. We need to recognize the strengths that each discipline brings to the research endeavor. We also need to understand the particular university rewards system and account for these concerns as we 1) develop an organizational framework for our collective research efforts, 2) prepare and submit research proposals to help fund our collective work, and 3) collaboratively work on projects together.

It is very important to develop mutually-beneficial research projects, recognizing that to benefit different disciplines at least one of the following components must be present: 1) funding to support the research; 2) the likelihood of obtaining meaningful results that lead to published and disseminated findings and lessons learned; and 3) development of meaningful, productive long-term research collaborations that address important issues and help further the careers of each participant.

Funding is essential to support students and faculty and to cover the costs of securing materials, monitoring equipment, and other needed project resources. We need to actively seek partnerships and interdisciplinary skills and knowledge that will help our research team secure internal and/or external grants, donations, and contributions of time and insight. Sharing equipment and resources can help defray costs and support our collaborative research endeavors.

Interdisciplinary research is made possible as relevant expertise is brought together to address the many questions and issues related to green roofs. These relationships should help us create reciprocal relationships and leverage mutual interests—which may include finding other new and important questions to explore together, and sharing knowledge to help improve design and create more resilient, enjoyable cities, landscapes, and larger ecological systems.

Green roof research gives scientists the opportunity to explore novel, smaller-scale ecosystems with designers and those from other disciplines right on or near to campus, reducing travel times and providing the opportunity to address practical, applied problems important to society. Examples of applied problems include: the creation of more sustainable infrastructure and cities, the restorative possibilities of contrived rooftop ecosystems for people and the ecosystems, and the specific roles of living roofs in sequestering carbon, reducing the heat-island effect, managing urban stormwater runoff, supporting pollinators, enhancing biodiversity, and helping address other important issues.

Living roof research by interdisciplinary teams allows us to explore ecosystem services and how these particular landscapes function related to aesthetics and ecology. This research is deepened by creating opportunities for dialogue and feedback from stakeholders, practitioners, and those working in the green roof industry.

Student learning should be at the heart of academic research endeavors as we are training the next generation of researchers and educators. To do this well both we and our students need to learn to effectively collaborate with those from other disciplines, skillsets, and perspectives. Co-advising student research and publishing with students is vital in their education and growth as future planners, designers, engineers, scientists, and researchers. Student research and the need to have robust interdisciplinary committees has been a major driver for the breadth of disciplines involved in green roof research at Kansas State University.

## Concluding Thoughts

Living roof research by interdisciplinary and transdisciplinary teams is vital if we are to improve green roof design, implementation, and management that supports the creation of just, sustainable, and ecologically-sound urban ecosystems. As noted by Bousselot et al. (2020) one of the most important ways to promote interdisciplinary green roof research is to provide consistent and adequate funding. They also suggest, and I concur, that the green roof industry needs to be a major player (along with others in the public and private sectors) in supporting unbiased, peer-reviewed scientific inquiry regarding long-term green roof functions and dynamics. These ideas likewise correspond to the collective thoughts shared by 18 researchers in early July 2021.

Kansas State University plant pathologist Tim Todd noted that as novel ecosystems, green roofs provide “the opportunity to address questions that haven’t been widely investigated”—the heart of science and learning. Entomologist Dr. Brian Spiesman said: “Living roof ecosystems are increasingly recognized as important for biodiversity conservation and for preserving ecosystem services that contribute to human well-being” and as such, green roofs need to address functional and aesthetic goals; designers, engineers, ecologists, and other scientists need to collaborate to really understand these essential, interrelated services. As mentioned by Dr. Mary Beth Kirkham, Bruce Dvorak, Daniel Roehr, Dr. Trisha Moore, and others, fruitful partnerships provide opportunities for sustained monitoring, research, applying, testing, learning, and publishing in venues readily accessible to all as well as ongoing dialogue between designers, researchers, local governments, stakeholders, and those who implement and manage living roof systems.

## Appendix A: Involvement in Living Roof Projects and Green Roof Research by Kansas State University Faculty and by Emerging Professionals, Practitioners, and Suppliers

**2008-2021 Upper Seaton Hall Green Roof (UGR) Design-Build Work, Research and Weed Management - https://www.k-state.edu/greenroofs/seaton.html**:

Design – Faculty leaders: Lee R. Skabelund and Todd Gabbard; concept design by Lee Skabelund and four students in a 2008 NRES Capstone Class; final design with two architecture students – Michael Knapp and Mark Neibling; structural engineering work: Sutton Stephens.

Implementation – Faculty leaders: Lee R. Skabelund and Todd Gabbard, with Stacy Hutchinson, Edwin Brokesh, Carol (Blocksome) Baldwin and Melanie Kline and six BAE students.

Observational Monitoring/Research and/or Data Analysis – Faculty: Lee R. Skabelund, Carol Baldwin, Mary Knapp, Dede Brokesh, Timothy Todd and Rhonda Janke; graduate students: Jeremy Merrill and Allyssa Decker; undergraduate student: Anna Schnacker (agriculture).

Irrigation (2009-2012) and Vegetation Management– Faculty leader: Lee R. Skabelund.

**Reasons for faculty research involvement –** Lee R. Skabelund (interest sparked by a former student who said we ought to implement a green roof at K-State; Lee began teaching about green roofs to LA and NRES students in 2007 and 2008 and secured funding to implement the UGR from the Kansas Dept. of Health and Environment, with substantial material and in-kind time donated by American Hydrotech, Derbigum, Danker Roofing, and others), Carol Baldwin (interested in plant dynamics in stressed environments), Mary Knapp (interested in learning how a green roof might respond to a very hot rooftop environment and thus provided sensors and a data logger and helped with data collection, trouble-shooting, and accessing and analyzing the data), Dede Brokesh (interested in broadening her design and research capabilities as a landscape architect; she helped download and analyze data, and collect plant coverage data), Timothy Todd (interested in these novel, urban ecosystems and willing to help analyze temperature data), Rhonda Janke (interested in substrate characteristics and ecosystem contributions); Jeremy Merrill (APDesign doctoral student who collaborated with Lee Skabelund on another project and was interested in helping collect plant data at the end of one growing season); Allyssa Decker (Lee Skabelund's doctoral student; helped download sensor data as a green roof researcher learning about Manhattan, Kansas green roofs; part of her paid research assistantship). Lee also worked with an undergraduate student from the College of Agriculture. who was interested in learning about soil-plant-water relations (and they put a research symposium poster together).

**2011-2021 Lower Seaton Hall (LGR) Green Roof Design-Build Work, Research and Weed Management - https://www.k-state.edu/greenroofs/seaton.html**:

Design and Implementation – Faculty leaders: Lee R. Skabelund and Todd Gabbard; concept design by LAR Planting Design Studio and NRES Capstone Class; final design with 3 students (two architecture students – Geoffrey Ekey and Maxie Henkle, and one landscape architecture student – William Mann); structural engineering work: Sutton Stephens; implementation support: Lance Kline, Josh Cheek and Mark Loberg and about six students. Cistern design and implementation involved additional faculty, staff and students.

Observational Monitoring/Research – Lee R. Skabelund and Dede Brokesh; undergraduate student: Laura Heskett (civil engineering).

Irrigation (2012-2021) and Vegetation Management – Faculty leader: Lee R. Skabelund

**Reasons for faculty research involvement –** Lee R. Skabelund, Todd Gabbard and Dede Brokesh were interested in comparing a mostly shaded and protected rooftop with the UGR through observations made over time and use of temperature sensors; Todd attempted to collect temperature below the Seaton Lower Green Roof but the used equipment that was deployed did not record data; Lee and Dede used new Hobo Pro v2 data-loggers to collect surface temperature data that could be compared with UGR data. Skabelund saved and counted weeds removed from and plants clipped on the LGR so that this data could be synthesized at a later date (and this was done by an undergraduate student in the Civil Engineering Dept, who was interested in learning about green roof research as a point of introductory research curiosity); together they created a research symposium poster, summarizing selected weed removal and plant clipping data.

**2015-2020 Memorial Stadium Green Roofs (MSGR) Research and Weed Management https://www.k-state.edu/greenroofs/memorial.html**:

Design and Implementation by professionals, led by designers at Jeffrey L. Bruce LLC and the contractor Blueville Nursery Inc. Note: conceptual designs for both green roofs were completed by Jeffrey L. Bruce in 2008, with refinements by Lee Skabelund for the East MSGR in 2011.

Observational Monitoring/Research – Faculty leader: Lee R. Skabelund, with Deon van der Merwe, Trisha Moore, Stacy Hutchison, Ajay Sharda, Dale Bremer, Dave Haukos, Brent Chamberlain, Jeff Taylor, Mark Mayfield, Brian Spiesman, Tania Kim; graduate students: Pam Blackmore, Lekhon Alam, Ryan Peters, Harman Sangha, Allyssa Decker, Priyasha Shrestha and Kyle Koehler; undergraduate student: Marcos Aleman and two other bio-ag engineering students. External partners: Jeffrey L. Bruce (MSGR design team leader) and Chuck Dixon (soil scientist who guides and supports planning/design work).

Vegetation Management (2016-2021) – K-State Grounds staff with support from Blueville Nursery during the first year of establishment; weed management led by Lee R. Skabelund, with Richard Colwell, Marcos Aleman, and several other students; local resident: Candelaria Easton.

**Reasons for faculty research involvement –** Lee R. Skabelund was interested in observing species survival and vegetation dynamics and monitoring sub-surface soil moisture and temperature on these steep-sloped green roofs to see how slope-aspect influenced changes in vegetation coverage, dominant plant species, and moisture and temperature dynamics on these two large, highly visible green roofs. He was able to use funding from his three-year Mary K. Jarvis Research Chair in Landscape Architecture to bring in three graduate students (two masters students and one PhD student) to assist with this research.

Skabelund invited faculty and students from various disciplines to discuss and then assist with research and worked with Pam Blackmore to connect her Memorial Stadium green roofs research (ultimately focused on butterfly use of the green roofs and other similar ecosystems in a local city park and the Konza Prairie natural area) to larger landscape ecology questions. This necessitated involvement of ecologists, botanists, and experts in GIS and landscape planning and landscape ecology (including wildlife biologist David Haukos, landscape planner and GIS

expert Brent Chamberlain, and Konza Prairie botanist Jeff Taylor; Jeff helped Pam identify plants at the MSGRs, the local park, and at two Konza Prairie watersheds). Pam Blackmore completed her thesis in spring 2019 (https://krex.k-state.edu/dspace/handle/2097/39694).

Learning about the green roofs and Lee's research, K-State entomologists Brian Spiesman and Tania Kim became interested in exploring pollinator use on the MSGRs and undertaken initial exploratory studies (Brian working with Lee and Tania with her entomology students). Some of Brian's initial findings and observations (along with mammal studies at the MSGRs by biologist Andrew Hope) have been shared in several of Lee's presentations (including his MSGR study of green roof performance—completed by Lee and Lekhon Alam for the Landscape Architecture Foundation (LAF)—between January and December 2020 and published in September 2021.

In order to identify changing plant dynamics experts in flying drones were brought onto the team so that thermal, true-color, and infrared imagery could be captured three different times. Unmanned aerial systems owned by Deon van der Merwe (a wildlife biologist working at K-State's Vet Med college) and Ajay Sharda (Bio-Ag Engineering) helped collect, collate, analyze, and synthesize initial thermal and infrared images and data. Professional botanists and students in horticulture played important roles in plant identification (including botanist Mark Mayfield). We documented the total number of species present at the MSGRs and also examined plant dominance on the two MSGRs by conducting plant surveys along eight transects.

Jeff Bruce (the lead Memorial Stadium green roofs designer) and Chuck Dixon (a soil scientist who worked with Jeffrey L. Bruce and Company to develop the substrate specifications for the MSGRs) helped collect and pay for substrate analyses over a three-year period to allow our team to better understand changing nutrient and organic matter levels and the microbiological dynamics of the two MSGR substrates.

Interested in how these novel ecosystems evolve, landscape architects, bio-ag engineers, biologists, botanists, soil scientists, and agronomists with expertise in green infrastructure, stormwater management, soils, and prairie dynamics contributed to the discussion and exploration of plant-soil relations at the MSGRs.

**2018-2021 APDesign Experimental Green Roof (APD-EGR) Research https://www.k-state.edu/greenroofs/apdesign.html**:

Design and Implementation by professionals, led by designers at Confluence and contractors at Blueville Nursery Inc. Note: conceptual design by Lee Skabelund (2015).

Observational Monitoring/Research – Faculty leader: Lee R. Skabelund, with Trisha Moore, Mary Beth Kirkham, Charles Rice, Timothy Todd, Michael Gibson, Timothy Keane, Gerard Kluitenberg, Ajay Sharda, Brian Spiesman; graduate students – Allyssa Decker, Lekhon Alam, Priyasha Shrestha and Harman Sangha; undergraduate student: Miguel Perez. Note: visiting scholar Jialin Liu (Southwest University in China) provided invaluable research support and collaboration in 2018 and 2019, working closely with Lee, Priyasha and Allyssa.

Irrigation and Vegetation Management (2018-2021) – Faculty leader: Lee R. Skabelund, with Allyssa Decker, Priyasha Shrestha, Jalin Liu and Lekhon Alam and support from Eliza Seagrist, Kiona Freeman, and other students. Included selectively weeding of other adjacent green roofs between 2019 and 2021.

**Reasons for faculty research involvement –** Lee R. Skabelund was interested in observing species survival and vegetation dynamics and monitoring sub-surface soil moisture and temperature on the three experimental green roof beds that he co-designed with plant pathologist Tim Todd and designers at the professional landscape architecture firm Confluence. Their collective desire was to see how six-species plant mixes would perform in two distinctly different substrate types at three different depths (4 inches, 6 inches, and 8-inches).

Lee was able to use funding from his three-year Mary K. Jarvis Research Chair in Landscape Architecture to focus research by two of his graduate students (Priyasha Shrestha, MLA and Allyssa Decker, PhD) on the experimental green roof. Lee, Priyasha, and Allyssa invited faculty from various disciplines to discuss and then assist with their "plant growth and health" and "plant-soils-water-relations" research. This necessitated involvement of experts in plant-soil-water relations (especially Mary Beth Kirkham, Trisha Moore, and Gerard Kluitenberg), native plant dynamics (Tim Keane), and statistics (Tim Todd). Priyasha completed her thesis in spring 2019 (https://krex.k-state.edu/dspace/bitstream/handle/2097/39678/PriyashaShrestha2019.pdf).

Learning about Lee's research, Jialin Liu from Southwest University in Chongqing, China (PhD, landscape architecture faculty member, and green infrastructure researcher) asked if she could join our team as a visiting scholar for one year. She arrived in April 2018 and stayed until April 2019, and provided excellent research support and then led out—working step-by-step with Lee—on our first international publication. Although Lee served as co-author on the paper preparation, he put Priyasha as second author given the significant data collection and synthesis work that Priyasha did to support our *STOTEN* paper findings (Liu et al. 2019).

Our growing interdisciplinary APD-EGR research team was also very interested in how aerial imagery might support our understanding of vegetation and temperature dynamics so a student (Harman Singh Sangha) and a faculty member (Ajay Sharda) in bio-ag engineering took imagery of the APD-EGR twice ion 2018 using a UAS (supported by Lee and another K-State student). As at the Memorial Stadium, thermal, true-color, and infrared imagery were captured, but this imagery has yet to be analyzed, written about, and submitted for publication.

An ecological engineer (Trisha Moore), a soil scientist with experience using soil moisture sensors (Gerard Kluitenberg), a statistician, plant pathologist, and nematode scientist (Tim Todd), our plant-soil-water relations expert (Mary Beth Kirkham), an agronomist with expertise in carbon sequestration and microbiology (Charles Rice), and climatologist (Mary Knapp) have each contributed to the discussion and exploration of vegetation, hydrology, microbiology, and substrate dynamics.

Skabelund's second PhD student to focus on green roofs (Lekhon Alam, architect and environmental design student funded by the College of Architecture, Planning and Design) brought Dr. Charles Rice onto our team by inviting him to be a member of his dissertation committee. In addition, a graduate student with expertise in analyzing soils related to microbiological activity and carbon sequestration (James Lin, who works in Dr. Rice's soils microbiology lab) has worked closely with Lekhon, Lee, and other students and a volunteer, to collect soil samples—which James and Lekhon have been analyzing in the soils lab. Tim Todd has also supported Lekhon's substrate nematodes data collection and analysis.

Lekhon also invited architect and faculty member Michael Gibson to serve on his committee to help him with his research interest in urban heat island mitigation and building insulation (exploring if the APD-EGR helps to reduce heat loads and thus energy use and climate change impacts). During the summer and fall of 2020, Skabelund invited a first-year architecture student

in K-State's Developing Scholars program to focus on similar issues since Miguel Perez (who finished his first year as an undergraduate in spring 2021) is keenly interested in sustainable architecture. Lee, Miguel, and Lekhon have been working closely together to collect and analyze surface temperature data on and near the APD-EGR and record and analyze ceiling temperatures beneath the APD-EGR and adjacent walkways to determine if there are significant thermal differences during different seasons related to the green roofs. Allyssa Decker completed her dissertation in August 2021 (https://krex.k-state.edu/dspace/handle/2097/41683) while Lekhon is completing data analysis and writing his dissertation (having successfully defended his research proposal in December 2020).

**Appendix B: July 2021 Green Roof Question by Lee R. Skabelund (LRS) and Responses**

**LRS Question** (sent to 26 contacts—scientists, designers, engineers, and green roof researchers): ***How does a landscape architect and green infrastructure designer [who teaches and does research] bring other busy university researchers to the table to study living roof ecosystems?***

**Answers** (18 email responses shared in early July 2021; edited by LRS for clarity):

***A)*** "The living roof ecosystems transect multiple disciplines. The landscape architect and designer can appeal to researchers' desire for interdisciplinary projects, projects of scale, and the proximity to the research project." Mary Knapp, Service Climatologist, Weather Data Library, Dept. of Agronomy, K-State Plant Science Center, Manhattan, Kansas

***B)*** "The busy researcher must see relevance in the work to his or her area of knowledge. Therefore, the landscape architect and green infrastructure designer studying living roof ecosystems must contact people who are doing research that is needed for studies on green roofs. This should not be difficult, because researchers from many areas of science are needed for successful growth of plants on green roofs. Botanists are needed to know the proper type of plant that will grow on a green roof. Ecologists are needed to know how different groups of plants will grow and compete on a green roof. Climatologists are needed to monitor the weather on the green roof to know when irrigation is needed or to orient the plants in the proper direction according to prevailing winds. Microclimatologists are needed to study gas exchange of the plants. Soil physicists are needed to study the media that the plants grow in to make sure it has proper aeration and water. Soil fertility experts are needed to make sure the plants have the proper nutrition. Weed scientists are needed to show how to control weeds on green roofs. People doing remote sensing are needed to fly drones over green roofs to monitor the temperature or the change in the vegetative index. Engineers are needed to make sure buildings are structurally sound and can hold green roofs. Engineers are also needed to provide proper barriers so water from the roof does not leak into the building. If a student of the busy university researcher can get involved in the research, too, the project will provide training for the next generation of scientists, and this is a goal of professors. Many scientists today are motivated to do research that sustains the environment, which research on green roofs does. If scientists can contribute their knowledge to a green-roof study, they not only will be helping to maintain green infrastructure but also ensuring a sustainable environment." Mary Beth Kirkham, Ph.D., University Distinguished Professor, Dept. of Agronomy, Kansas State University, Manhattan, Kansas

***C)*** "I think the aspects of climate change, carbon sequestration, urban heat (island) effects, and water shortages ought to attract geographers and perhaps bio-ag folks. Urban planners and urban economists should be interested in things such as tax credits, conservation credits, and the positive/promotional press from promoting green roofs (pollinators, protection of species, etc.). Ours is a discipline which can understand and embrace all of these issues creatively and effectively." Tim Keane, Ph.D., FCELA, Emeritus Professor of Landscape Architecture, Dept. of Landscape Architecture, Regional and Community Planning, Kansas State University, Manhattan, Kansas

***D)*** "1. I believe in long time [or long-term] collaborations and cooperation and would prefer to engage with designers and researchers who have a long-standing experience.
2. I prefer researchers and designers to have experience in each other's fields, for example a designer in writing a paper and a researcher who has designed a landscape or has a horticultural background.
3. Apply for research grants on subjects that both parties are interested in.
4. Have ideas to research which are worth researching from an applied science and a designer's perspective. For example, bigger issues concerning society such as the positive impact of rooftop wildflower habitats on bee populations, to increase their survival and pollination capabilities in cities.
5. Large-scale projects [since] there is a lack of large-scale projects researched and [and how green roofs fare] over a longer period and how they are maintained.
6. Collaboration with municipalities on real project sites.
7. Funding is often a big issue, as grants are very time consuming."
Daniel Roehr, Associate Professor, Landscape Architecture and Environmental Design Program, University of British Columbia, Vancouver, British Columbia, Canada

***E)*** "The answer is funding. University researchers need money to pay for graduate assistantships (stipend, tuition, health insurance), pay undergraduate labor, purchase research materials (plants, equipment such as data loggers, lab analyses, etc.), rent research space, and in some cases pay their own salaries. Without funding, they won't have a job so they will do research on funded projects." Bradley Rowe, Ph.D., Professor, Dept. of Horticulture, Michigan State University, East Lansing, Michigan

***F)*** "I am ALWAYS contemplating this question. The best way that I have found is to propose a mutually beneficial project. Ideally the project will include a few key aspects: 1) a readily available funding source, 2) an opportunity to publish the work, and 3) building a longer-term collaboration as that is what most faculty are interested in to further their careers."
Jennifer Bousselot, Ph.D., GRP, Assistant Professor, Dept. of Horticulture + Landscape Architecture, Colorado State University, Fort Collins, Colorado

***G)*** "There are multiple ways designers and researchers can become engaged:
1. Designers should be aware of the wealth of peer-reviewed research online and in print such as research outcomes, design guides, and recommendations for green roofs. Research can be cited in design proposals and outcomes of studies can inform the design process. Evidence-based design can make use of peer-reviewed research to make decisions and support claims.
2. Designers can invite research teams to participate during the design process and provide post-occupancy reports or research. Teams can compete for state or federal grants to support and provide resources to conduct research.

3. Group gatherings such as GRiT (Green Roof information Think Tank) in Portland, Oregon provide an example of how the design community, the research community, industry suppliers, and municipal representatives can begin and sustain dialog and work together. The Gunderson's Ecoroofs in Portland is an example of a multi-partnered pilot green roof project on private property. Such partnerships allow for sustained research and learning between [designers, researchers,] and local governments. See: https://www.greenroofthinktank.org/
4. If local guidelines don't exist, then researchers and designers can collaborate with local government representatives and industry leaders to develop a set of research and evidence-based guidelines. FLL and ASTM provide guidance, but local research may be needed to address challenges presented from local climate, material availability, and educated industry." Bruce Dvorak, ASLA, RLA, Green Roof Researcher, Associate Professor, Landscape Architecture and Urban Planning, Texas A&M University, College Station, Texas

***H)*** "This a two-way street. I believe it is easier for a private practitioner [or design educator] to involve researchers IF they have specific questions they seek to specific and well-thought-out problems to be answered when working on a project. For example, I have been consulted (and paid) by LA green roof designers who seek my expertise with native plants. The other direction is more problematic because while I have found cooperators to allow my research on their roofs, many designers (and their clients) have no interest in cluttered and often failing experiments (e.g. dead or dying plants). Research uses failure to gain insight, commercial design shuns it." Richard K. Sutton, Green Roof Researcher, Emeritus Professor, Program in Landscape Architecture, University of Nebraska, Lincoln

***I)*** "If I understand your question correctly, my number one answer would be grant funding, including industry sponsored (matching, or leveraged) grant funding. In Canada, we have multiple categories of federal science funding (NSERC) that are applicable, as well as specific call for environmental or climate change research funding (also federal), and industry (federal or provincial) funding (MITACS, OCE, etc.). The funding is essential for salaries of student researchers and for the set-up construction and operation costs (including technicians). The other avenue is university funding dedicated to institutional goals around sustainability, climate change, living labs (i.e. collaboration with Facilities and Operations to study the integration and performance of green infrastructure, etc.). And finally, Dean's or Associate Dean of Research's discretionary funding (competitive) for specific research categories on sustainability." Liat Margolis, Associate Professor, Director of the Master of Landscape Architecture Program, Associate Dean of Research, and Director of the Green Roof Innovation Testing Laboratory, University of Toronto, Toronto, Ontario, Canada

***J)*** "Living roof ecosystems are increasingly recognized as important for biodiversity conservation and for preserving ecosystem services that contribute to human well-being. Landscape architects and green infrastructure designers provide researchers with an opportunity to study these benefits in systems that are appropriately designed, both functionally and aesthetically. These two factors are important for adoption of green roof infrastructure by stakeholders. Input from ecologists on how to blend aesthetics and function with the ecosystem components that are most likely to promote biodiversity would also help bring researchers to the table to study these systems." Brian J. Spiesman, Ph.D., Research Assistant Professor, Dept. of Entomology, Kansas State University, Manhattan, Kansas

***K)*** "This is hard to answer. Somehow the discussion has to tie in with their research interests, including grant opportunities or learning opportunities for their graduate/undergraduate students. I think it might be helpful to start with the questions: Why do I want busy university researchers to study living roof ecosystems? What do I hope to achieve, or what outcomes am I wanting?" Carolyn (Blocksome) Baldwin, Extension Associate, Coordinator of the Great Plains Fire Science Exchange Project, Kansas State University, Manhattan, Kansas

***L)*** "From my perspective, I think that the research would have to (1) include clear, compelling hypotheses that could best be tested using the living roof facility and which were relevant to broader questions in grassland ecology or ecology in general, (2) include a statically rigorous experimental design (e.g., adequate replication, appropriate treatment comparisons, etc.), and (3) be likely to produce results that could be generalized to apply to other living roof designs or other ecosystems." John Blair, Ph.D., University Distinguished Professor, Director of the Konza Prairie Biological Station, Dept. of Biology, Kansas State University, Manhattan, Kansas

***M)*** "I've found that it's a reciprocal relationship that you build with other research disciplines. You provide your skill sets and disciplinary perspective when they ask or invite you to help them and then they are more eager or willing to help contribute to your research. By growing the relationships, you also have a better understanding of where their motivation lies and how to leverage their interests in the work." Paul Coseo, Ph.D., Associate Professor of Landscape Architecture, Senior Sustainability Scientist, The Design School, Arizona State University, Tempe, Arizona

***N)*** "Green roof ecosystem research involves plants, water, soil, thermophysics, meteorology, and entomology. Such ecosystems can be the study site for many subjects. Researchers in related fields can find new research questions [by considering] green roof [structure, functions, and dynamics]. Researchers can put forward green roof design optimization methods from different professional perspectives. The results of these studies can be [shared with] landscape architects." Jailin Liu, PhD, Green Roof Researcher, Landscape Architecture Instructor, Southwest University, Chongqing, China; 2018-19 Visiting Scholar at Kansas State University (worked with Lee Skabelund and graduate students)

***O)*** "I'm not certain I understand the context of your question—but my initial reaction is with the proper rewards and/or recognition (e.g. items that get faculty tenure and promotion) and funding. I have always been impressed and amazed at your dedication and commitment to green infrastructure, green roofs in particular, and the time you invest in making sure things work! I think it is very challenging to match that dedication and commitment from a group of busy university researchers without having support for those faculty. While I believe there are many that would like to dedicate time and energy to living roof ecosystems, there are too many demands on their time—and thus, without funding to conduct studies, support graduate students, publish papers, etc., they dedicate their time to other activities they view as a "better investment" for continuing their careers (I fully recognize that these "better investments" are not always better—and are many times pressures from "societal/academic norms"). I also think the complexity and multi-disciplinarity of living roof ecosystems enhances the challenges because you need a relatively large group of expertise to fully address the issues—which further limits potential funding available to each faculty.

My second thought revolves around changing what we value—I am currently getting ready to teach Ecological Engineering for Fall 2021. It will be the first time in the classroom in two years—and the first time I have taught this class without having taught the majority of the students the prerequisite material. I am having a lot of debates with myself on how to guide the students to a deeper understanding of the environment, systems thinking, ecology, etc.—and how a different mindset is needed to solve the most pressing issues of today. This has to push back on decades of engineering thought and disciplinary silos—which we seem to value more than progress… You caught me at an interesting time—looking at University budgets and knowing we have serious financial issues while also planning for pushing students to try a figure out how to push change!" Stacy L. Hutchinson, Ph.D., Professor of Biological and Agricultural Engineering, Associate Dean, Office of Research and Graduate Programs, College of Engineering, Kansas State University, Manhattan, Kansas

***P)*** "I'm not sure that I'm representative of the general population of university researchers, but for me, it is the novelty of the system—i.e. the opportunity to address questions that haven't been widely investigated. Science is first and foremost about curiosity. Beyond that, the likelihood of obtaining meaningful results is certainly a determining factor. In terms of ecological research, a robust interdisciplinary approach is essential. I think that the enthusiasm for involvement would be directly proportional to the quality of the research team and the research questions. Lastly, it goes without saying that participation in research projects is (regrettably) driven by funding opportunities. Even if a researcher is enthusiastic about novel ecosystems, their involvement will necessarily be limited without an adequate source of funding. A major issue that I see with living roof ecosystem research is competition for resources—ecological research is an expensive undertaking, and most ecologists are going to invest their time in systems with significant funding opportunities." Timothy Todd, Instructor and Research Scientist, Dept. of Plant Pathology, Kansas State University, Manhattan, Kansas

***Q)*** "I think you are already doing many of these things! But here you are:

- Provide an organizational framework with short and long-term goals/desired outcomes so that outside researchers can see how they/their expertise fits in and how they support project outcomes through time. Part of this may also need to connect short-term outcomes (e.g., preliminary datasets of proof-of-concepts) to potential funding mechanisms/sources.
- Identify where you can double up on resources, particularly if there is not yet dedicated funding for the project or for potential collaborators (e.g., maybe you have a student who can collect samples for professor X, or professor/researcher Y has equipment that your student can use to run some analyses).
- Offer "carrots" that are counted on annual reviews, e.g., opportunity to co-advise students or to serve on committees, and co-author papers or conference proceedings."
- Trisha Moore, Ph.D., Associate Professor, Dept. of Biological and Agricultural Engineering, Kansas State University, Manhattan, Kansas

***R)*** "The short answer is to have more people who pull in teams to their projects and synthesize queries like the one you just sent. It is funny because on my side, the question is always about how to get designers to consider research. We have a BioScience paper on that ("Mapping the design process for urban ecology researchers" by Felson et al., 2013); I guess it works both ways... i.e. maybe help designers understand the research process, recognizing the publication as academic currency. For example, if designers recognized the need for replication more, that

would help the conversation get started (I understand it is not always feasible, but...). Funding isn't always necessary, but help with fieldwork, connections to grant opportunities, donors, etc. are carrots." Olyssa Starry, Ph.D., Associate Professor, University Honors College, Portland State University, Portland, Oregon.

**Funding for Faculty, Student, and Staff Research Involvement – early July 2021 email discussion between Lee R. Skabelund and Dr. Bradley Rowe (as a survey follow-up):**
***LRS:*** "Securing substantial grant funding is no easy task. In recent years I was very fortunate to secure three years of funding internally. I've not yet found major external funding but have had some financial support from one design firm, one material supplier, and LAF. One of my students (Pam Blackmore) also received several external scholarships and grants. And, we have had lots of other internal and external contributions and support (some financial, lots of in-kind time, and a number of donations of materials and loans of monitoring equipment)."
***BR:*** "Most of my monetary funding came from the EPA, Ford Motor Co., HRI (Horticulture Research Institute), and internal MSU (Michigan State University) grants. I did get some monetary funding from LiveRoof and Xeroflor America. I tried, but was never able to secure any NSF (National Science Foundation) or DOE (Department of Energy) grants. I did get a lot of gifts in-kind for green roof materials from manufacturers, irrigation suppliers, plant nurseries, and media and compost mixers. Although they were very helpful, the MSU administration doesn't count it as they can't charge me any overhead on materials. The difficulty in securing funding is one of the reasons I am retiring. I officially retired a week ago, but agreed to stay on part time to teach classes next year as we haven't been hiring new faculty. My research days are over other than I still want to get a couple papers published."

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