Summer 2022

SMART AGRICULTURE

The BRIDGE

LINKING ENGINEERING AND SOCIETY

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The Bridge publishes articles on engineering research, education, and practice; science and technology policy; and the interface between engineering and technology and society. The intent is to stimulate debate and dialogue both among members of the National Academy of Engineering (NAE) and in the broader community of policymakers, educators, business leaders, and other interested individuals. *The Bridge* relies on its editor in chief, NAE members, and staff to identify potential issue topics and guest editors. Invited guest editors, who have expertise in a given issue's theme, are asked to select authors and topics, and independent experts are enlisted to assess articles for publication. The quarterly has a distribution of about 7000, including NAE members, members of Congress, agency officials, engineering deans, department heads, and faculty, and interested individuals all over the country and the world. Issues are freely accessible at *www.nae.edu/TheBridge*.

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News and Notes

President's Perspective

Laura Castillo-Page and John L. Anderson

Laura Castillo-Page

John Anderson

Laura Castillo-Page is the National Academies' chief diversity and inclusion officer. John Anderson is president of the National Academy of Engineering.

Diversity and Inclusion: Essential Drivers of Leadership

> "It ain't what you don't know that gets you in trouble. It's what you know for sure that just ain't so."
> – *Mark Twain*

What has been fundamental to many leadership theories over time is the tenet that good leadership is "doing the right thing." There are, however, two challenges with this tenet: determining what the "right thing" is, and executing action to do it. The second is often easier than the first.

In all but trivial situations, deciding on the right thing to do may involve compromise among ideas and ideals, or, in engineering terms, trade-offs based on constraints. Because ideas and ideals are informed not only by an institution's mission and by social and cultural factors but also by personal perspectives, diversity and inclusion are absolutely critical to the decision process—to reduce the likelihood of troubling outcomes from decisions based on "what you know for sure that just ain't so." A diverse and inclusive leadership team is essential.

The accompanying photograph shows 15 of the original 25 members elected to the National Academy of Engineering when it was founded in 1964. All these men had great achievements and were giants in their fields. But, as the photo shows, it was a very homogeneous group.

Founding members attending the first annual meeting of the National Academy of Engineering, April 27–29, 1965. From left to right, standing: Ernst Weber, Michael L. Haider, Charles A. Thomas, William L. Everitt, Julius A. Stratton, Frederick E. Terman, Thomas K. Sherwood, Clark B. Millikan, James N. Landis, Hendrick W. Bode, and Nathan M. Newmark. Seated: Thomas C. Kavanagh, Augustus B. Kinzel, Eric A. Walker, and first NAE secretary Harold K. Work.

That homogeneity characterized engineering education and practice for centuries, with consequences largely unrecognized by those in the predominant group. But as Bill Wulf, a former president of the NAE, observed more than 20 years ago, "as in any creative profession, what comes out is a function of the life experiences of the people who do it…. [Without] diversity, we limit the set of life experiences that are applied, and as a result, we pay an opportunity cost…."[1]

In addition to opportunity costs there can be unintended consequences of projects and products engineered without representative input. For example, major highways that separate communities, social media systems that create divisiveness rather than harmony, and responses to a pandemic that cause many to lose their livelihood all could have been avoided had a variety of life experiences informed the decision makers.

There is evidence that diversity helps particularly in solving complex problems. The work of Scott E. Page (University of Michigan) shows that having diverse teams can lead to better innovation, creativity, complex problem solving, and forecasts based on diverse life experiences and insights—producing better organizational outcomes, which is exactly what leaders strive for.[2] As he puts it, "What you want to do is think, 'Who has tools or understanding that we don't have?'… If you hire people from the same ethnic group, who went to the same schools, worked at the same places—you're just kind of shooting for a B-plus…. Nothing great's going to happen."[3] Similarly, diversity in the boardroom, with input from people of different backgrounds, competencies, viewpoints, and perspectives, supports more effective and innovative decision making.

Diversity alone is not sufficient in helping leaders do the right thing. A purposefully inclusive environment is also a must in order to leverage that diversity and reap the benefits. The leader must listen to the varied input and challenge her own beliefs. An inclusive environment should allow individuals to bring their authentic selves and life experiences to work, and should provide the psychological safety to be creative and take risks. When employees feel included and a sense of belonging, they are more engaged and productive, and trust between employees and leadership is enhanced.

Individuals naturally act and make decisions according to their own experiences and knowledge. To avoid "getting into trouble," we need to admit that we don't know the experiences of others and deliberately seek their input to make a well-informed decision.

As leaders in technical fields, we are at the helm of tackling our nation's biggest and most vexing problems related to STEM. How effectively we do so is increasingly a function of the intentional, inclusive engagement of diverse teams and governing boards, as well as an inclusive culture, to strengthen our decision-making capabilities and improve our organizational outcomes. At the NAE, we are committed to this philosophy through our strategic plan and actions, membership initiatives and leadership, a presidential advisory committee on racial justice and equity, and the National Academies' Office of Diversity, Equity, and Inclusion.

[1] Wulf WA. 1998. Diversity in engineering. The Bridge 28(4):8–13.

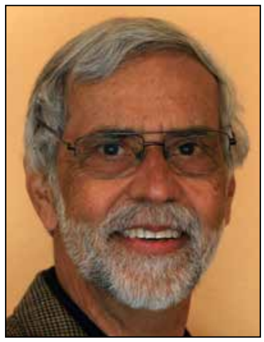
[2] Page SE. 2017. The Diversity Bonus: How Great Teams Pay Off in the Knowledge Economy. Princeton University Press.

[3] Interview, IEEE Spectrum, Sep 2017, pp. 22–23.

Guest Editors' Note

Norman R. Scott and R. Paul Singh

Norman Scott



Paul Singh

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Science and Engineering to Transform the Food and Agriculture System for the Future

There is no area of human activity more basic to society than a sustainable agricultural, food, and natural resource system. With projections that global population will grow to as much as 10 billion by 2050 (Pew Research Center 2022), there is increasing concern as to how this system should be transformed to feed this population sustainably.

Evolving Challenges and Progress

Serious questions need to be addressed; for example: What will constitute a healthy diet? Will natural resources and ecosystems be compromised—or even destroyed—in efforts to provide such a diet? Will the food system reduce or increase hunger and poverty? And will the system enhance or decrease equity and access to food for a healthy and productive global population? These and other critical questions challenge all who participate in the food and agriculture system (FAS), and more broadly everyone is involved at some level, from daily consumption to innovative scientific research.

As the focus on food and agriculture has heightened, numerous reports and diagrams have called for a major transformation of the FAS. Yet, as Per Pinstrup-Andersen writes in this issue, "The definitions and descriptions of food systems vary from a narrow focus on food and agricultural supply chains to inclusion of virtually all aspects of a national economy. The former is likely to miss important opportunities for improvements, while the latter basically calls for an overall economic transformation in the name of a food system transformation." Nevertheless, we believe that figure 1 provides an informative illustration of the FAS, the complexity of this system of systems, and its drivers, activities, actors, and outcomes (CIAT 2017).

The existing FAS evolved from the domestication of plants and animals that has been traced back to 11,000–9,000 BCE (Zeder 2011). While providing safe and affordable food remains a driving force, numerous factors challenge the present and future FAS. These include impacts of the FAS on the environment, distrust in science and technology, increasing urbanization, climate change, changing food preferences, globalization, integrated value chains, energy, water, international trade and regulations, the economic viability of rural communities—and, more recently, recognition of the disruption that major events, such as a pandemic, can create for the FAS.

From its origin, a fundamental element of the FAS has been land-/soil-based agricultural production. This remains largely true as soil remains a consistent factor amid advances attributed mainly to science and technology, as reported in this issue—in nanoscience and engineering, genomics (including CRISPR), sustainable and regenerative agriculture, digital agricul-

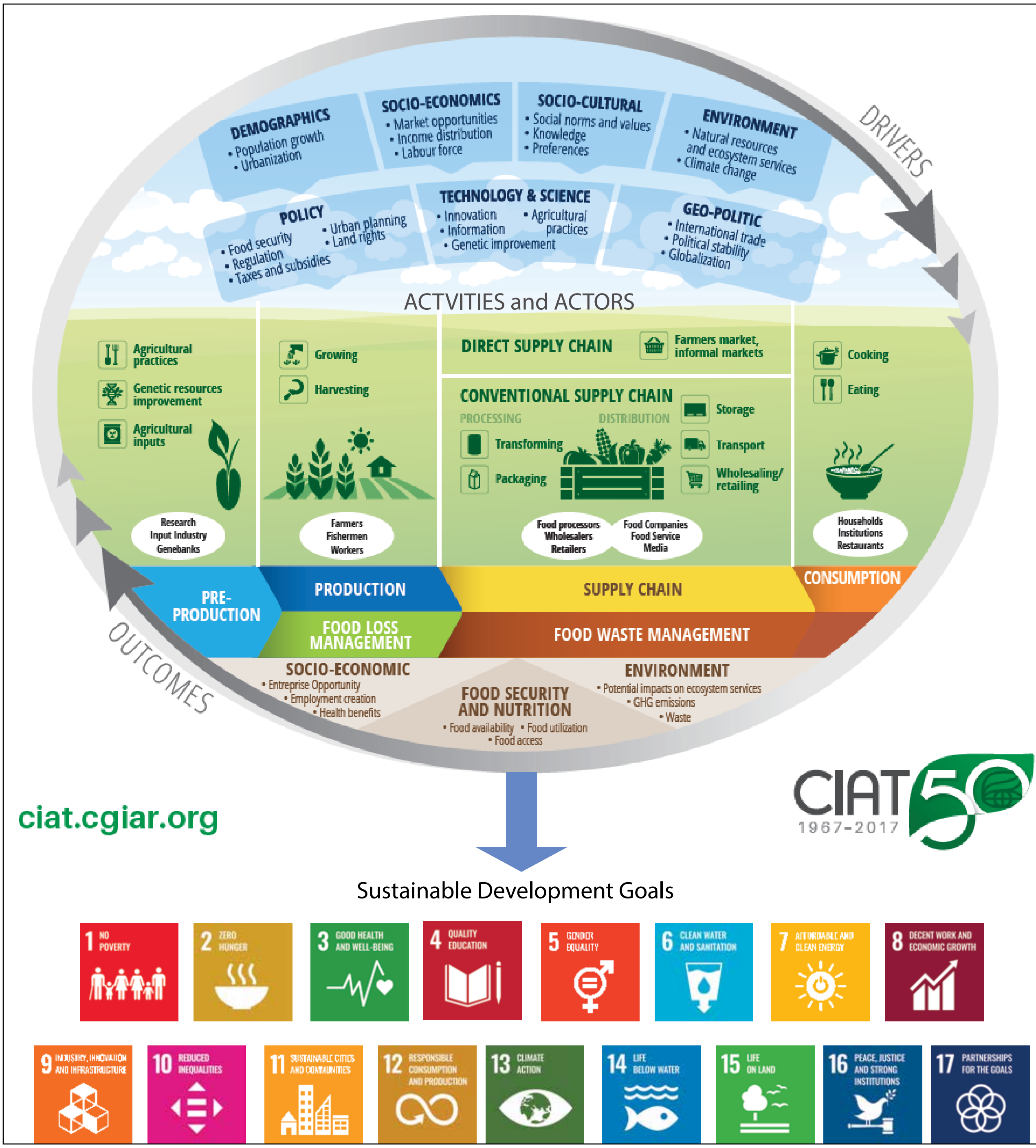

FIGURE 1 Interpretation of the international food and agriculture system and its drivers, activities, actors, and outcomes. All elements of growing, harvesting, storing, processing, distributing, consuming, and managing the food and agriculture system are encompassed in the UN's Sustainable Development Goals. GHG = greenhouse gas. Source: Adapted from CIAT (https//:ciat.cgiar.org/about/strategy/sustainable-food-systems).

ture, digital biology, advances in food processing, the urban-regional food-energy-water nexus, and the role of policies. However, emerging subsystems of precision indoor (controlled environment) agriculture, aquaculture, aquaponics, and alternative protein food systems are largely established in soilless facilities—and they are experiencing significant growth.

In This Issue

The authors in this issue examine progress, possibilities, and challenges in this highly complex, adaptive system that functions across a spectrum of economics, biophysical, and sociopolitical contexts (IOM and NRC 2015). We acknowledge, though, that, notwithstanding the scope of the nine articles, this issue does not adequately address a number of FAS-related issues, such as diet and human health, energy efficiency, food loss and waste, bioenergy, social impacts, and depth of climate change effects. These and other FAS-related topics are being actively studied to ensure sustainable agriculture for people and the planet; readers are encouraged to explore resources such as IPCC (2022).

In the first article, Hongda Chen, Jason White, Antje Baeumner, and Dan Luo present a vision of scientific discovery and engineering innovation based on the understanding and control of matter at the nanometer scale to solve societal challenges facing the FAS. They highlight promising areas to ensure and improve food safety, support precision agriculture, and create value-added uses of nanobiomaterials. From the unique use of DNA as both a genetic and generic material (easily obtainable from agricultural biomass, which is renewable and degradable), to applications of nanomaterials to increase crop yields with environmental benefits, they show that nanobiomaterials have many uses.

Rodolphe Barrangou[1] (NAS) describes "a genome editing revolution" brought on by the remarkable precision of CRISPR-Cas9 technologies. The availability of affordable resources to use these technologies has resulted in a spectacular increase in the number of researchers engaged in this field worldwide. Agricultural applications of this emerging technology abound, from breeding desirable traits in crops with enhanced environmental resilience to improving starter cultures for food fermentation, such as cheese and yogurt. He emphasizes the need to "promote trust through risk mitigation and transparency" to successfully adopt genome editing in the quest for sustainable agriculture.

A.G. Kawamura, Rattan Lal, Marty Matlock, and Charles Rice note that the sustainable agriculture concept has been effective in engaging stakeholders across the agriculture supply chain in developing key performance indicators to assess greenhouse gas emissions, water quality and quantity, soil erosion, and biodiversity across the plant-animal-human nexus. Sustainable agriculture is complemented by regenerative agriculture, which focuses on initiatives to promote soil health. Together, the two represent a holistic framework to engage communities to protect and preserve soils, rebuild the capacity of degraded lands, protect water resources, and reduce food loss and waste.

Innovations in controlled environment aquaculture systems help reduce water and energy use.

An article by the CROPPS Research Community emphasizes the need for a deeper understanding of the biology of plants and their responses to a changing climate, among other factors. The vision and work of the Center for Research on Programmable Plant Systems (CROPPS) focus on understanding the deep biology of plants to create an Internet of Living Things. The vision depends on transdisciplinary collaboration—biotechnology and synthetic biology, robotics and automation, sensing and automation, and computing—to enable a digital dialogue with plant systems.

Expanding on the role of digital technologies, John Schueller and **John Reid** explain that digitalization will underpin a sustainable increase in the global food supply for the increasing population. They note that the automatic guidance of equipment on farms, made possible by the availability of GPS, helped realize dramatic improvements in machine performance and subsequent advances in precision and accuracy. The authors foresee further enhancements with the increasing integration of cloud computing, electrification, connectivity technologies, and use of robotics and drones, while acknowledging that implementation of autonomous systems on the farm presents challenges that will require engineering solutions.

K.C. Ting, Michael Timmons, and Ricardo San Martin describe food and agricultural production inno-

[1] Bold denotes NAE members.

vations involving precision indoor farming and alternative protein food systems. Traditional greenhouses are evolving into advanced controlled environmental plant systems, including vertical farms, with computer-controlled environments, robotic handling systems, and soilless growing media. Innovations in controlled environment aquaculture systems help reduce water and energy use. In addition, plant-based alternative protein products are readily available in the marketplace, and cultured/cultivated meat products are ready for or nearing commercial availability. Scale-up and cost of production facilities, cost to consumers, and consumer acceptance remain challenges.

Josip Simunovic and **Kenneth Swartzel** discuss the critical role of food processing in a sustainable food supply system. Industrial processes that help preserve food are vital to reducing food losses and waste. The authors foresee flexible and mobile processing systems located closer to farms and methods that rely more on electrical technologies such as microwave processing. They also note the challenges of "getting high-quality food in sufficient quantities" to growing urban areas, especially megacities. They expect that integrated approaches to processing, distribution, preparation, and preservation will drive further advances in food process engineering.

Anu Ramaswami and Dana Boyer present eight principles for designing a sustainable circular economy at the urban-regional food-energy-water systems (FEWS) nexus using a supply chain–linked urban metabolism model. They define a sustainable circular economy "as one that advances resource circularity by achieving resource sustainability, reducing pollution, preserving/regenerating natural capital, and generating employment and broader benefits to human health and wellbeing, including social equity." The focus is a quantitative systems framework to analyze transboundary linkages across sectors from consumption to production at the farm level to assess circularity potential of resource circularity pathways.

Wrapping up the series with an overarching perspective, Per Pinstrup-Andersen writes that a policy framework is necessary to facilitate access to knowledge and technology for potential users, including but not limited to food producers and processors, and promote evidence-based decisions among stakeholders. Past emphasis on production (e.g., in the Green Revolution) met an important need to avoid mass starvation in Asia; it is now time to address widespread micronutrient deficiencies, obesity, and negative health outcomes. Government policies should also facilitate renewable energy sources, reduce food loss and waste, enhance antimicrobial resistance, and ensure animal welfare. The author calls for "A facilitating policy framework… to fully capture the benefits from science and engineering for improved food and agriculture systems."

Acknowledgments

The theme of this issue resulted from a perchance conversation with the managing editor of *The Bridge*, Cameron Fletcher, at the 2018 NAE annual meeting in Washington. That discussion led to an agreement that an issue should focus on the impressive advances in science and technology in the food and agriculture system. *The Bridge* last addressed agriculture and information technology in 2011[2]; the articles in this issue present achievements and advances since then, including areas of science and technology that were "not on the radar" a decade ago.

We thank all the authors and staff who contributed to this issue, as well as the experts who evaluated the manuscripts to help ensure quality and accuracy: Suresh Babu, Bruno Basso, Ranveer Chandra, Liang Dong, Alan Franzluebbers, Ben Goldstein, **James Jones**, Melanie Kah, Martin Kremmer, Carlos Messina, Stewart Moorehead, Raul Piedrahita, Prabhu Pingali (NAS), Pamela C. Ronald (NAS), Cristina M. Sabliov, Eric Schulze, **Juming Tang**, Alison Van Eenennaam, and Mark Williams.

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[2] https://www.nae.edu/52548/Fall-Issue-of-The-Bridge-on-Agriculture-and-Information-Technology

Nanotechnology will enable smarter strategies of food production while protecting the environment.

Nanoscale Science and Engineering for Agriculture and Food Systems

Hongda Chen, Jason C. White, Antje J. Baeumner, and Dan Luo

Hongda Chen

Jason White

Antje Baeumner

Dan Luo

National pursuit of nanoscale science and engineering (NSE) for agriculture and food systems started in 2002 with a strategic roadmap workshop organized by the US Department of Agriculture. The report of that workshop articulated a vision of scientific discovery and engineering innovation based on the understanding and control of matter at nanometer scale to solve pressing societal challenges facing agriculture and food systems (Scott

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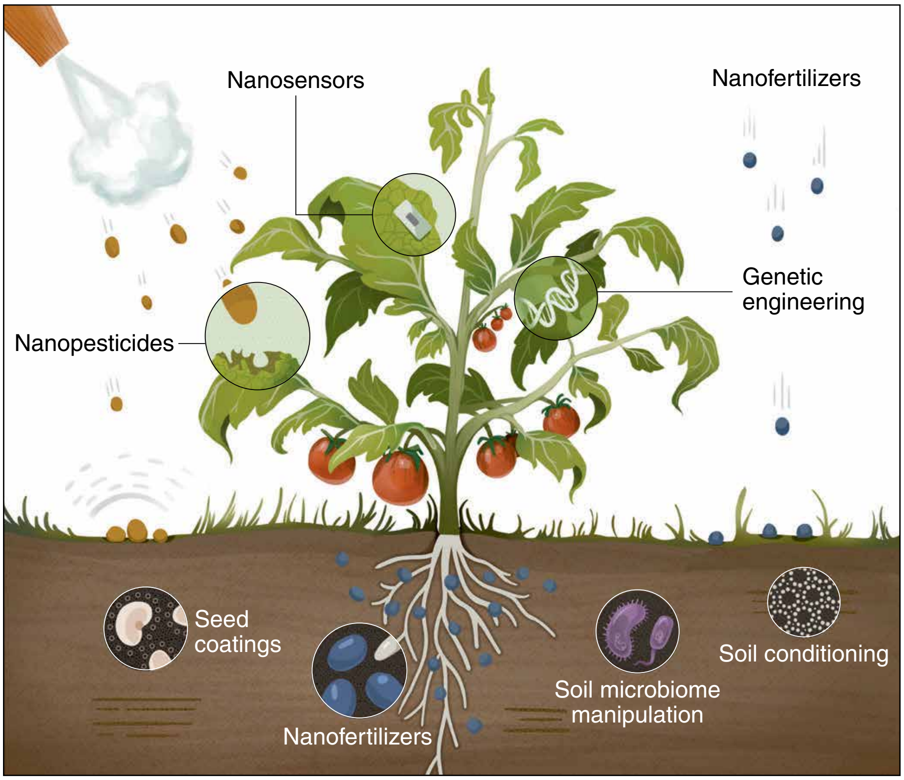

FIGURE 1 Potential applications of nanotechnology in crop agriculture (Hofmann et al. 2020; reprinted with permission from Springer Nature Group).

and Chen 2003). To be effective, NSE in this area must involve at least the following:

- recognition of the tremendous potential for new scientific inquiries;
- multidisciplinary collaboration among the biological, physical, social, and regulatory sciences, engineering, and industry;
- significant advances in scientific exploration and engineering innovation, evidenced by numbers of publications, patents, and projects; and
- substantial investments by both the public (e.g., the National Nanotechnology Initiative) and private sectors.

We highlight the most promising areas to ensure food security, support precision agriculture, improve food safety, and create value-added uses of nanobiomaterials. We then explain NSE's importance for basic science and novel applications to support sustainability and address the most significant challenges facing agriculture and food systems.

Sustainable Agricultural Production to Ensure Food Security

Achieving and maintaining global food security is possible only with sustainable agricultural practices.

Crop Production and Protection

The Green Revolution of the 1950s and 1960s dramatically increased agricultural output through the development of higher-yield grains and the use of agrochemicals and irrigation, but it was not sustainable and the rate of annual crop yield increases has been declining since 1980 (Kah et al. 2019). This stands in stark contrast to the projected 70 percent increase in food production needed by 2050 to feed the world population of over 9 billion, further complicated by the changing climate.

Agriculture is resource intensive and highly inefficient, consuming 6–30 percent of global energy production and 70–80 percent of fresh water (Wang et al. 2022). The efficiency of agrochemical delivery is also low: annual fertilizer losses from leaching, volatilization, or conversion to unavailable forms exceed 60–70 percent (Kah et al. 2019; Wang et al. 2022). For pesticides, less than 25 percent reaches the target, and 20–40 percent crop loss from pests and disease is typical (Kah et al. 2019).[1]

The goal is to dramatically increase yield per unit of input (inputs are soil, water, energy, agrochemicals, labor, and cost). Potential solutions are many (figure 1) but in all cases require a systems-level approach involving convergence of expertise in materials science, formulation chemistry, plant biology, agronomy, engineering, toxicology, agricultural economics, life cycle analysis, social science, and regulatory policy.

A survey of 500 publications and 36,000+ patents on nanoscale pesticides showed that nanoscale strategies

[1] We do not discuss here the environmental and public health impacts associated with agrochemical exposure of nontarget organisms, pharmaceutical use in animal agriculture, or nutrient use in aquaculture.

improve agrochemical delivery efficacy by 32 percent and reduce toxicity for nontarget receptors by 43 percent (Wang et al. 2022). Additional benefits include improvements in stress tolerance, yield, crop quality, and foliar attachment as well as decreased leaching potential.

Numerous nanoscale strategies have been explored over the past 2 decades (figure 2). Approaches include agrochemicals in nanoscale form (e.g., nutrient metal oxides) and nanoscale carriers to deliver cargo of interest where tunable chemistry at synthesis can "hardwire" nanoscale-specific biological benefits in the field. Certain nanoscale elements or element oxides promote tolerance to pathogen stress (CuO, S, SiO_2, carbon nanomaterials [CNM]; Kang et al. 2021; Ma et al. 2020) and to abiotic stress such as salinity or drought (ZnO, CeO_2, CNM) (An et al. 2020; Dimkpa et al. 2020; Pandey et al. 2018), or enhance electron capture/transfer to photosynthesis (Fe and Mn oxides; Wang et al. 2020a). Importantly, these benefits are observed *only* with nanoscale materials.

Other techniques include the use of nanoscale biopolymers as responsive seed coatings (Xu et al. 2020), nanoscale materials to facilitate RNA interference for disease management (Shidore et al. 2021), and nano-enabled biofortification strategies to increase crops' nutritional value (De La Torre-Roche et al. 2020).

Livestock and Aquacultural Production

Nanotechnology-enabled vaccines are sought to control infection in livestock to sustain a safe food supply and improve rural economic wellbeing (Chandrasekar et al. 2020). Biodegradable polymeric nanoparticles are another promising vehicle to deliver antibiotics and improve efficacy against enteropathogenesis in livestock (Paudel et al. 2019).

NSE approaches also help minimize food waste and loss due to chemical and microbial deterioration, which are estimated to affect 30–60 percent of food production. For example, cellulose nanocrystals, corn protein (zein), and starch-based electrospun nanofibers can improve food safety and quality by releasing antimicrobial agents in response to bacterial enzymes or elevated humidity (Aytac et al. 2021).

Nanotechnology-Enabled Sensors to Enhance Precision Agriculture and Food Safety

Sensors used in precision agriculture and food safety are mostly based on physical or chemical principles for

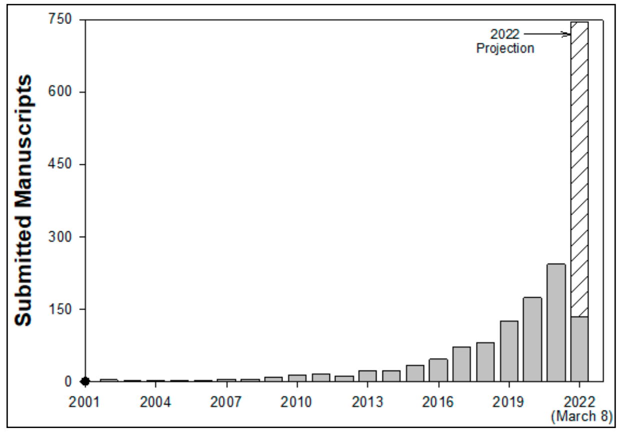

FIGURE 2 A Science Direct literature search shows a roughly 2000 percent increase in the number of submitted manuscripts in this area since 2001. The search used the following terms in the title, abstract, or keywords: AB = [((agri*) OR (agro*) OR ("crop protection") OR ("plant protection") OR ("crop yield") OR ("plant yield") OR (pesticide) OR (herbicide) OR (fertilizer) OR (micronutrient) OR (fungicide)) AND (nano*)].

the detection of humidity, temperature, chloride ions, gases, and biological parameters such as estrous cycles or biogenic amines. New types of sensors are needed to address more complex questions involving challenging analytes, such as the metabolic state of a single plant, the local concentration of pesticides in a field, or the safety of foods beyond expiration dates. Nanotechnology can provide the technological boost for this new generation of sensors.

In terms of existing technology, standard electrochemical biosensors are mounted on fish to monitor their cholesterol levels (Takase et al. 2014). But they perform for only 48 hours, require recalibration, and both vary with and degrade due to environmental conditions, making them ineligible for precision pisciculture. Nanostructured sensors that integrate additional functionality and that can easily be embedded in an animal, as is done with certain types of human health monitoring (Sharma et al. 2016), will solve this challenge and enable large-scale individual livestock monitoring.

Similarly, the integration of sensors in plants will provide direct information on plant or crop health rather than monitoring soil composition to infer effects on plants. Research that started with measuring plant transpiration (Shihao et al. 2021) can now detect hormones, pesticides, and other biomolecules in cells, provide nondestructive sensing of plant metabolism and effects of chemicals, and inform precise agricultural practices (Ang et al. 2021; Yin et al. 2021).

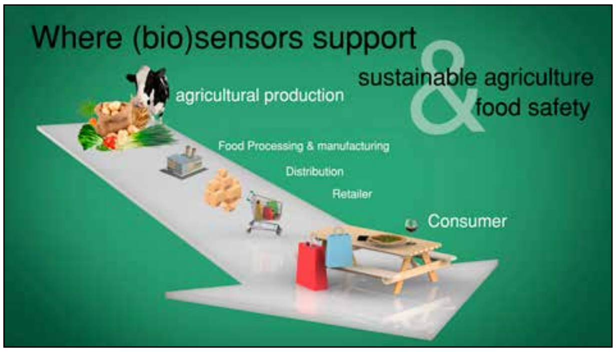

FIGURE 3 Food safety must be monitored ideally along the entire food value chain from farm to fork to identify possible degradation, contamination, and adulteration and enable the reduction of food waste and loss.

To ensure food safety and prevent food waste and loss, monitoring throughout the food value chain is necessary—from agricultural production to food processing and manufacturing, distribution, retail, and the consumer (figure 3). Nanosensors for food packaging are a first step, with physical and gas sensing capabilities (Abad et al. 2007), and nanomaterials may also be applicable in packaging systems where high sensitivity is needed. Research shows that nanofibers can lower detection limits tenfold relative to bulk material for biogenic amines that indicate the safety of meat and fish products (Yurova et al. 2018).

Nanosensors have the capability to enable sustainable agriculture by decreasing chemical and energy inputs while increasing output and product lifetimes. Connecting sensor outputs with data infrastructure and data analytical sciences can improve the decision making of agricultural and food enterprises.

Nanobiomaterials for Value-Added Applications

Most food packaging materials are from petrochemical manufacturers, and the nondegradable and nonrenewable nature of most synthetic polymers is of significant environmental concern, especially as more than 8 million metric tons of plastics are discarded annually into the oceans (Schmidt et al. 2017). This clearly is not sustainable.

Novel Material Production from Biomass

NSE research has provided many strategies to combat this challenge and to promote convergence with agriculture. A prime example is research involving DNA, which has been used as both a genetic and a generic material.

DNA is nanoscale, renewable, degradable, and easily obtainable from biomass, including from agricultural production. The total amount of global biomass DNA is approximately 50 billion metric tons (Landenmark et al. 2015).

DNA has been converted into bulk-scale membranes, fabrics, and plastics (Wang et al. 2020b; figure 4), hydrogels (Um et al. 2006; figure 5), and cell-free protein-producing gels for large-scale protein production (Park et al. 2009; figure 5). DNA can function as nanoscale barcodes (Li et al. 2005), as lifelike soft robots (Hamada et al. 2019; figure 5), or as an organizer for gold nanoparticles to obtain ordered superlattices with different plasmonic properties (e.g., different transmittal and reflectional colors) (Derrien et al. 2020; figure 5).

Nanobiomaterials

Other nanobiomaterials include nanodiatoms from ocean and soil, and nanoparticles assembled from biology such as exosomes, nanofibers, and nanoscale celluloses. Some nanoscale cellulose products are abundantly available in agricultural crops and forest.

Commercially manufactured cellulose nanocrystals and cellulose nanofibrils have been tested for applications such as food packaging, coatings, delivery of active

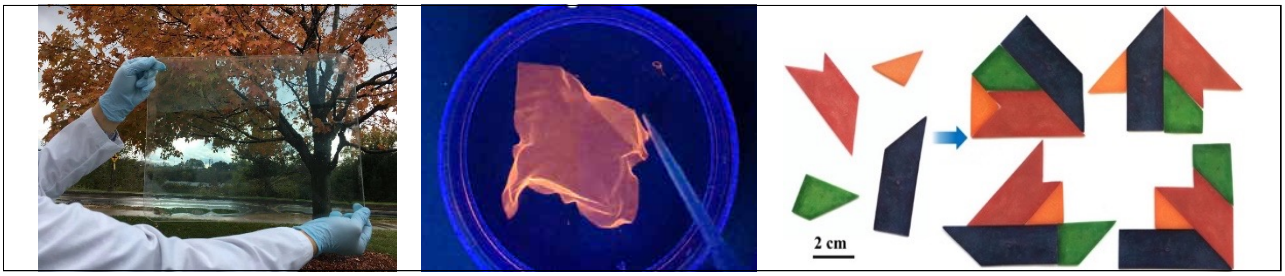

FIGURE 4 A large-scale gel (left), a thin membrane (middle), and plastic toys (right) fabricated entirely from biomass DNA (Wang et al. 2020b; reprinted with permission from the American Chemical Society).

payloads, industrial catalysts, and sensors (Li et al. 2021). For example, a promising technology using cellulose nanomaterial–based dispersion has been applied on delicate fruit buds of sweet cherry and apple trees for protection against frost damage (Alhamid et al. 2018). Bulk-scale, ultrastrong materials were fabricated using aligned nanocellulose fibers (Han et al. 2019). Nanocellulose membranes were also engineered into a device converting heat to electricity, demonstrating that nanocellulose is a promising sustainable material for harvesting energy (Li et al. 2019).

Value-added realization of these products will increase economic revenue for farmers, strengthen a circular economy, and enable sustainable agriculture and food systems.

NSE in Fundamental Agricultural Biology Research for Sustainability

Improved Understanding from Molecular to Systems Levels

Integration of nanomaterials in devices and systems has propelled the development of new tools for understanding and controlling agricultural biology at the molecular level.

- In situ gene editing improves plant production and product quality.
- Desirable transient expression is obtained using carbon nanotube–mediated DNA delivery without transgenic DNA integration in the host genome.
- Higher yields are possible as the nanocarrier protects cargo in transit from degradation, as demonstrated with arugula, wheat, and cotton (the latter two are particularly challenging to genetically transform; Zhang et al. 2021a).

Furthermore, gold nanoparticles have revealed nanoparticle transport mechanisms in plants and enabled the efficient and safe delivery of molecules to plant cells, an example of "green nanoscience" (Zhang et al. 2021b).[2]

Decoding and monitoring plant stress signaling to better understand plant diseases will enable timely deployment of effective and precise interventions. Nanobionics, involving specifically functionalized near-infrared fluorescent single-walled carbon nanotubes, is uniquely positioned to achieve this in a nondestructive way. These nanoprobes allow real-time in vivo spatiotemporal monitoring of endogenous H_2O_2 produced as a stress response (Lew et al. 2019).

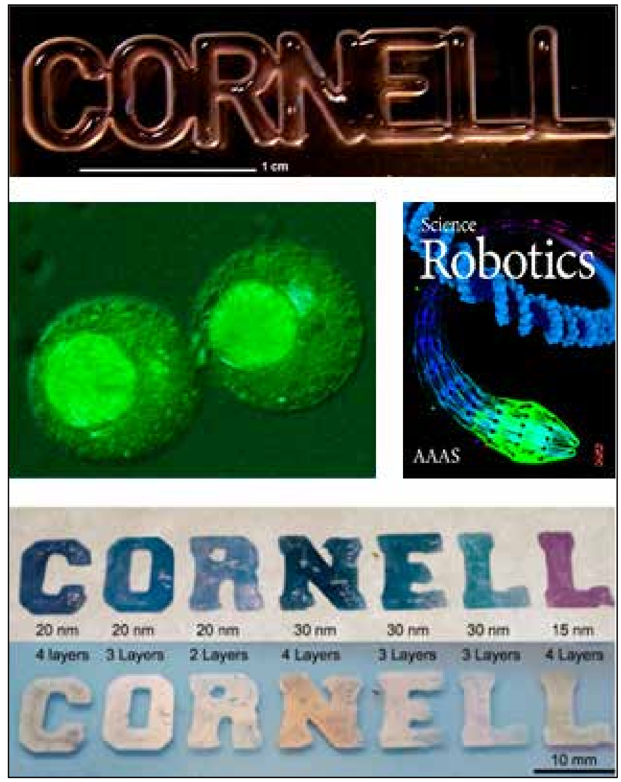

FIGURE 5 Different applications of DNA as both a genetic and generic material. **Top**: Bulk-scale DNA hydrogels (Um et al. 2006; reprinted with permission from Nature Publishing Group). **Middle left**: DNA-gel-based synthetic cell producing green fluorescent proteins in a cell-free fashion. **Middle right**: Life-like soft robot made entirely from DNA (Hamada et al. 2019; reprinted with permission from the American Association for the Advancement of Science). **Bottom**: Different plasmonic properties from gold nanoparticle assemblies organized by DNA materials (Derrien et al. 2020; reprinted with permission from Elsevier Ltd.).

Nanotechnology-based Agricultural Products

The generation and control of nanoscale materials afford engineers tremendous opportunities to use abundant agricultural biomaterials for novel applications to meet societal needs, as illustrated in the following:

- Biomanufacturing for cultured meat and seafood production, like tissue engineering in medicine, shows that nanoscale scaffolding supports cell alignment and muscle tissue formation that is scalable and safe.

[2] Similar advances have been made in health and food sciences, where nanoparticle size and structure affect delivery and facilitate study of nutrient use across the digestive system (Yao et al. 2014).

This supports a circular bioeconomy by using naturally abundant resources such as sugars from grains and cellulosic byproducts (Ostrovidov et al. 2014).

- Nanoparticles in combination with specific enzymes are a key component in cell-free synthetic biology that converts bulk feedstock molecules (e.g., sugar) into complex and highly nutritious food ingredients (vitamins, nutraceuticals, peptides, and proteins) (Díaz et al. 2021; Ellis et al. 2021). This conversion technology can be incorporated in distributed manufacturing plants built near feedstock sources in rural communities.
- Proteins responsible for photosynthesis may become the key component of sustainable solar cells rather than the current use of rare earth elements (Wolfe et al. 2021).

Conclusion

Looking at the short history of nanotechnology for agriculture and food over the past 20 years, numerous innovative concepts and prototypes of promising technologies have progressed toward societal benefit. Novel ideas and possibilities are constantly emerging as new properties, phenomena, and processes of nanoscale materials are discovered and created. Nanotechnology makes it possible to make agricultural systems more efficient, to directly probe biological systems, and to develop new, sustainable materials for diverse applications.

NSE will enable agriculture and food systems to continue to support a planet that is more sustainable, safer, and healthier, even with high population and climate crisis conditions. Advances in NSE, along with other disciplines, will provide new fundamental knowledge about agricultural systems and enable smarter strategies of food production while protecting the environment.

Scientists must continue to study environmental, health, and safety effects of these new systems to ensure responsible deployment. Convergence of multidisciplinary approaches has been critical to the successful exploration of NSE, and further efforts must include a broad range of disciplines, such as the social sciences, risk communication, and policy.

Disclaimer

The views expressed in this publication are those of the authors and not necessarily those of the US government.

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Genome engineering is enabling the design of enhanced organisms such as crops, livestock, and trees to promote sustainability.

Engineering Genomes for Sustainable Agriculture: Opportunities and Challenges

Rodolphe Barrangou

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The realm of biology and genetics is in the midst of a genome editing revolution, fueled by CRISPR-based technologies for manipulating and engineering the DNA blueprint of virtually all organisms in the tree of life. These molecular machines are derived from the adaptive immune systems in bacteria, which consists of *clustered regularly interspaced short palindromic repeats* (CRISPR) and their associated effectors (Cas) (Barrangou et al. 2007). Building on the clinical success of CRISPR-based gene therapies, breeders are rapidly deploying genome editing in research and development activities, seeding commercial pipelines.

Given the tremendous potential of genome engineering for agricultural applications, it is essential to determine the role and implementation of genome engineering as part of the solution for a sustainable agricultural system.

CRISPR Basics: Engineering Genomes with Molecular Machines

The genomes of every organism are composed of a series of four letters, A-T-C-G, arranged in the mesmerizing double helix whose complementary strands encode signals for genes (DNA sequences). These sequences are expressed into messenger molecules (RNA transcripts) that are in turn translated into effectors (proteins with physical and chemical attributes). Over the past 2 decades, the world of genetics has been revolutionized by the ability

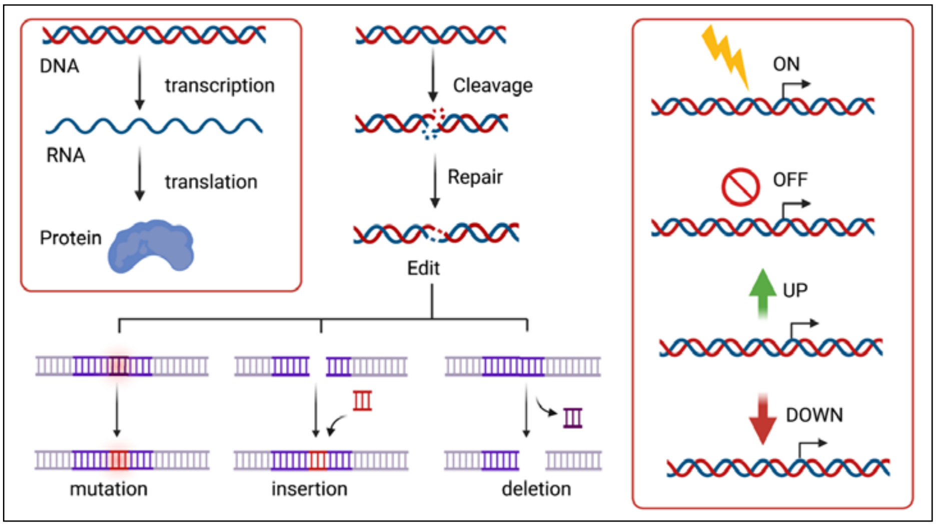

FIGURE 1 Genome engineering basics. **Top left:** DNA is transcribed into RNA, which is then translated into proteins. **Middle and bottom left:** Using CRISPR, DNA molecules can be cleaved at programmable locations to trigger repair pathways that can be coopted to generate selected mutations, insertions, or deletions in the genome for desired outcomes. **Right:** Versions of CRISPR effectors tethered to transcriptional effectors can control transcription by turning it on or off or modulating the level of gene expression up or down, enabling fine-tuning of the amount of a protein and the activity of the encoded protein in the host.

to both read genomes, transcriptomes, and proteomes at very high scale and manipulate them. Genome editing now enables molecular engineers to rewrite selected portions of the genome of virtually any species.

CRISPR-Cas systems enable immunity by picking up DNA sequences from invaders (e.g., viruses) and using them as sequences (DNA "mugshots") that drive the specific targeting and cleavage of matching elements with molecular scalpels (the Cas effectors) (Makarova et al. 2019). A decade ago, these bacterial tools were repurposed as programmable molecular machines in a biochemical advance worthy of the 2020 Nobel Prize in Chemistry for their inventors (Jinek et al. 2012). This tool was subsequently deployed to cut the genomes of human cells and enable editing precisely at the site of cleavage (figure 1) (Cong et al. 2013).

By placing the CRISPR cursor at a particular location in the genome sequence, geneticists can rewrite the DNA code precisely at that position to engineer genomes through the insertion and/or deletion of single letters or whole chapters in a DNA blueprint. Mechanistically, once the chromosome is cleaved at the intended location, the DNA is patched through various naturally occurring repair pathways.

Versions of these tools fused with other effectors and enzymatic machinery allow genome engineers to also modulate the strength of the signal (turn on/off, up/down the level of transcription; figure 1). If the genome were a series of letters in text, the content of a book could be edited and its oratory delivery guided. If the genome were a series of notes in a score, it would be possible to change the chords and tune the strength with which each note is played. While we shall refrain from editing Sir William Shakespeare's sonnets or tinkering with Wolfgang Amadeus Mozart's scores, typos in books and operas can now be corrected.

There are many practical benefits, notably efficiency, precision, affordability, and convenience of deployment, although improvements are needed in the control and prediction of repair outcomes and in delivery modalities to increase penetrance of effectors in larger amounts of cellular material.

Amazingly, barely a decade into the CRISPR craze, this disruptive technology has already enabled the medical community to correct DNA typos in the genomes of patients with genetic diseases. Individuals with debilitating diseases caused by inherited faulty genetic signals have had their genomes recoded at the affected locus by CRISPR engineers, with supraclinical therapeutic benefits (Gillmore et al. 2021); for example, FDA-enabled clinical trials have recently reported success for sickle cell disease (Frangoul et al. 2021). This opens intriguing opportunities beyond translational biotechnology. . . .

Recoding Agriculture: From Sustainable Crops to a Healthier Forest

The ability to engineer genomes and tinker with DNA sequences with unprecedented ease, speed, and scale is inspiring breeders of all biological entities. Genome engineers have deployed CRISPR tools in species from viruses and bacteria to plants and trees (whose genome can be 10 times larger than the human genome), including species used in food and agriculture (Zhu et al. 2020). Importantly, besides the practical advantages of this

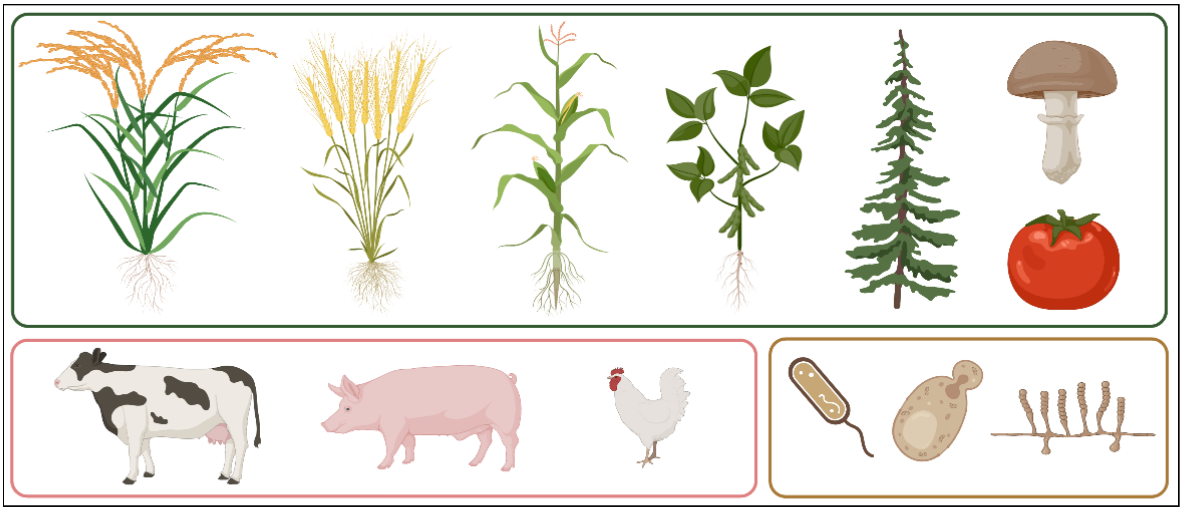

FIGURE 2 Diverse realms of genome editing in agriculture. Top: Plants and crops such as rice, wheat, corn, and soy; trees; and fruits and vegetables such as mushrooms and tomatoes. Bottom left: Livestock including cattle, swine, and poultry. Bottom right: Microbes including bacteria, yeast, and fungi.

molecular "Swiss Army knife," benevolent repositories provide open access to best-in-class technologies from a collaborative network of innovators to tens of thousands of academic researchers around the globe (Huang et al. 2019).

Starting small, bacteria used in food fermentations have had their genomes enhanced to optimize their functional attributes linked to the flavor and texture of fermented dairy products such as yogurt and cheese. The fact that CRISPR-Cas systems provide adaptive immunity against viruses in dairy bacteria led to the commercial launch, more than a decade ago, of bacterial starter cultures with enhanced phage immunity in industrial settings. Most fermented dairy products are now manufactured using CRISPR-enhanced starter cultures. Since then, a variety of bacteria, yeast, and fungi (figure 2) involved in the manufacturing of bioproducts has also been CRISPR enhanced to yield commercial products such as enzymes, detergents, and dietary supplements.

Moving along the farm-to-fork spectrum, most commercial crops—from corn, soy, wheat, and rice to fruits and vegetables—have had their genomes altered (figure 2). Genome engineering is used to increase yield (e.g., meristem size, grain weight) and improve quality (e.g., starch and gluten content), pest resistance (e.g., to bacteria, fungi, viruses), and environmental resilience (e.g., to drought, heat, frost). For instance, nonbrowning mushrooms with extended shelf life can be generated, and tomatoes with increased amounts of gamma aminobutyric acid (GABA) to enhance brain health have been commercialized. In addition, efforts are underway to enhance nutritional value.

Expanding Applications

Besides edible plant species, much ongoing work aims to optimize both the biochemical composition of biomass for biofuel genesis and the traits of species such as cotton, hemp, grasses, and flowers. In an era of plant-based meats, alternative protein sources, and lab-grown foods, it seems nothing is impossible—imagination might be the only limiting factor with regards to how CRISPR can be exploited for foods. As a gauge of industry enthusiasm and commercial adoption, it is worth noting that leading agricultural players like Bayer, Corteva, BASF, and Syngenta as well as startups like Inari Ag and Pairwise Plants are actively breeding commercial crops.

Livestock breeders have joined the fray, with genome engineering of main farm species such as swine (leaner bacon), poultry (CRISPR chicken), and cattle (for both meat and dairy). Swine have also been edited with a viral receptor knockout to prevent porcine reproductive and respiratory syndrome; the approach is being evaluated for regulatory approval (Burkard et al. 2017). Breeding applications include hornless cows (for more humane treatment), resistance to infectious disease (tuberculosis in cattle), and removal of viral sequences in the genome of elite commercial livestock,[1] notably swine. The CRISPR zoo also encompasses genetically diverse

[1] "Elite" here refers to the genetic background of the animals in which the editing was done.

species—fish (tiger-puffer and red sea bream), cats (efforts are underway to develop hypoallergenic variants), and even butterflies (wing pattern)—illustrating the ability to deploy this technology broadly.

A World Economic Forum report, *Technology Innovation in Accelerating Food Systems Transformation* (WEF 2018), projected that genome editing for seed improvement could boost farmer income (up to $100 billion value creation), increase food production (by 5 percent), and help reduce human micronutrient deficiency (for up to 5 percent of the affected population). With rapid population growth and challenges to the global food supply chain, the use of enabling technologies for more efficient, sustainable, and resilient agriculture is critical.

Historical mistakes in public relations and ethical concerns are reminders of the importance of science communication.

Given climate change concerns, it is noteworthy that genome engineering of trees—whether for enhanced wood properties, tree resilience, pest management, or environmental stewardship—can yield a healthier and more sustainable forest. For example, altering lignin content and fiber composition and linkage could substantially impact the efficiency of the pulping process, which generates paper, cardboard boxes, and hygienic tissue. Lower lignin renders wood more amenable to bioprocessing, in turn reducing the amount of energy, enzymes, and chemicals needed to generate pulp. Similar approaches hold promise for fiber-based bioethanol production and wood-derived bioproducts, with DNA-free modalities (Cas effectors loaded with guide RNA, forgoing the need to use DNA constructs) that rely on delivery of ribonucleoprotein complexes directly into seed embryos that develop into non-GMO-edited trees.

As genome editing matures, it is appropriate to strategically determine how these powerful tools can best be deployed and prioritized to optimize the benefits of this disruptive technology, especially for energy efficiency and resource use.

Learning from Mistakes and Shortcomings

The technical challenges, however difficult and problematic, may prove to be the easier part of genome engineering. Historical mistakes in public relations for GMO technology, genetic engineering regulatory hurdles, and ethical concerns about CRISPR use in humans are all reminders of the importance of science communication. The rise of CRISPR tools has been accompanied by some drama, notably with regards to intellectual property in a high-profile kerfuffle covering interference proceedings (Sherkow 2022). Likewise, the legal and ethical ramifications of the birth of genome-edited children in China have compelled the international scientific community to define and update guidance for the responsible and transparent deployment of genome editing technologies in human cells and individuals (NAM, NAS, and Royal Society 2020).

Regulation

The success of genome engineering technologies in medicine and biotechnology has triggered efforts in agriculture that encompass regulatory considerations. Of particular note is the Sustainable, Ecological, Consistent, Uniform, Responsible, Efficient (SECURE) rule implemented by the USDA's Animal and Plant Health Inspection Service; it covers plants generated through techniques that use recombinant, synthetic, and/or amplified nucleic acid to modify a genome.[2] Welcomed by the scientific community and the agriculture industry, the SECURE rule lays a foundation for other jurisdictions to adopt similar guidelines allowing some genetic edits to be exempt from the federal regulatory process for plants.

Political and regulatory support is not evenly distributed, and there is some recalcitrance in a number of countries, especially in Europe, as activist groups sow antiscience bias and skepticism. Given the business implications and geopolitical stakes, there is a case to be made that it is a question of when, rather than whether, genome engineering technologies will be broadly enabled. The debates are a reminder that organizations such as the National Academies of Sciences, Engineering, and Medicine were conceived to support evidence-informed policies, and it is encouraging that members of these academies have been asked for input regarding many of these aspects.

[2] 7 CFR Part 340 of the Plant Protection Act (85 Fed. Reg. 29790, May 18, 2020); available at https://www.govinfo.gov/content/pkg/FR-2020-05-18/html/2020-10638.htm.

Communication for Consumer Acceptance

On a practical basis, much depends on consumer acceptance of technology. Several pandemic-related aspects illustrate the challenges of antiscience bias and shortcomings in public science literacy. Thankfully, engineering disciplines benefit from historical credibility and associated feats and milestones (e.g., aviation and mechanical engineering, computers and electrical engineering).

In molecular biology, lessons learned from human genome editing highlight the need to promote trust through risk mitigation and transparency. Fortunately, there are great CRISPR stories and storytellers. The chronicles of Jennifer Doudna's Nobel journey are inspiring (see Isaacson 2021). Likewise, the societal stakes and implications have been pondered by masterful storyteller Adam Bolt in a documentary entitled *Human Nature*. Such compelling narratives, in combination with the promise of genome engineering technologies for agriculture and sustainability, following the path blazed by CRISPR medicines and pioneers, lay a foundation for bridging the gap between science and society.

The Future Is Now

Given the need to build a resilient and more sustainable food supply, and the aggressive timeline under which this needs to happen, the ability to exploit innovative technologies is critical. To ensure that by 2050 the food supply chain can support the world's rapidly expanding population, genome engineering requires prompt market deployment, regulatory approval, and societal acceptance so the production supply chain can be managed accordingly.

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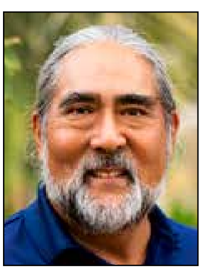
Protecting, restoring, and enhancing life on Earth begins and ends with the soil.

Sustainable and Regenerative Agriculture

A.G. Kawamura, Rattan Lal,
Marty D. Matlock, and Charles W. Rice



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Charles Rice

Agricultural sustainability and regeneration have become common approaches for driving improvements in US and global food and agriculture supply chains. Multistakeholder organizations have emerged over the past 2 decades to provide coherent and effective strategies for reducing the environmental impacts of agricultural production.[1]

[1] In the United States examples include Field to Market (https://fieldtomarket.org/), the Stewardship Index for Specialty Crops (https://www.stewardshipindex.org/), and the US Roundtable for Sustainable Beef (https://www.usrsb.org/),

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Introduction

Sustainable Agriculture

The most common definition of sustainable agriculture is some variant of the Brundtland Commission's call for sustainable development that "meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED 1987, §3:27).

To achieve sustainable agriculture, organizations have adopted a continuous improvement strategy based on identifying key performance indicators (KPIs), benchmarking them at a point in time, setting time-bound improvement goals, developing a strategy to accomplish those goals, and monitoring KPI status. This continuous improvement process has no endpoint but rather provides a dynamic approach to addressing environmental, social, and economic challenges to agriculture as they emerge.

Interest in sustainable agriculture engages stakeholders from across the food and agriculture supply chains to respond to environmental KPIs such as greenhouse gas emissions, water scarcity, soil erosion, water quality, biodiversity, and the plant-animal-human health nexus. These and other sustainability initiatives also implement KPIs for the social and economic domains, including worker safety, living wages, and community infrastructure.

Regenerative Agriculture

There isn't a standard definition for regenerative agriculture, but it represents a holistic framework to understand and respond to global challenges in food and agricultural production at the production unit (farm) scale. It has been described as "farming and ranching in harmony with nature."[2]

Regenerative agriculture expands on sustainable agriculture to include outcomes from "Practices that (i) contribute to generating/building soils and soil fertility and health; (ii) increase water percolation, water retention, and clean and safe water runoff; (iii) increase biodiversity and ecosystem health and resilience; and (iv) invert the carbon emissions of our current agriculture to one of remarkably significant carbon sequestration thereby cleansing the atmosphere of legacy levels of CO_2."[3]

Soil health is the key focus (Schreefel et al. 2020), which has led organizations to expand regenerative agriculture to include "building resilience of agro-ecosystems" (IPCC 2019).

[2] https://www.nrdc.org/stories/regenerative-agriculture-101

[3] https://regenerationinternational.org/why-regenerative-agriculture/

Putting Them Together for an Agricultural Renaissance

Sustainable and regenerative agriculture complement each other with similar goals. Sustainable agriculture is based on outcomes and generally avoids dictating practices, while regenerative agriculture has both outcome- and practice-based approaches (Newton et al. 2020).

Integrating these approaches is the way to accelerate an agricultural renaissance, by coordinating the intensification of production necessary to protect habitat for other life while feeding the world's projected 2050 population of 10 billion (Pew Research Center 2022). Integration of the two approaches also recognizes the critical need to engage communities to protect and preserve their soils, rebuild production capacity on degraded lands, reduce the gap between realized and potential yield of a crop (the yield gap), protect water resources, reduce food waste, and restore woodlands and forests (Solutions from the Land 2021).

> *Regenerative agriculture expands thinking about agricultural production to a metasystems understanding of the interconnected relationships between Earth and humanity.*

Regenerative agriculture in particular represents an expansion of systems thinking about agricultural production to a metasystems understanding of the interconnected relationships between Earth and humanity. Farmers, ranchers, and foresters must be recognized and engaged as the key stewards for any legitimacy of outcomes. A shared ethic among stakeholders is respect and value for soil conditions.

It All Begins and Ends with the Soil

"Soil health" is an anthropomorphic characterization of a complex ecosystem, defined as "an integrative property that reflects the capacity of soil to respond to agricultural intervention so that it continues to support both the agricultural production and the provision of other ecosystem services" (Kibblewhite et al. 2008, p. 685). A more ecologically accurate characterization of the complex and integrative elements of soil ecosystems that yield both human sustenance and ecosystem functions without degrading capacity would be "soil resilience."

Soil resilience is the ability of soil ecosystems to continue to provide key functions under stress and to recover those functions after disturbance. Stressors on soils from agricultural activities result in cumulative impacts on four major soil ecosystem functions (Kibblewhite et al. 2008; Lal 2020a):

- physical and chemical structure,
- nutrient cycling,
- carbon transformation, and
- regulation of diseases and pests.

These ecosystem functions are interdependent, nested somewhat in the order listed, and the product of soil environment and microbe interactions (soil biology). Practices such as conservation tillage, cover crops, and nutrient restoration implemented by producers directly drive the outcomes necessary for soil resilience.

Nutrient depletion in soils from human activities contributes to yield losses, erosion, food insecurity, and human malnutrition.

Physical and Chemical Structure of Soils

The physical and chemical structure of soils determines the movement and interactions of gases and liquids, which in turn determine the ability of soils to support life below and above ground (Billings et al. 2021).

The most important indicator of soil structure is aggregation (Bronick and Lal 2005), the process of soil particles forming into micro- (53–250 μm) and macroaggregates (251–2000 μm) (Tisdale and Oades 1982). Aggregation creates the structure of soils that results in the dynamic exchange of liquids and gases across the surfaces of mineral and organic matter in the soil ecosystem. When soils lose resilience or become degraded, they lose the capacity to cycle nutrients that support plant and microbial life. Loss of aggregation is often caused by mechanical disturbance, chemical disruption (particularly with sodium salts), weathering through freeze-thaw and wet-dry cycles, and compression.

The mechanisms that create soil aggregates are complex and depend on geologic, chemical, biological, and climatic factors as well as soil management. Aggregates generally form from organic molecules attached to clay particles (or sometimes particulate organic matter) and ions (especially polyvalent ions) (Bronick and Lal 2005; Wilson et al. 2009). Plant roots and fungal hyphae create physical entanglement with soil particles and also create pore spaces between aggregates (Wilson et al. 2009).

In addition to the formation of aggregates, soil fertility is dependent on other dynamics. Macro- and microaggregate formation and turnover drive biochemical reactions that govern labile and recalcitrant soil organic carbon (SOC) pools, which affect microbial and plant nitrogen dynamics (Lal 2008). Water infiltration is a function of bulk density and aggregation, and water-holding capacity is a function of clay type and organic matter. Taking into account all these factors, the formation or restoration of soil aggregates mediated by human activities is a key outcome of regenerative agriculture practices.

Nutrient Cycling

Nutrient cycling in soils—the source of human sustenance and thus the most critical feature of the soil ecosystem (Lal 2009)—is the process of movement of soil nutrients from the atmosphere and geosphere through the soil into the biosphere, where the nutrients cycle through ecosystems. Soil nutrients that support plant life—which in turn supports animal and human life—come from the atmosphere (carbon, hydrogen, oxygen, nitrogen) and geosphere (phosphorus, potassium, sulfur, calcium, iron, and the so-called micronutrients boron, manganese, chlorine, copper, molybdenum, selenium, and others).

Removal of plant biomass from the ecosystem through harvesting or grazing, or of soil through erosion, depletes the nutrient stocks (especially nitrogen, phosphorus, and potassium) in the system. When nutrients are not replenished on cultivated cropland or grazed lands, the ecosystem must be replenished through mineral or organic fertilization (Tan et al. 2005).

Nutrient-depleted soils result in plants that are more vulnerable to drought and disease and produce less biomass (forage and crops). Globally, nutrient deple-

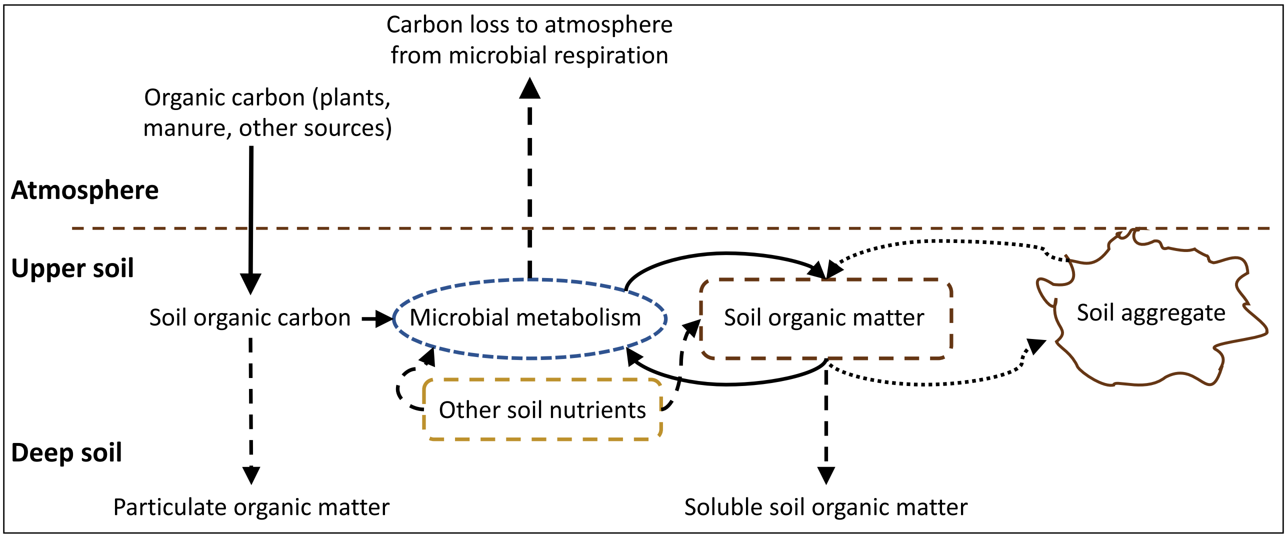

FIGURE 1 Carbon transformation pathways in soil, supporting nutrient cycling and carbon sequestration.

tion in soils from human activities is widespread (e.g., potassium depletion affects as much as 90 percent of harvested areas) and contributes to yield losses, erosion, food insecurity (Tan et al. 2005), and human malnutrition (Lal 2009).

Carbon Transformation

Transformation of atmospheric carbon dioxide to phytochemicals such as glucose and other carbohydrates through photosynthesis is the basis of most life on Earth. Carbon transformation in the soil makes atmospheric carbon transformation possible. Carbon enters the soil as organic particulates from plants, animals, manures, and organic amendments and becomes SOC, which is the energy source for the soil microbiome (figure 1).

Tillage transports SOC to deep soil where atmospheric exchange is limited and therefore carbon is sequestered. But agricultural practices over the past 100 years have resulted in the depletion of SOC pools by 25–75 percent (10–30 Mg/ha) (Lal 2013, 2018), a loss that impacts microbial activity, soil aggregation, and nutrient cycling (Denardin et al. 2022; Dynarski et al. 2020). Adoption of recommended management practices can restore SOC stock over a generational time scale (Lal 2008, 2018) while enhancing soil health and improving productivity (Lal 2020b).

SOC in upper soil is transformed by microbial metabolism to become soil organic matter (SOM), a complex matrix of organic materials that contain as much as 50 percent SOC and high concentrations of crucial nutrients (Lal 2018, 2020a). SOM can be a critical factor in plant-available water in the root zone as it supports increased porosity, allowing greater water infiltration during precipitation and less runoff and erosion. Thus SOM and porosity make the soil more climate resilient (Lal 2018, 2020b).

The dynamic exchange of nutrients through the soil microbiome occurs in pore spaces and flow paths from soil aggregates, which provide liquid and gas exchanges that are necessary for plant growth. Soluble SOM can leach to deep soil to be sequestered from the atmosphere. The carbon transformation process that creates SOM increases aggregate formation, nutrient availability, and carbon sequestration potential, and supports a diverse microbial community.

Regulation of Diseases and Pests

The role of soils in regulating plant diseases and pests is a form of allelopathy, the inhibitory or stimulatory biochemical influence of one species on another in an ecosystem. Many plants have evolved strategies to exude sugars and other substances from their roots into the rhizosphere to support beneficial rhizobacterial, fungal, and insect communities and inhibit deleterious ones. Some plant leaves leach chemicals into the soil with similar beneficial impacts (Sturz and Christie 2003). In addition, soil biotic and abiotic parameters impact plant disease suppression (Janvier et al. 2007).

The relationship between SOM and plant disease is becoming clearer. Biofertilizers (combined organic, humic, and nutrient fertilizers) provide a plant-beneficial consortium against fungal pathogens (Tao et al.

2020). Organic amendments that promote populations of *Pseudomonas* and *Streptomyces*, for example, have been demonstrated to suppress wilt-causing *Verticillium* (Bonanomi et al. 2018).

Priority innovations in data acquisition include sensors for subfield monitoring of soil density, pH, temperature, moisture, SOC, and nutrients.

The complexity of these interactions makes simple causal relationships difficult to demonstrate across diverse soil and cropping systems. This complexity is often interpreted as uncertainty about the relationships, and thus becomes a barrier to policy and practice implementation that support soil resilience. But there is little uncertainty that the impact of agricultural cultivation is often the loss of the soil biodiversity that supports regulation of plant disease and pests (Billings et al. 2021). Preserving and restoring soil biodiversity and resiliency is key to increasing yields while preserving soil biome health (Waqas et al. 2020).

The Path to Resilient Soils

Management (or mismanagement) of life systems, resources, and water has defined the practice of agriculture from the beginning in the pursuit of productivity for human benefits. It is increasingly understood that such single-minded motivation is not sustainable. A new, integrated framework of understanding is essential to make better decisions for better outcomes. This new framework cannot be created just by collecting more data or developing a new sensor, but rather requires development of a more holistic way of understanding and managing the dynamic soil ecosystem.

The exploration of soil ecosystem dynamics, indicators of soil health, and soil resilience has expanded exponentially in the past decade (Karlen et al. 2019; Rice et al. 2021). This new way of understanding the dynamic interactions between the physical, chemical, and biological processes in soil has resulted in the emergence of a renaissance in soil sciences (Hartemink and McBratney 2008). Integration of the four soil ecosystem functions into a metasystem understanding of soil dynamics is accelerating the emergence of this renaissance in soil ecosystem management with the aim of enhancing resilient soils.[4]

Because soil is equated to land in most societies and largely held in private ownership, developing portfolios of practices that increase high-value functions in soils, such as sequestration of atmospheric carbon, will require high-resolution decision support systems (DSSs) for land owners and managers. Such systems require more sophisticated data acquisition methods and models than are currently available (Amelung et al. 2020).

Decision making to support resilient soils may benefit from a dynamic soil information system (DSIS) with high temporal and geospatial resolution (NASEM 2021). Priority innovations in data acquisition to support the DSIS include sensors for subfield monitoring of soil bulk density, pH, temperature, moisture, SOC, and plant-available nutrients at multiple depths and at high temporal and spatial resolutions. These data will need to be integrated into a decision support model populated with both historic and current land uses and practices.

While the combined DSIS-DSS database and model will be dynamically integrated with precision agriculture data acquisition systems—providing planting, cultivation, and yield data at subfield (square meter) spatial resolution—an active artificial intelligence model will learn to make risk-based recommendations for land managers. Combined with a growing toolbox of technologies, these integrated data acquisition and model systems describe pathways forward (figure 2) and support the convergence of knowledge, new technologies, and integrated understanding.

The Way Forward: Opportunities and Needs

Many producers recognize the complex and dynamic interactions that drive soil resilience, but these interactions have only recently been recognized across the scientific community (Bonanomi et al. 2018; Giller et al. 2021). Creating a science-based framework for understanding and managing the metasystems that create resilient soils requires full stakeholder engagement. It is imperative to translate science into action through (i) active involvement of the private sector, (ii) policy interventions supporting farmers' decision making that enhances soil health, and (iii) provisions for payments

[4] https://www.farmfoundation.org/

for ecosystem services (e.g., for carbon sequestration).

The catalytic model (figure 3) developed by Solutions from the Land describes the pathway from the current state to the desired future state. The first step is to recruit conveners who have a clear understanding of the challenges and opportunities from the DSIS. Conveners are trusted organizations that can mediate location- and context-driven conversations between stakeholders (interested and affected parties) to increase understanding of complex problems and identify potential pathways to reconciliation. Action plans developed by the conveners through the multistakeholder process should be developed in such a manner that they can be championed by organizations with resources and authority to act.

The way forward demands disciplined focus and determined action to achieve the promises of sustainable and regenerative agriculture approaches. The connections between more data, a better understanding of the unique dynamics in each soil production system, and crop production resilience need to be embraced and incentivized. The innovations and integrations necessary to accelerate the soil renaissance will require novel public-private partnerships with strong commitments to public sharing of data and knowledge for the more than 2 million US farmers and

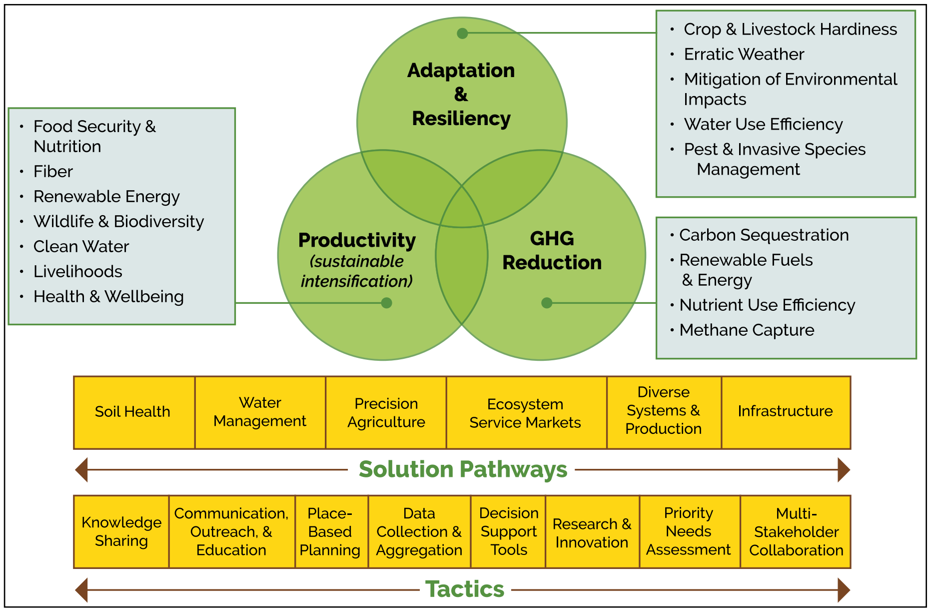

FIGURE 2 Soil management to achieve sustainable and regenerative agriculture. GHG = greenhouse gas. Reprinted with permission from Solutions from the Land (2021).

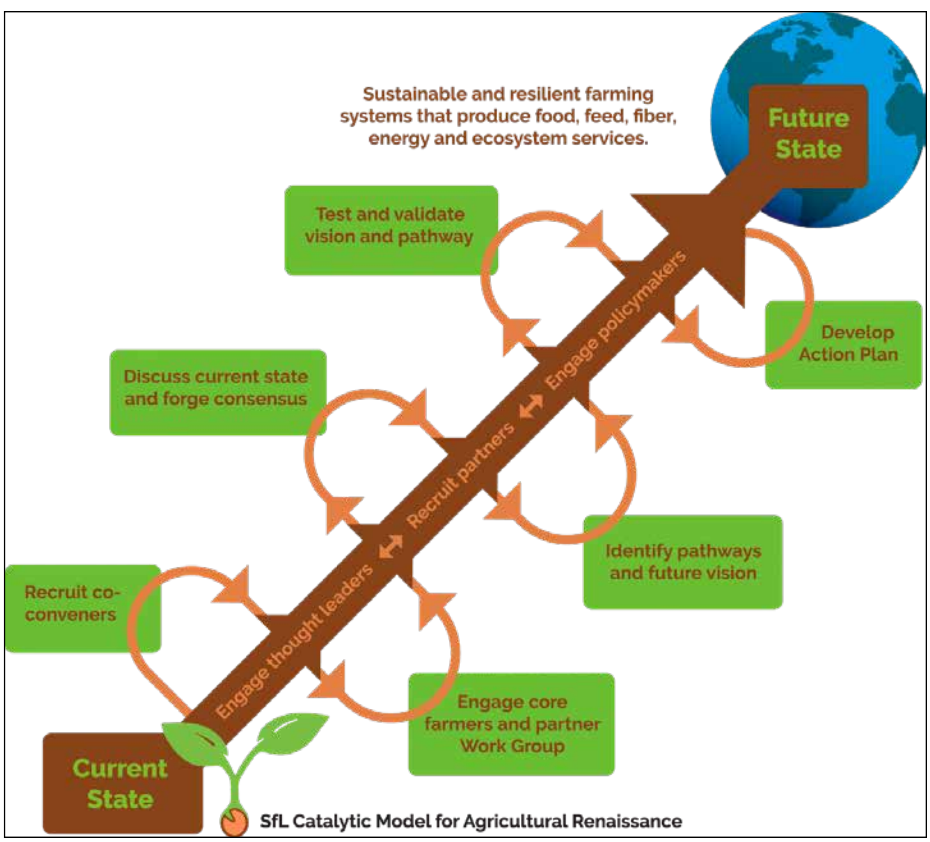

FIGURE 3 Catalytic model for an agricultural renaissance. Reprinted with permission from Solutions from the Land (2021).

570 million farmers around the world who generate and curate these data.

Improved knowledge and understanding will encourage the replication and scalability of successful practices for sustainable and regenerative agriculture. Ultimately the people who manage the soils are the farmers who till the land, the land owners who put marginal lands in conservation programs, and the agencies who support them. Protecting, restoring, and enhancing life on Earth begins and ends with the soil.

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Progress in understanding and production of crops requires transdisciplinary collaboration and innovation.

Digital Biology to Enable Sustainable and Resilient Agriculture

The CROPPS Research Community

The Center for Research on Programmable Plant Systems (CROPPS; cropps.cornell.edu) is an NSF Science and Technology Center partnership of Cornell University, University of Illinois Urbana-Champaign, University of Arizona, and Boyce Thompson Institute.

Preparing for a future of resilient and sustainable agriculture that produces nutritious calories for the globe's growing population requires a deeper understanding of the biology of plants, their associated organisms, and their responses to a changing climate. The discovery and translation of this knowledge will require the intensive collaboration of engineers and computer scientists with life scientists. The resulting technical innovations will have implications beyond plant science and agriculture, and the biological discoveries will have impacts on other branches of the life sciences.

Because the practice and outputs of agriculture affect all people, this effort must involve the social sciences and be informed by strong engagement with stakeholders along the agrifood value chain, including farmers, consumers, and public and private organizations. This transdisciplinary effort represents a new form of "digital biology" and calls for the intentional cross-training of life scientists, engineers, computer scientists, and social scientists to lead discovery, innovation, and responsible translation in this critical area.

Agriculture as a Complex System

The practice of crop-based agriculture, like that of medicine, involves developing and deploying interventions to influence the behavior of an extraordinarily complex system that is still incompletely understood. For crops, this system involves

- the plants themselves as highly differentiated, multicellular, eukaryotic organisms;
- a local environment that spans from the atmosphere to below ground—the soil in particular presents massive physical, chemical, and biological complexity;
- local ecologies that include microbes, insects, and other plants, each of which can present benefits and costs for a crop; and
- human contexts, in the form of farm management of cultivars, inputs, labor, and markets as well as consideration of the preferences, health, and economics of consumers.

Progress toward a more complete understanding of crop systems and the ability to interact with them in more sophisticated ways will help secure a healthy future for people and the planet. This pursuit also presents diverse scientific and technical challenges, with strong potential to advance other areas of science and technology, and provides a richly multidisciplinary context in which to train life scientists and engineers.

Challenges in Agricultural R&D and Practice

Through the 10,000-year history of agriculture, humans' ability to learn from and innovate in their interaction with plants has provided a foundation—in calories, nutrition, fuel, and fiber—for population growth and stable societies. Discoveries in the study of plants, such as evolution (Darwin) and genetics (Mendel and McClintock), are landmarks in the history of science. Innovations in crop agriculture have enhanced environmental modeling and measurement and provide some of the earliest examples of self-driving vehicles and applications of genetically engineered organisms.

Yet despite important advances in both biological understanding and technology, there remain critical limitations in the speed, precision, and robustness of approaches, in both research and development (R&D) and on-farm practices. Following are some important examples of these limitations:

- In the R&D context of breeding new cultivars for increased yield, nutritional value, resource efficiency, and resilience, the development cycle requires most of a decade, a span of time over which both climate and market conditions can change dramatically. Visions for accelerating this cycle, such as the use of gene editing to move useful gene variants rapidly into high-performance genetic lines, require a deeper understanding of the biology of, for example, gene regulation as well as breakthroughs in the throughput, versatility, and precision of emerging tools for gene editing (Varshney et al. 2020).
- Characterizing plant-microbe interactions in the soil is a challenging frontier in crop sciences, with enormous potential benefits from the capture of native symbioses or design of new beneficial interactions to lower dependence on external inputs and increase resilience and sustainability (Arif et al. 2020). Lack of tools to navigate, study, and model the complex and poorly accessible ecosystem formed by plants and microbes in the soil has hindered both science and application in this area.
- On the farm, management of inputs such as water and nitrogen, detection of and response to disease and pests, and mitigation of extreme climatic conditions remain limited in precision and speed. For example, crops make use of only about one third of the nitrogen delivered by fertilization, and the rest is lost via leaching and gaseous releases (Omara et al. 2019). Lack of access to high-frequency or real-time information about plants' internal biological states and processes hinders discovery, the development of predictive models, and, in turn, farmers' ability to manage these challenges.

> *Lack of real-time information about plants' internal biological states hinders the development of predictive models and farmers' ability to manage challenges.*

A common theme in these examples is the interconnection between tools and knowledge in efforts to achieve important outcomes in crop-based agriculture: acquiring understanding requires tools, and the development of tools requires understanding.

The Center for Research on Programmable Plant Systems (CROPPS)

Colleagues at Cornell University, the University of Illinois at Urbana-Champaign, the University

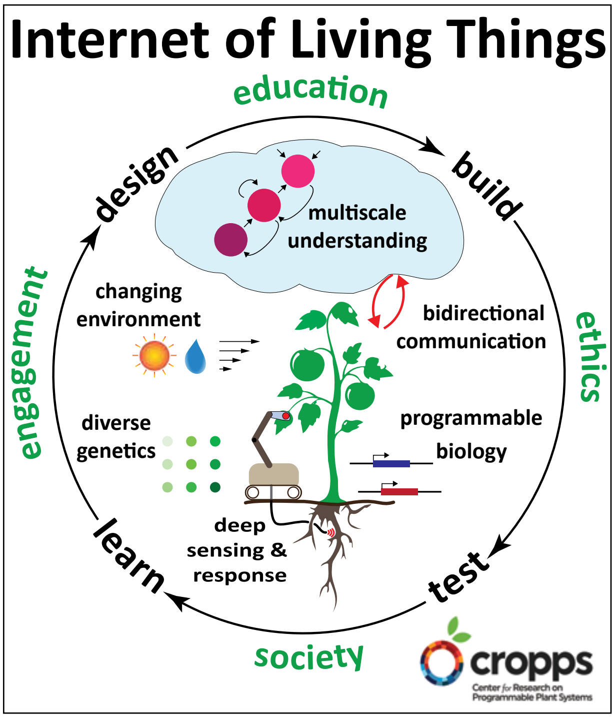

FIGURE 1 Illustration of the vision pursued in the Center for Research on Programmable Plant Systems (CROPPS), which is developing a suite of technologies to allow plants to serve as nodes on an Internet of Living Things (IoLT). This IoLT will enable multiscale understanding based on efficient two-way exchange of information with plants, above and below ground, across genetically diverse populations, and in changing environments. The center pursues its science and engineering in cycles (design-build-test-learn) that are continuously informed by public engagement and a commitment to education, ethical practices, and positive societal outcomes.

of Arizona, and the Boyce Thompson Institute are pursuing a research program that fosters close, multifaceted collaborations among life scientists, engineers, computer scientists, and social scientists. In the newly established Center for Research on Programmable Plant Systems (CROPPS), a Science and Technology Center of the National Science Foundation, we aim to define a new kind of transdisciplinary digital biology in which experts in these areas collaborate to create technology that supports discoveries that inform and inspire new technologies and applications.

In CROPPS, we are pursuing a vision focused on developing new modes of interaction with plants' internal biological processes to decode the rules of living systems. We will use this newly acquired knowledge to improve outcomes in both the research pipeline and practice of agriculture.

An Internet of Living Things

The CROPPS vision builds on advances in embedded systems, edge and cloud computing, and communication systems that have inspired the concepts of Industry 4.0, the Internet of Things, and digital agriculture (Chandra et al. 2022; Schueller and Reid 2022). We extend these developments to the tight coupling of living systems—plants—in a network of information flow to form an Internet of *Living* Things (IoLT; figure 1).

In developing the IoLT, we aim to create a virtuous cycle of discovery, refinement, and optimization. In the context of research, this cycle involves access to new data, *in planta* and in relevant environments, that feed the development and maturation of multiscale models; predictions from these models, in turn, inform the design of new technologies and experiments to access further data and insights.

In parallel with advancing understanding of plant systems, this research cycle serves as an incubator of innovations in engineering and computer science. A critical goal of this research phase is to assess, through cycles of design-build-test-learn, the robustness, effectiveness, and safety of prototypes of hardware, software, and plants to foster their adoption in agricultural R&D and crop production. In assessment cycles, we prioritize engagement of stakeholders from across the agricultural sector—growers from both large and small farms, and representatives of private, governmental, and nongovernmental organizations—as well as the general public to inform our visions and approaches with their perspectives and concerns.

The realization of our vision of digital biology and an IoLT will require a richness of interconnected innovations across biology, engineering, and computing. The following sections present examples focused on opening new pathways to exchange physical, chemical, and biological information with plant systems.

Biotechnology and Synthetic Biology

Genetic engineering and gene editing are powerful approaches for defining the flow of information to and from plants' inner biology and for programming changes in plant function, as in the introduction of genetic variants (gain and loss of function) and gene-encoded sensors, reporters, and inducers. With the emergence of synthetic biology, one can now look toward more complicated functions for gene circuits with logic elements and multiple inputs and outputs.

Realizing the full potential of these approaches will require integrated advances to address bottlenecks in plant transformation related to (i) the efficiency and versatility of gene delivery technologies; (ii) slow, labor-intensive processes such as cell and tissue manipulation and diagnostics for quality control; and (iii) the design of robust gene circuits to enable, for example, new mechanisms of bidirectional transduction (Altpeter et al. 2016). The pursuit of these advances presents interesting opportunities for collaboration between molecular biologists, biomolecular engineers, roboticists, optical engineers, and computer scientists for computations ranging from machine vision to molecular simulation.

Synthetic biology also provides a particularly rich context for learning across disciplinary boundaries with, for example, biologists benefiting from the powerful conceptual tools of circuit design and engineers gaining access to a vast diversity of new functional elements (Wurtzel et al. 2019).

Robotics and Automation

Robotics and automation have a long history of contributing to agriculture, in both R&D and production contexts. They have enabled, for example, self-driving tractors, platforms for high-throughput screening of plants for breeding ("phenotyping"), and increased in-field autonomy with rovers and aerial vehicles (Shamshiri et al. 2018).

Digital biology and the IoLT present new challenges for robotics, calling on them to mediate communications with plants' inner biology via mechanical, chemical, and optical interactions. An important frontier for these engagements is the development of autonomous tools for exploration of the belowground realm of plant systems, in which kilometers of roots are interspersed with the highly heterogeneous, biologically active environment of the soil.

The multifunctional and dexterous actuators emerging in the area of soft robotics present promising opportunities to address these challenges (e.g., Zhao et al. 2016).

Sensing and Actuation

Micro- and nanoengineered systems have proven valuable in biomedicine in contexts from drug delivery to imaging, glucose sensing, and pacemakers. Injectable or implantable systems can similarly play important roles in opening access to internal states and dynamics in plants and enabling tailorable modes of transduction into digitizable signals.

Plants present challenges distinct from mammals for the design of such tools with respect to, for example, gaining access through tough external tissues and selective membranes and controlling the translocation of materials once they have passed these barriers. Device function must also be informed by specific physiological contexts, such that the transfer of strategies directly from biomedical technologies is often not possible.

In synthetic biology, biologists benefit from the tools of circuit design and engineers gain access to new functional elements.

Members of the CROPPS team have collaborated on the successful design of a nanoparticle that reports local water stress in leaves as easily readable changes in fluorescence spectrum. This development involved iterations of design to achieve the necessary responsiveness and compatibility with delivery to and operation in the microscopic spaces in leaves (Jain et al. 2021). Engineering of these systems requires consideration of both biological and environmental appropriateness relative to toxicity, degradation processes, and potential for retrieval and reuse.

Computing and Modeling

Innovations in computing can both contribute to an IoLT of plant systems and benefit from the unprecedented data streams that this infrastructure will create. For instance, the IoLT will enable the creation of digital twins of every plant in the cloud, and such a detailed dataset will help drive artificial intelligence models that were not possible until now.

We focus on the vast challenges and opportunities of building predictive models of the multiscale processes—from molecules, cells, and tissues to the whole organism and its local environment—that define a plant's growth, resource use, response to stress, and productivity. This effort needs to define new ways to combine the mechanistic approaches of systems biology with the data-driven approaches of bioinformatics. Such hybrid approaches can exploit the robustness to extrapolation of mechanistic models across environmental and other conditions, while data-driven models provide scalability to manage, for example, full genome-scale analyses. Such approaches are emerging as accelerators of plant breeding (Wang et al. 2020).

These modeling contexts present interesting targets for innovation in data science and machine learning with resources such as massive datasets (genomic, transcriptomic, proteomic, and metabolic) between which bridges must be built (Cheng et al. 2021). As models mature, the IoLT provides a context in which strategies from systems engineering will need to be developed to make their predictive power useful in defining optimal interactions with plants to support both continued research discoveries and improved crop management.

Digital Biologists and the Public Interest

In closing, we emphasize the human dimensions of our vision of digital biology for discovery and translation in crop-based agriculture. Food and other products produced by plants touch everyone, and the environment in which plants are grown belongs to all.

The success of the CROPPS vision depends on the cultivation of true digital biologists who pursue their innovations with humble awareness of the need to engage seriously with the public, reflect continuously on the implications of their work, and be adaptive in updating approaches to target outcomes that benefit people and this planet.

Acknowledgments

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System-oriented precision agriculture production leverages sensors, machine learning, and cloud computing to enhance productivity.

The Digitalization of Production Agriculture

John Schueller

John Reid

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Agricultural productivity has expanded for over a century because of successful replacement of human and animal power with mechanization combined with advances in fertilization, agricultural chemicals, and genetics. These developments freed workforces in developed countries to focus on building and advancing their societies. A second wave of productivity expansion has occurred since the 1980s that can be associated with the impact of digital technologies following the trends of Moore's law. The result is system-oriented precision agriculture production solutions that leverage sensors, machine learning, and cloud computing to achieve productive outcomes.

Continued expansion of digital technologies and widespread connectivity are important enablers for the development of future production systems for food, feed, fiber, and fuel that are more economically, environmentally, and socially sustainable. Fully integrated precision agricultural production systems link a network of processes, organizations, and stakeholder relationships and enable higher levels of optimization. Digitalization can improve agricultural production to meet the needs of increasing populations and changing diets. It also provides tools to adopt and evolve new production

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practices that address degradations (e.g., salinization, desertification, erosion) and facilitate progress toward sustainability objectives.

Early Digital Agriculture: Promises and Challenges

Digital agriculture began in the 1980s as machinery was endowed with electronics, embedded computing, software, and other digital technologies. Agricultural adoption of digital technology has typically closely followed similar enabling technologies in automotive and other industry verticals.

Initially electronics and controls were incorporated in tractors and self-propelled vehicles. Automatic control systems ensured that vehicle operations were optimized according to control setpoints. Cooperation between European and North American engineers led to the ISO 11783 standard, which defined communications between tractors and attached implements over a CAN bus (Oksanen and Auernhammer 2021). But lacking external sensing, communications, and other off-board technologies, agricultural vehicles were "islands of automation" limited to specific machines.

Automatic guidance supports reduced operator fatigue, consistent job performance, 24-hour operational capabilities, and increased field operation accuracy and productivity.

The ability to make the most of mechanization had a practical limit. Larger, more powerful equipment and fewer field passes increased productivity with a reduced agricultural workforce, but fields' varying topography and soil characteristics caused nonuniform yield outcomes. The concept of precision agriculture was founded on the principle of using advances in mechanization to address spatial variability.

Pioneering research and commercialization made it possible to spatially sense and map instantaneous crop harvest yields on the go, and that remains a core crop sensing solution for modern combine harvesters (Myers 1996; Searcy et al. 1989). The integration of crop yield sensing with the location of the machine in the field via the Global Positioning System (GPS) provided farmers with basic geospatial information to make (limited) strategic or tactical decisions (Schueller 1992), such as whether to improve field drainage or spatially vary fertilization.

Some early solutions were complex to set up and manage, though, frustrating farmers with the planning and preparation required before productive work could begin. And although GPS promised future benefits, its accuracy was initially adequate only for large harvesting machines.

Early precision agriculture created a vision of tighter integration of machine systems to provide better agronomic outcomes, but the reality was challenging because of missing or erroneous data, unknown accuracies, weather, and complex physical/chemical/biological plant growth processes. Value propositions struggled to move beyond these challenges until automatic guidance evolved to enhance machine productivity and reset expectations.

Enhanced Accuracy through Automatic Guidance

Agricultural vehicle guidance was a game-changing innovation that offset some early precision agriculture challenges. While vehicle guidance solutions had been proposed or demonstrated since the 1920s (Wilrodt 1924), commercial realization required vehicle electronics technology combined with electrohydraulic steering controls that became viable only in the 1990s. Guidance required position sensing enabled by public availability of the GPS network and subsequent advances that increased precision and accuracy to the centimeter levels necessary to meet various agricultural application requirements.

Automatic guidance unlocked significant value that varied with the machine system, operator, and crop production system. Its benefits included less operator fatigue, consistent job performance, operational capabilities day or night, increased field operation accuracy, higher productivity (through higher-speed operations), and increased crop density through accuracy in planting patterns.

Guidance requirements depend on the specific agricultural field operations and vehicle system characteristics. Meter-level sensing accuracies are suitable for yield sensing in harvesting operations, which have a wide swath. Decimeter-level accuracies through dual-frequency GPS are needed for tillage and basic spraying systems, and they provide information required for weed control or chemical placement with minimal overlap between machine passes. And centimeter-level accuracies, provided by real-time kinematic positioning–GPS systems, enable control of vehicle guidance proximate to rows of plants.

As GPS accuracy improved, automatic guidance displaced manual steering with closed-loop control of the vehicle to desired straight lines or curved paths (figure 1). Early solutions in the market were options or aftermarket retrofits to vehicles, but over time factory-integrated solutions emerged as guidance and vehicle control became mainstream. GPS expanded to broader Global Navigation Satellite System (GNSS) solutions that leverage multiple constellations (e.g., Galileo from the European Union and BeiDou from China) to improve positioning solutions.

Agricultural guidance requires understanding of vehicle system characteristics (for prime movers and implements), vehicle pose with respect to the terrain, and soil surface properties. And the sensing and control need to control the working implements to a precise location proximate to crops, sometimes traversing between planted crop rows.

There remain some guidance use cases requiring a solution to sense and follow crop rows or to operate relative to a given crop. Mechanical feelers are a basic solution to sense and follow sturdy, established crops. And machine vision and lidar solutions have succeeded in sensing guidance cues for emerged crop applications and crop edge during harvesting operations.

Examples of the advanced farming practices that have emerged include the capacity to follow precise paths from previous operations, field-level path planning to optimize path traverses, documentation of agricultural practices at the row or plant level, ability of vehicle systems to operate relative to infrastructure (e.g., drainage and irrigation systems), tractor-implement management, compaction management, and other forms of protection for cropping systems and plants.

Machine Precision and Efficiency through Electrification

During the past decade electrification has enabled greater precision and accuracy, for example in planting. In traditional planting systems, seeds are separated (singulated) from hoppers through mechanical or vacuum means and then dropped to the soil trench

FIGURE 1 Automatic guidance enables machines to operate with consistent precision and accuracy across the production steps, as illustrated by this accurate planting outcome.

through gravity-feed seed tubes. The seed interaction with the tubes effectively limits planting speeds to less than 3 m/s for consistent seed spacing.

Electrification enables independent closed-loop control to separate and transport individual seeds to the ground (Garner et al. 2013). Electric drives on independent row units not only precisely place seeds at speeds approaching 5 m/s with precision control but also solve challenges in mechanical-drive seeding systems to produce fields where every plant emerges at the desired location and depth. And these systems enable potential new forms of crop production such as grid-based farming methods (Kremmer et al. 2021).

High-voltage electrification solutions in transportation verticals are beginning to be commercialized in production agriculture, improving the performance of vehicle drivetrains for traction and task automation. Increasingly electrified machine forms will create additional opportunities for production system efficiencies through precision control and systems-level power efficiency gains. And systems electrification will be part of future solutions that farmers can leverage in the transition toward alternative energy sources to support decarbonization (e.g., Gavioli 2021, p. 6).

Digital Expansion of Precision Agriculture

Digital technologies (machine-to-X connectivity, cloud, and mobile) are a hinge point for modern precision agri-

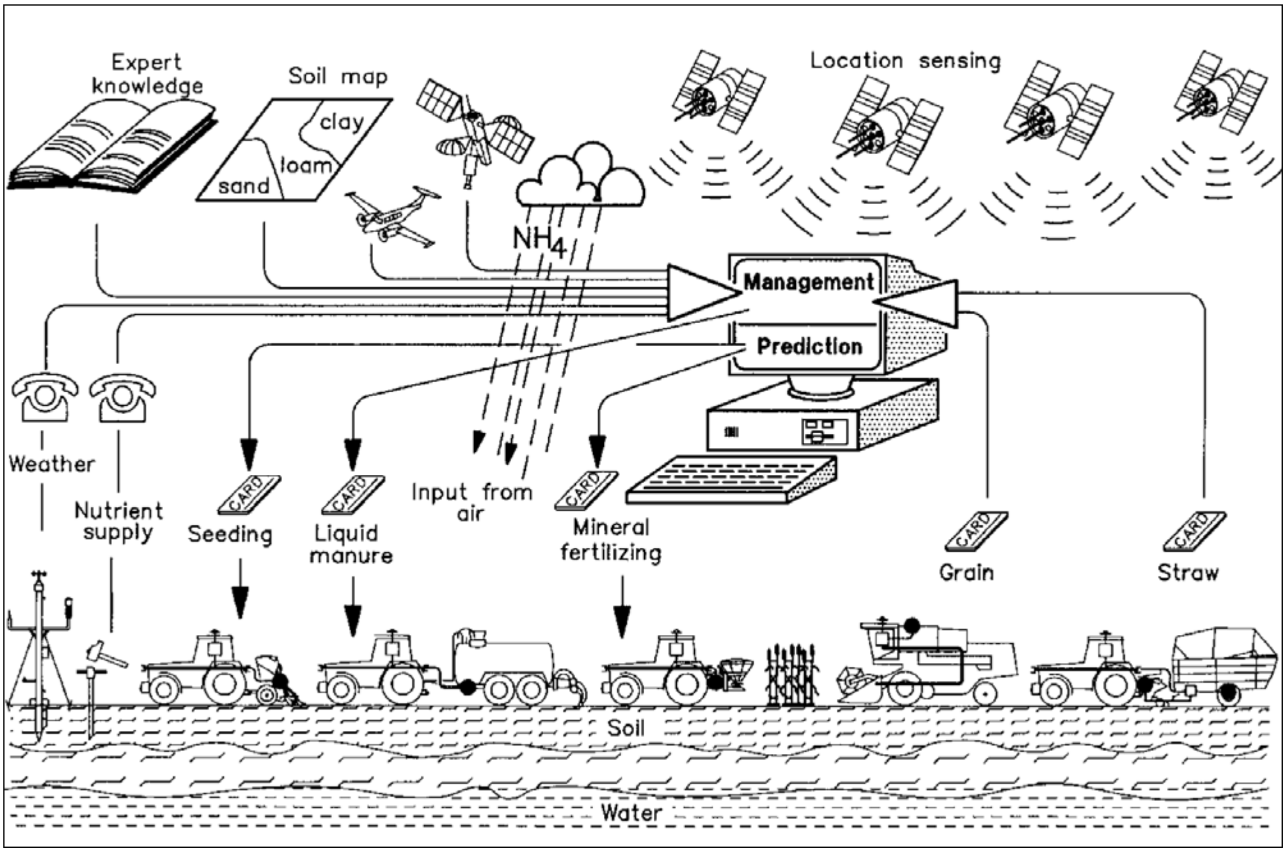

FIGURE 2 Late 20th century concept of precision agriculture from Hermann Auernhammer. Wireless communications and the internet have replaced datacards and rotary phones, and drones supplement the remote sensing of satellites and aircraft, but the agricultural activities remain similar. NH_4 = ammonium. Reprinted with permission from Auernhammer and Schueller (1999).

culture, enabling new ways to enhance production systems through the flow and management of information resources.

Connectivity

Information from tractors and mobile machines used for planting, crop protection, nourishment, and harvesting operations must be uploaded to management computers to support operations. Similarly, settings and actuator commands must be downloaded to the machines to drive field outcomes. Multiple vehicles working collaboratively in the same field must communicate to optimize performance.

Connectivity technologies couple information transfer for machine-to-machine interactions and off-vehicle storage of agronomic and vehicle data to support job steps in crop production system performance. Connected agricultural vehicles with bidirectional information flow are mobile sense-and-control platforms. Connectivity also enables the use of off-vehicle resources for precision management (figure 2). Soil, weather, crop, and pest data can be used for crop management decisions closer to real-time operations.

Lack of connectivity in some rural areas will affect realization of digital agriculture. Some producers are overcoming this barrier by installing private connectivity infrastructure,[1] and others have conceived of field-edge networks for local data transfer and storage. Without connectivity, farmers are limited to manual data transfer and other inefficient methods of information exchange.

In the past decade, cloud computing capabilities have emerged and matured for agriculture, enhancing data management and storage and opening opportunities for value-added services. For example, the cloud has enabled the integration of crop modeling with remote sensing, resulting in predictive information for in-

[1] US Sugar has its own wi-fi network, spanning 270 square miles, at its Clewiston refinery in Florida (https://www.ussugar.com/technological-innovations/).

season crop management and yield. Furthermore, cloud-based management enables insights from vehicle use to measure operational effectiveness, including the ability to infer information on operator performance (Pfeiffer and Blank 2014).

Drone Use

Low-cost drones can be deployed for precision data acquisition, quickly traversing fields, collecting images, or performing operations without disturbing soils or crops. They can be flown exactly when and where desired to efficiently collect information for crop management or vehicle control. Field scouting via drones can map crop growth and identify pest infestations with high precision. Drones can scale to apply pesticides or fertilizers, either in response to sensed infestations or based on previously generated application maps, without the need to traverse fields with heavy equipment.

Drones can be integrated with terrestrial agricultural vehicles performing field operations (Sugumaran 2017). Launched from a vehicle, a drone can take an appropriate aerial vantage point to assess conditions ahead of the vehicle or to inspect vehicle task performance.

But given that farmers are overloaded with demanding and varying tasks, agricultural drones can achieve maximum utility only if they are easy to operate, seamlessly integrate into the production process, and quickly translate collected data for management actions.

From Automation to Autonomy: Opportunities and Challenges

Many of the technical elements that have enabled precision agricultural production systems also are critical for autonomous machine deployment (Reid et al. 2016), including precise positioning, path planning, connectivity, cloud, and drones.

Opportunities

Likely advantages are clear; for example:

- Autonomous systems may be part of the solution for agriculture's varying labor requirements during the crop production cycle by augmenting the labor force.
- Autonomous vehicles can consistently perform over longer durations (day and night) without performance degradation.
- And autonomy may enable some operations to be performed without interruption and/or simultaneously. For instance, autonomy allows combine harvesters to unload grain on the go into driverless carts to improve in-field transport logistics with reduced labor.

FIGURE 3 Rowbot Systems LLC interrow platform enables in-season fertilization management and cover crop planting before the standing crop is harvested. Reprinted with permission from Rowbot Systems LLC.

Autonomy opens possibilities for innovative machine forms that may become part of the resources used in determining total factor productivity (Reid 2011). Small autonomous machines are available for executing jobs with less soil compaction and other benefits, like operating in growing crops. One example is a robotic interrow solution that traverses standing crop and enables new management practices such as precision in-season nutrient application and cover crop planting ahead of harvest (figure 3).

Challenges

Despite nearly unlimited possibilities, there are significant challenges for the successful implementation of autonomy, starting with the need to identify use cases with reasonable paybacks. Agricultural seasonality and the associated importance of timeliness in crop production increase the hourly value of autonomy, but many tasks have limits to the hours of operation in a crop year for a specific production step. For commercialization success, autonomous agricultural vehicles must find tasks that provide enough economic benefit through labor savings, higher job quality, or removal of humans from dangerous tasks.

The total job requirements must also be considered. Autonomous operation is more than machine systems executing the task. There are also setup, planning, logistics, documentation, and management of the autonomous operation. More research needs to approach autonomy from the perspective of the jobs to be done (Christensen and Raynor 2004). Design and programming must consider how the vehicle systems get to desired fields to execute production tasks and the farmer's role in autonomous mission execution.

In addition, perception sensing is needed for vehicle situation awareness. Such sensing is maturing, but requires further development to outperform an operator's capabilities to sense proper machine operation and variable field conditions. And sensing is often difficult through impairments in the normal operation of the machine (e.g., from precipitation or dust).

Artificial intelligence, such as computer vision/machine learning approaches, may provide value in precision agriculture applications. A challenge is the acquisition of significant image data representing the extremely wide variety of crops, production situations, and soil types.

Summary

Agriculture mechanization is advancing toward digital precision agriculture. Electronics and digital technologies commercially available in other verticals have been adopted and resulted in higher systems-level productivity of people, vehicles, fields, and farms.

The precision and accuracy of automatic guidance create opportunities for further agronomic and management advances and contributions from agricultural vehicle systems. Digitalization also creates value through data that can be leveraged beyond the vehicle system and the farm to provide additional commercial and societal benefit. Societal investments in assets such as GPS and the internet have accelerated the transformation of agriculture.

The technological advances in agriculture are timely to address challenges of increasing demands on global food supply. Digital precision agriculture provides new tools that better document production practices and enable the optimization of production systems toward decarbonization, regenerative farming approaches, and reduced impacts on climate change. Precision agriculture technologies can also shed light on new methods and increase efficiencies in production agriculture practices.

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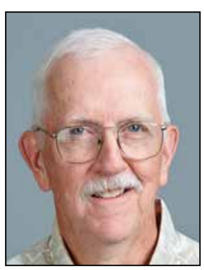
Research and new technologies are needed to develop precision plant growth and other systems alternatives for food production.

Precision Indoor Farming and Alternative Protein Food Systems

K.C. Ting, Michael B. Timmons,
and Ricardo San Martin

K.C. Ting



Michael Timmons

Ricardo San Martin

Food and agriculture systems (FASs) are physical and conceptual models of people's use of natural and human-made resources to produce food, feed, fiber, fuel, and furnishing. It has become increasingly important for FASs to be socially, economically, and environmentally sustainable.

Continuous modernization of FASs takes advantage of scientific and engineering advances to ensure both quantity and quality of products and services. FAS development has particularly benefited from advances in the following areas: machine intelligence enabled by automated perception, reasoning/learning,

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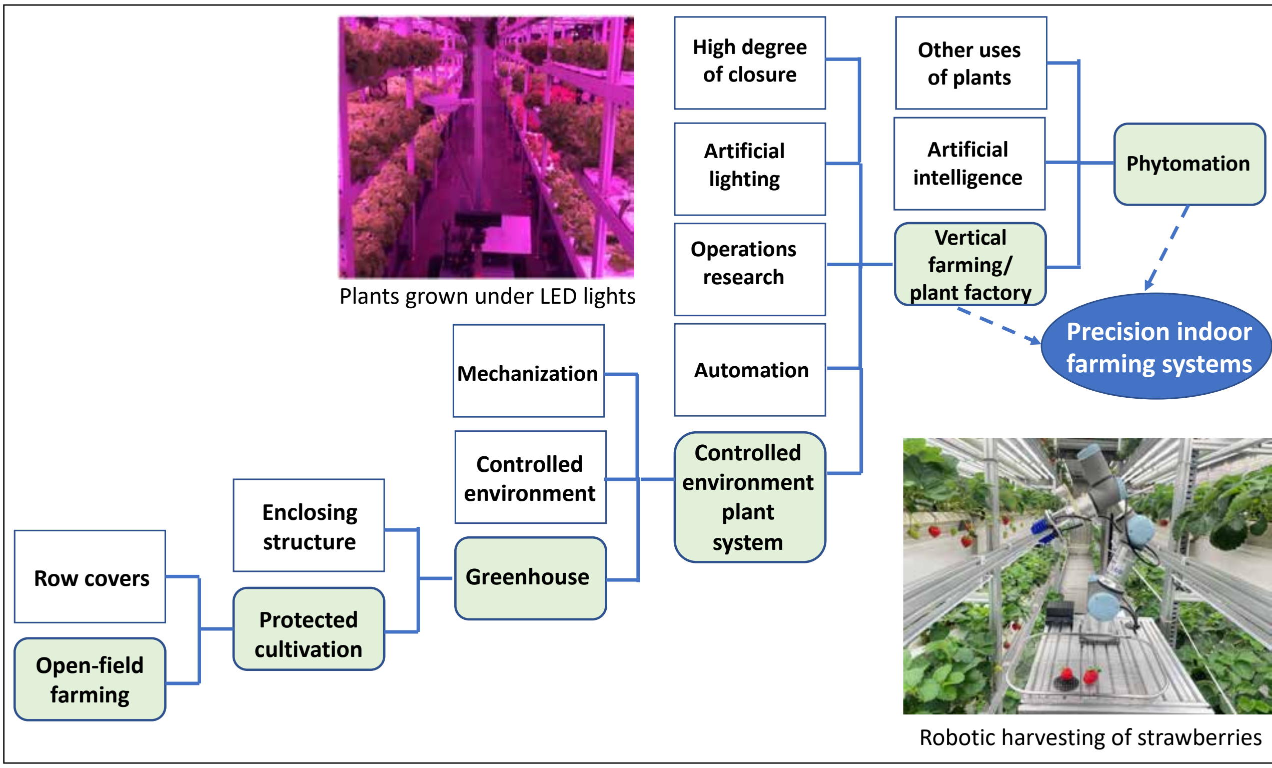

FIGURE 1 Forms of plant production ranging from open-field farming to precision indoor farming systems. Adapted with permission from Ting et al. (2021); photos courtesy of Guoqiang Ren.

communication, and task planning/execution; biological science, biotechnology, and bioprocessing; understanding, control, and management of environmental factors; and engineering of systems informatics and analytics.

Two rapidly evolving forms of high-tech food and agricultural production systems are worthy of attention: the precision indoor farming system (PIFS) and alternative protein food system (APFS). PIFS, mostly used for plant and/or aquaculture production, is arguably the most technology-intensive form of agriculture. APFS offers solutions to the challenges inherent in large-scale meat production.

Precision Indoor Farming Systems

A precision indoor farming system comprises numerous interrelated components, from the plants and animals to the enclosing structure(s), growing facility, equipment, environmental and operational control apparatus, information gathering and processing devices, and labor and management practices. PIFSs have evolved from production under simple, modified environments to precise, controlled environments. We focus on their application in plant and aquaculture systems.

Controlled Environment Plant Systems

The most advanced form of controlled environment plant system (CEPS)—also known as a vertical farm, plant factory, and phytomation (Ting et al. 2021)—falls within the concept of PIFS. The ability to optimally integrate indoor and outdoor environments, plant culture, human workers, machines, social acceptance, market demand, and economic viability is essential to a successful advanced CEPS (Gómez et al. 2019; Shamshiri et al. 2018; Ting et al. 2016). Figure 1 shows various forms of the CEPS.

Advanced Greenhouses and Urban Farms

Basic greenhouses provide modified and protected environments for crop production under cover. Past and future improvements emphasize measures such as recycling glazing materials, minimizing discarded waste and chemicals, maximizing usable products, using waste energy, and adopting consumer-centered production planning.

Notable differences between advanced and basic greenhouses are stronger and larger outer structures, computer control of production environments, innovative crop growing systems with various soilless forms, AI-supported operations, and sophisticated mechanization/automation for task planning and execution. Advanced greenhouses allow maximization of nutrient use for crop growth and reduced distance between crop production facilities and markets.

Urban farms and other food systems have been promoted as an important component of new urban infrastructure. Technology needs for their support include system of systems (SoS) engineering solutions for plant production, environmental controls, materials handling, process control, and decision support. With these features these innovative food production systems may enhance social, economic, and surrounding environmental conditions in urban centers (Despommier 2010; Nelkin and Caplow 2008).

Advantages

In addition to being well suited for integration in urban farming systems in "smart cities," the CEPS shares the concept of advanced manufacturing facilities and is capable of producing plant-based materials for food as well as pharmaceutical and chemical feedstocks. And it is particularly useful in areas where conditions are not conducive to conventional crop production.

A CEPS can readily implement the most modern automation, crop culture, environmental control, and systems integration methods and technologies (Ting 2013). Their high degree of closure allows not only the use of sun-independent light (i.e., sources completely powered by electricity) to provide precise quantity and quality of photons to plants but also the application of advances in artificial intelligence.

In terms of sustainability, CEPSs may facilitate the breeding of seeds to maximize crop productivity and meet production targets, the use of green building principles in facility design, autonomous capabilities including robotics, marketing strategies that respond to customer interests, and just-in-time operations that minimize inventory (van Delden et al. 2021).

For all these reasons, the CEPS is an ideal form of agriculture that will both benefit significantly from and promote the convergence of science, engineering, and technology to transform FAS (Benke and Tomkins 2018; Kozai 2018; Kozai et al. 2016). To ensure its effectiveness, it would be beneficial to create a comprehensive, concurrent analysis cyber platform, using an SoS approach, to enable solution-based decision support for collaborations among cross-disciplinary experts and multisector stakeholders.

Controlled Environment Aquaculture and Aquaponics Systems

The production of fresh and saltwater seafood in a precision indoor farming system is done in recirculating aquaculture systems (RASs), which discharge less than 50 percent of their standing water volume to the environment (river, lake, or ocean) per day (Timmons et al. 2018, p. 769).[1] Their normal hydraulic retention times (15–45 minutes) and fish tank geometric designs are similar to those of a flow-through system, but in a RAS most (>95 percent) of the discharge water from the fish tanks is returned to the tanks after treatment to remove ammonia, settlable solids, and carbon dioxide and to restore oxygen and other water quality parameters.

Advanced greenhouses offer computer control of the environment, soilless crop growing systems, and automation of task planning and execution.

A deterrent to widespread RAS adoption is cost: for yearly production capacity it exceeds \$15 per kg for a salmonid species, compared to net pen systems (\$3–\$5). RAS production costs are higher because of the energy consumed to pump water in the recirculating process (10 kWh per kg of fish produced). Systems have been designed and built to require less than 50 percent of the energy used by traditional RAS, thanks to mixed cell raceway technology (Timmons et al. 2018, pp. 122–28) and low-head pumps (Ledford 2021) that move 11,000 lpm per kW of power input (figure 2). Production systems designed as a combination of RAS and outdoor bioflock systems can be the most cost-effective.

Consumer Concerns

Consumer concerns that farmed fish tend to have lower levels of beneficial omega-3 fatty acids than wild fish (WRI 2019, chapter 23) are valid. But the old adage that "we are what we eat" holds true for farmed fish: if a RAS fish is fed a diet nutritionally similar to that of a pig

[1] Cornell University offers a virtual course on RAS (see www.eCornell.com/fish).

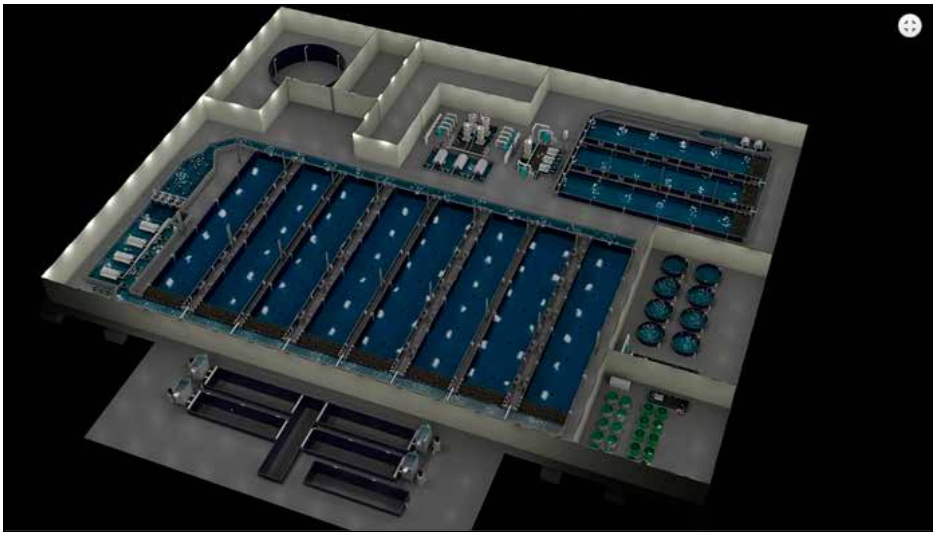

FIGURE 2 Illustration of a 1000 tonne/year steelhead farm, with 8 large RASWays™ as the main grow-out units, surrounded by hatchery/nursery, smolt, SuperSmolt RASWays™, Growout RASWays™, presale purge tanks, new water storage, main flow RAS, and side loop RAS and oxygenation. RAS = recirculating aquaculture system. Printed with permission from JLH Consulting Inc. (Courtenay, British Columbia, Canada).

or chicken, it will have a similar polyunsaturated fatty acid (PUFA) profile. The beauty of a RAS-produced fish is that any PUFA profile can be created—such as one with a high ratio of omega-3 to -6 that is beneficial to human heart health. But the costs associated with creating PUFA profiles may deter consumers unwilling to pay higher prices for such seafood.

Consumers also raise concerns about the wellbeing of RAS-raised fish, citing animal welfare and the use of antibiotics—high rearing densities can cause fish stress, and disease may result from poor water quality (Scott 2021). In all fish systems, control of the vectors that introduce disease is essential to minimize outbreaks. A RAS facilitates control of the two most important vectors, the water and the fish. Placing all new animals in quarantine to ensure that no diseases are present is critical to prevent outbreaks in any farm setting and particularly for a RAS.

Advantages

RAS-cultured fish coupled to a hydroponic vegetable system—a combination called aquaponics—is probably the most sustainable method of food production available. Generally, fish capture 50 percent or less of the macro- and micronutrients ingested (Timmons et al. 2018, p. 200). In aquaponic systems, hydroponic plants, through their root structures, receive all their required nutrients from the nonassimilated nutrients generated from the RAS. Comparisons of hydroponics (based on inorganic nutrients) and aquaponics (natural organic nutrients supplied by the fish) demonstrate the viability of aquaponics (Anderson et al. 2017; Rodgers et al. 2021; Timmons et al. 2018, chapter 19).

Alternative Protein Food Research

Growing global consumption of animal-based products, particularly red meat, significantly contributes to greenhouse gas emissions and poses tremendous burdens on the resource-intensive and complex systems of raising and slaughtering animals. Alternative protein food systems promise to remedy these issues, though significant challenges must first be overcome, as described below.

Three routes for the development of APFS are being explored: production of animal cells via fermentation ("cultured" or "cultivated" meat), use of plant components (e.g., proteins, fats) to produce plant-based foods (PBF), and precision fermentation. Each has advantages and challenges.

Cultured Meat

Cultivated meat is edible animal tissues or cells produced in a controlled environment, bypassing the body of the animal in favor of direct, additive construction from genes. The process results in a food product that is similar or equivalent to conventional meat products in sensory and nutritional character.

Producers of cultivated meat are motivated by several factors:

- climate change and the need to develop alternative food production systems that result in familiar consumer goods,
- reduction in the resources used and animals needed to feed a growing global population, and
- innovation to help meet the expected doubling of meat demand by the year 2050, absent any significant intervention in human diet preferences.

Although it is possible to grow mammalian, avian, fish, or crustacean cells in small bioreactors for demonstration purposes, both fermentation theory and industry experience indicate that this approach may not yield economically viable whole-animal replacements because of limitations inherent to the growth of mammalian cells: low cell numbers (e.g., 2×10^7 cells/ml), high capital equipment costs to contain contamination, and expensive media.

Furthermore, analysis shows that metabolic enhancements, different bioreactor configurations, or cheap media derived from plant hydrolysates are not enough to yield cost-competitive products (Humbird 2021). This probably explains why some companies are shifting to the production of animal cells as ingredients (e.g., lipid cells) to enhance the organoleptic properties (e.g., taste, smell, mouthfeel) of PBF. A major research effort led by Tufts University may help improve the economics of this approach (Nicholas and Silver 2021).

A further complicating factor is that cultivated meat products, unlike other products discussed here, are subject to a distinct US regulatory paradigm based on a risk assessment process that did not exist before 2018. In contrast, plant-based products have well-established regulatory systems that allow a more direct pathway to market than cultivated meats.

Plant-based Foods

In recent years several companies have shown that plant-based ingredients can be processed to mimic ground beef burgers in both taste and texture (e.g., Impossible Foods). Expanding the range of products to other categories—such as whole-cut meat, fish, cheese, eggs, and yogurt—requires sophisticated research based on a deep understanding of the scientific principles involved in creating such foods and knowledge of protein, lipid, and carbohydrate chemistry, microstructure, rheology, emulsification, and cooking behavior (McClements and Grossmann 2021).

The necessary expertise is mostly proprietary in companies, with little sharing of open-source knowledge. Major US universities with food science programs, such as the University of California, Davis, and Cornell, are not yet fully active in this space. Fortunately, this is rapidly changing with the work led by Julian McClements at the University of Massachusetts at Amherst and Atze Jan van der Goot at Wageningen University in Holland.

Precision Fermentation

This newer approach consists of expressing unique animal proteins, fats, or pigments into microorganisms grown in fermenters—for example, for replacement of palm oil (Karamerou et al. 2021) and casein (Hettinga and Bijl 2022). Because fermentation is expensive, it is not expected that this technology will yield bulk food ingredients but rather functional ingredients to be used in combination with cheaper plant-based matrices.

Besides cost, important hurdles include the need to obtain proteins with the right functionalities, such as susceptibility to posttranslational modifications.

Challenges to Alternative Protein Food Production

As detailed above, APFS production at scale is limited to PBF, particularly ground meat analogs. Despite media attention, the penetration rates of meat analog products remain low (Van Loo et al. 2020) and USDA data indicate that overall meat consumption has not declined with the introduction of alternatives.[2]

Production of animal cells as ingredients may enhance the organoleptic properties (e.g., taste, smell, mouthfeel) of plant-based foods.

Besides customer adoption, the plant-based food industry must address important production challenges to achieve greater impact:

1. *Limited number of protein sources:* At present, the industry uses a handful of proteins (e.g., soy, pea, and wheat gluten) available at scale. However, these proteins lack the functionality to produce important products such as eggs, yogurts, or cheese. Significant research is needed to obtain novel sources at scale with the right functionalities. Proteins from algae and green leaves (e.g., rubisco) show good functionalities,

[2] USDA Economic Research Service, Food availability (per capita) data system (as of Jul 2021) (https://www.ers.usda.gov/data-products/food-availability-per-capita-data-system/).

but their very low extraction yields result in high-cost proteins (Tamayo Tenorio et al. 2018).[3]

2. *Limited range of plant lipids:* The plant-based industry relies heavily on the few plant lipids that have high melting points, such as coconut fat, which is sourced mainly from the Philippines and Indonesia (Pham 2016). Lipid replacements must be developed for more sustainable products and the supply chain must be strengthened.
3. *Standardization of plant ingredients:* Extraction and purification methods affect ingredient functionality and organoleptic properties. There is an urgent need to standardize plant ingredients from different origins.
4. *More efficient processing technologies:* The current approach to produce plant ingredients is to deconstruct grains such as soy to produce protein-rich fractions. This generates significant waste that is used as animal feed. Newer technologies must be developed to incorporate less refined fractions into PBF (van der Goot et al. 2016).
5. *Sustainability and health claims:* The industry and mission-oriented organizations have crafted a strong narrative (normally through non-peer-reviewed white papers) about the health and sustainability advantages of PBF. External, nonbiased peer-reviewed research must verify these claims and the research methods employed, and the FDA and USDA should take an active role to verify the validity of health claims/impacts.
6. *Novel production technologies:* Most plant-based products rely on extrusion to reconfigure the protein fractions. This is an expensive and complex process that works with only a very limited range of raw materials. Technologies for developing highly structured foods, like steak or fish, still need major research efforts.

Concluding Remarks

Creating a sustainable world with no hunger is a major challenge. Food systems of systems are economic engines that are locally operated and globally connected. PIFS is evolving toward intelligence-driven and empowered agricultural systems by implementing human-supervised cyberphysical systems that combine human management, computational power, and physical operations.

APFS is unquestionably a good option to reduce dependency on animal-based products. Plant-based APFS is more feasible, but still needs substantial research to deliver a variety of products acceptable to consumers in taste, texture, and price.

The challenge is to design food and agriculture systems that are economically viable in today's world markets. The convergence of physical, chemical, biological, and social sciences in the SoS value chain is required. Product differentiation (e.g., in terms of quality, source, traceability, and social, economic, and environmental factors) may support premium pricing, but the premium is generally only about 10 percent more than the price for a competing nondifferentiated product.

For the near term, production systems need to make incremental changes toward environmental sustainability to remain economically competitive. Societal needs, however, may require transition at an accelerated pace.

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Engineering advances in food processing ensure food safety and quality while reducing energy and waste.

Food Processing for Today and Tomorrow

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Food product preservation has advanced rapidly over the past 75 years. Thermally processed shelf-stable food is available worldwide, and frozen foods with long shelf lives are available throughout most of the developed world. Microwaves have revolutionized home food preparation.

But can food processing keep pace with global population growth? In this article we discuss several processing areas that will contribute to a sustainable food future for the planet.

Introduction

There are global, political, demographic, and cultural issues at play. As the world population grows to approach 10 billion by 2050 (Pew Research Center 2022), food waste and pollution—both of which occur in the transition from raw source to preservation and consumption—are critical challenges (FoodPrint 2022).

Moreover, the year 2010 saw the scale tip, with more people living in urban areas than rural, and there are now 26 "megacities" around the world, each with more than 10 million residents. By 2025 Tokyo is projected to

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have 39 million residents and New York is projected to grow 20 percent to 24 million. Getting high-quality food in sufficient quantities into these urban areas remains a major challenge (Knorr et al. 2018).

The global demand for meat quadrupled from 71 million tons in 1961 to an estimated 284 million tons in 2007 (Bittman 2008). In developing countries, per capita meat consumption doubled between 1987 and 2007, and by 2050 it may well double again.

In the United States in 2015, 22.4 percent of deaths among males and 20.7 percent among females were attributable to dietary factors (Benjamin et al. 2018). So there is a public health motivation for increasing the availability of healthy processed foods.

Finally, in most industrialized nations the population is becoming greyer, and more men are reaching the ages that women traditionally dominated. This is relevant because men typically consume more calories and require more inputs because of their generally larger body mass.

Changes in urban growth and an increase in the elderly population create challenges to food availability. Advanced technologies from multiple industries are being incorporated in the food industry to meet these challenges.

Taking Stock

Although cultured meats may reduce the need for live animal harvesting (Swartzel 2000), projected increased demand for animal protein in diets worldwide will require a strong live animal industry.

With current technologies, meats can be rendered sterile, packaged in large aseptic containers (low-weight bag-in-box, or recycled packaging), and shipped worldwide unrefrigerated. And thanks to mature aseptic transfer technologies, foods can be stored for long periods of time and transported around the world in tanker loads without losing nutritional value or taste (Howard 2012). Energy, waste, and quality all benefit from the technologies involved in each step.

Most large mass meal preparation operations (40,000 meals/day and more) involve sizable kitchens with raw food preparation. Meals that are not "made from scratch" are derived from ingredients in #10 cans (6 3/16" in diameter and 7" high) or reheated frozen products. The packaging of these products, especially cans, creates disposal and sanitation issues; advanced processing and well-developed aseptic packaging technologies may reduce such problems.

The technology exists to process an enormous variety of products that are high in quality and shelf stable over long periods. These products are commercially sterile and do not need to be prepared in the kitchen. They run the gamut from thin to thick/viscous fluids, purees, pulps, small discrete particles to low- and high-load large discrete particles (soups and stews), sauces, pastas, and any combination. With the elimination of cross-contamination, commissaries, cafeterias, and mess halls can be assembly areas with dinners made to order. Meal items can be selected from screens and trays filled with, first, items to be heated (microwaved) and then nonheated items—for delivery to the consumer in less than 1 minute.

Technological Advances

Technologies such as hydrogen generation and utilization, micro nuclear reactors, new solar technologies, novel battery materials capable of storing and delivering higher energy densities, more rapid methods of charging and swappable battery technologies—all of these will enable and accelerate the application of electric and electronic technologies in the food processing industry. In addition, smaller, modular, compact, flexible, and more mobile processing systems will be enabled by new thermal and nonthermal technologies.

Can food processing keep pace with global population growth?

Some of these developments are already in progress, with the advent of small, integrated, precision-scale processing systems that can be deployed to areas of high preharvest value and used to develop products that reduce postharvest losses and waste. For example, in 2020 the Tibbetts Award was presented by the Small Business Administration and Small Business Innovation Research program to a company that developed a small-scale, onsite food processing system to reduce widespread vitamin A deficiency in sub-Saharan Africa.[1]

The world cannot afford to leave high-nutrient crops and crop waste in the fields. Processing and preserving

[1] https://tibbettsawards.com/sinnovatek/

at or near the field site drastically reduce or eliminate transport losses and onsite crop waste.

New Expectations: "Functional Foods"

Raw inputs for foods fall mainly into two categories: animal and plant. With animals bred for consumption, selected parts are harvested for processing into a consumer packaged product (parts not suitable for human consumption find other processed product markets). Much effort has gone into reducing possible contamination and lowering energy and water use while maximizing profits. Similar aspects are seen in plant processing: reducing the waste stream, reducing energy use, and maximizing consumer appeal while maintaining product integrity and nutrient retention.

Processing and preserving at the field site drastically reduce or eliminate transport losses.

In addition to the overall driving forces of food safety and profitability, agriculture is under more and more pressure to not only generate food but also improve consumers' health. "Functional foods" (those reported to have positive effects on health beyond basic nutrition) may offer benefits in terms of gut health, reduced cancer risk or improved resilience and recovery, better heart health and cholesterol levels, a stronger immune system, energy boosts, and brain stimulation.

To address these needs and interests, agrifood businesses are increasingly driven by research and development to ensure nutrition and support consumer health and wellness. As animal and plant R&D results in more functional foods, it becomes the food processing engineer's job to retain product function all the way to the consumer.

Advances in Packaging Technology

Canning remains the most popular worldwide mode of preservation, and it was used long before people understood its principles. Canning knowledge took decades to develop, and every year more is learned about this traditional processing technique. Novel sterilization processes for foods require a "letter of no objection" from the Food and Drug Administration before production.

Aseptic Packaging

In the early 1950s industry pioneered the technology of aseptic packaging: sterilizing the package (e.g., a plastic or laminated cardboard carton) and filling it with sterilized product under sterile conditions. This technology ensures quality retention, allows regenerative heating (saving vast amounts of process energy), and lowers shipping costs since packaging materials are lightweight compared to cans and glass containers.

During the 1970–80s, intensive industrial and academic activities were focused on developing engineering solutions to sterilize products containing particles in continuous flow (e.g., soups and stews) and packaged in a presterilized container under sterile conditions. Documenting the least heated portion of the flow was the main issue and the subject of many studies worldwide (e.g., Larkin 1997). Initially, mechanical methods were tried to "hold" the particles for a required time while the fluid passed. These methods were unsatisfactory. The early 2000s saw sensor technologies that solved the problem (Swartzel and Simunovic 2004). Systems slowly began taking advantage as regulatory hurdles were overcome.

Uniform Heating

The science needed to document the least heated spot in a processed can of food is now well developed. But challenges remain. For example, varying degrees of heat treatment are still required for a can's contents. Thoroughly heating the largest can (#10) filled with a thick puree to a safety regulation–required temperature could take as much as 2½ hours and would both dramatically overprocess the product near the can's surface and reduce nutrient quality and functionality. (Liquids, such as milk, can be heated while being pumped through the heat exchanger, rendering a near uniform treatment of the product.)

Researchers turned their interest to novel heating methods in an effort to capture the most uniform rapid heating possible; they studied systems using electric resistance, pulsed-field, and microwave heating methods. Nonthermal systems like high pressure, pulsed electric field, ultrasound, and cold plasma were examined since processing at near room temperatures was thought to preserve food quality to the highest degree. However, components like enzymes were often not inactivated in nonthermal systems and caused food deterioration during storage, or were useful only for refrigerated products with limited shelf lives.

Continuous flow microwave technology yielded many of the desired answers. It is extremely fast and has uniform heating, providing a high-quality product. It also has very low energy loss compared to conventional canning operations, and is suited to almost all types of products with or without particles and a wide range of viscosities. Today rapid cooling methods are being examined and may soon add to the benefits of rapid continuous thermal flow processing.

Shelf-stable products have extremely long shelf lives at ambient temperatures without any need for refrigerated or frozen storage throughout their life cycle—from production to consumption. With the new technologies that use continuous flow microwave, many frozen products today can easily be made shelf stable. Nonfluid products can now take advantage of sterile chamber microwave treated processing (Tang and Liu 2018). Moving product out of the freezer while preserving high quality yields multiple energy savings from shipping through distribution and preparation.

Food Processing for Tomorrow

A paradigm shift in the agrifood processing industry is way overdue. With the new tools available, how will food processing plants be transformed to meet global needs?

An integrated approach to processing, distribution, storage, preparation, and presentation will minimize labor and handling, and reduce meal component degradation and energy use, food and packaging waste, and environmental impacts. Further advantages include increased food safety, security, and convenience while adding to nutrient and quality retention.

Growth in the aseptic industry may lead to smaller processing plants close to the raw products, leaving product waste to be recycled locally or used in a local biofuels operation or as animal food. Less weight would need to be transported. Only finished goods in large sterile bags supported by reusable lightweight containers would be shipped from the processing plant.

Aseptic transfer for meal assembly does not exist, although the benefits are enormous. A multitude of organizations must work together to change the paradigm of onsite mass meal preparation and delivery.

As an example, chilled soups dominate many local restaurants in the warmer months. In most cases ingredients are combined from a washed raw state, sometimes with dairy products or other low-acid ingredients. Products are made in the morning, refrigerated, and served throughout the day. No processing and no heating step is included. What is left over is dumped. Food safety and waste issues abound.

There is another way. Rapid volumetric heating methods can render the product sterile without affecting the fresh chilled flavor that appeals to customers. Such products have unlimited shelf life, are sterile and high in nutrient retention, and create no product waste at the end of the day. Additionally, these products can be provided year round.

Fast food dominates Americans' food consumption, driven by cost and convenience. A number of operations in the fast food industry have the potential to change to yield lower costs, lower waste, higher quality, and better customer satisfaction and health.

For example, nearly all fast food restaurants (millions worldwide) sell soft serve ice cream in cones, sundaes, and milk shakes. It comes from refrigerated ice cream mix in bags. The bags are poured into a barrel freezer, where freezing times can take 30 minutes or more. A set quantity is made in each batch. At closing time any product left over is dumped and then an hour or more is needed to clean the barrel freezer for the next day. Multiple freezers are needed as flavors cannot be mixed.

Rapid volumetric heating methods can sterilize a food product without affecting the fresh flavor that appeals to consumers.

But now ice cream can be made on demand using liquid nitrogen. With this method it is never necessary to waste either unused mix or leftover product. The mix remains sterile and is dispensed as needed without contaminating the product in the bag. No product need be left in a freezer barrel, nor is so much cleaning necessary since only the filling nozzle has to be cleaned.

Food processing innovations can also benefit other industries. For example, rapid freezing can be adapted for freeze drying medical supplies (e.g., blood plasma).

The current freeze drying operation can take from several hours to days; rapid liquid nitrogen freezing followed by rapid microwave drying would decrease the time to minutes. Product damage, if any, would be minimal and costs would drop.

Food process engineering advances are leading the way to ensure that foods are safe, quality is retained, energy and waste are reduced, and new ventures and markets are captured.

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We present an urban metabolism-based systems framework to assess resource circularity at the FEW nexus to support environmental sustainability, resilience, health, and equity.

Principles for a Sustainable Circular Economy at the Urban-Regional Food-Energy-Water Nexus:

Advancing Environment, Health, and Equity

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This paper elucidates eight principles for designing a sustainable circular economy at the urban-regional food-energy-water (FEW) nexus, using a supply chain–linked urban metabolism model. Connecting in- and transboundary FEW consumers, producers, processes, and interactions in cities, the model enables analysis of sustainability outcomes related to environmental dimensions, climate vulnerability, human health, and social equity. Our design principles are elucidated by an urban metabolism systems framework and a synthesis of recent works.

What Is a Sustainable Circular Economy?

The circular economy is an amorphous concept that, overall, seeks to reduce the linear throughput of natural resources, closing material and energy loops to advance sustainability (Geng et al. 2013). The idea has received much attention,[1] yet remains fuzzy, with more than 100 definitions in the literature (Kirchherr et al. 2017).

[1] See, e.g., the Ellen MacArthur Foundation (https://ellenmacarthurfoundation.org/topics/circular-economy-introduction/overview) and the World Business Council for Sustainable Development's Circular Economy Program (https://www.wbcsd.org/Programs/Circular-Economy).

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We define a sustainable circular economy as one that leverages resource efficiency and circularity as means to advance multiple sustainability goals, which include achieving resource sustainability, reducing pollution, preserving/regenerating natural capital, and generating employment and broader benefits to human health and wellbeing, including social equity. Resource circularity is thus effectively linked with the United Nations' Sustainable Development Goals (SDGs) addressing environment, health, and equity dimensions.[2]

A sustainable circular economy optimizes the scale and sectors engaged in resource circularity to advance environment, health, wellbeing, and equity.

Circular economy strategies are generally understood to encompass the "four Rs": reduce, reuse, recycle, and regenerate. Efforts to "reduce" include behavioral changes and demand shifts as well as technology-level efficiency to reduce resource demand for goods or services. The reuse and recycle options can be achieved within the same sector (e.g., food) or via cross-sectoral exchanges/interactions (e.g., through society-level efficiencies across FEW and construction sectors). Regenerative solutions include renewable energy and nature-based solutions that offer environmental value.

A circular economy requires the development of analytic tools to measure multiple sustainability benefits of resource circularity. Another practical question concerns the spatial scale and sectors for implementation of resource circular interventions to optimize environmental and societal outcomes. For example, resource circularity may be designed (i) within individual industries (e.g., the use of waste heat from food processing industries in desiccation operations, or of farm-level manure to generate onsite energy); (ii) across two or more colocated industries ("industrial symbiosis"; Chertow 2007), as in ecoindustrial parks; and (iii) in multisectoral resource exchanges at societal scales, such as the FEW and construction sectors in cities and nations (Ramaswami et al. 2017a).

In this paper we focus on the rationale and potential for a sustainable circular economy at the societal scale of urban-regional systems, leveraging linkages across FEW sectors, households, commercial entities, and industries. We posit that a sustainable circular economy is one that optimizes the scale and sectors engaged in resource circularity to advance environment, health, wellbeing, and equity. We discuss emerging methods to quantify sustainability outcomes, and elucidate eight design principles for achieving a sustainable circular economy at the urban-regional FEW nexus, drawing on recent works.

Why the Urban-Regional FEW Nexus?

The urban-regional scale offers strategic opportunities for a sustainable circular economy, addressing the key sectors that provide food, energy, water, and construction materials to urban areas, where a majority of the world's population lives. These sectors are critical since together they contribute to ~90 percent of global greenhouse gas emissions, >94 percent of global water withdrawals, and almost all the mass of materials extracted from nature globally (Ramaswami et al. 2008; Wiedmann et al. 2013).

Evaluating these sectors at the urban-regional scale is important for many reasons:

- More than 80 percent of the US population and two thirds of the world's population will live in urban areas by the year 2050, drawing vast amounts of resources (food, water, energy, and materials) (ACERE 2018).
- The concentration and colocation of homes, businesses, and industries in urban areas provide cost-effective opportunities for exchange of "waste" resources such as industrial waste heat, municipal solid waste, and wastewater (Lu et al. 2018; Ramaswami et al. 2017a[3]).
- Globally, a substantial percentage of food production occurs within 20 kilometers of urban areas (Thebo et al. 2014), allowing for regional exchanges between cities and surrounding farmlands.

Not all regional food production serves local consumption, so a transboundary supply chain perspec-

[2] The goals are available at https://sdgs.un.org/goals.

[3] Also see the Ellen MacArthur Foundation's "Circular economy in cities: Project guide" (https://emf.thirdlight.com/link/xj9mg8hcbvd5-bropux/@/preview/1?o).

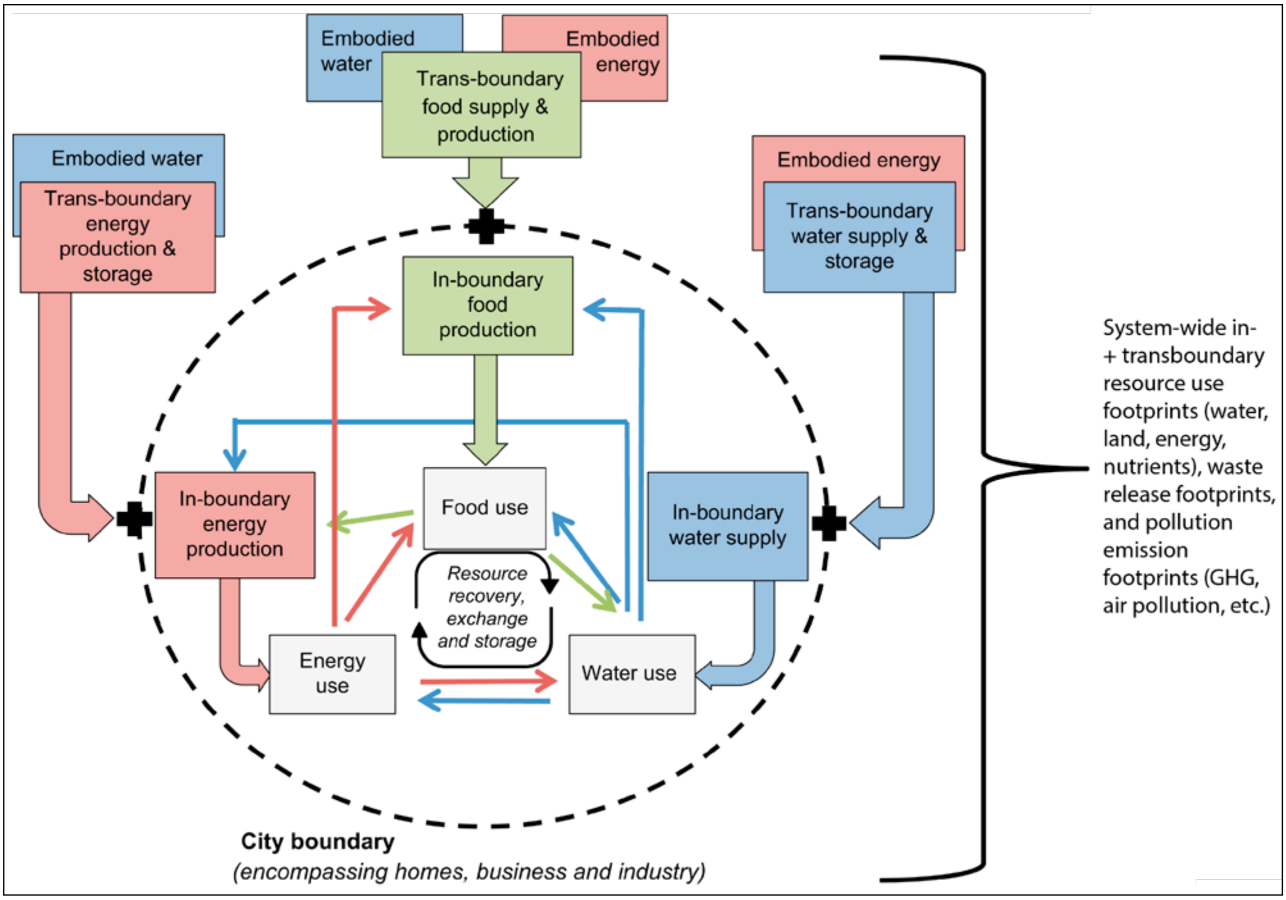

FIGURE 1 Transboundary multisector framework to analyze environmental impacts of the provisioning of agrifood (F), energy (E), and water (W) to homes, businesses, and industries in a city. The framework connects community-wide FEW demand with in- and transboundary FEW production. It also incorporates in-boundary cross-sector interactions shaping resource exchange and recovery, such as energy inputs to water use (E→W), water inputs to energy production and use (W→E), and FEW storage within and outside the city. Connecting in- and transboundary interactions informs the city's systemwide water, energy, and greenhouse gas (GHG) impacts. Reprinted from Ramaswami et al. (2017a). © IOP Publishing Ltd.

tive (Ramaswami et al. 2017a) is needed, highlighting material-energy flows and associated opportunities for circularity across the supply chain of key provisioning systems.

Figure 1 illustrates a metabolism framework of FEW flows into and out of cities. The traditional metabolism framework tracks the direct flows of materials, water, fuels, and waste in and out of cities (Kennedy et al. 2011; Wolman 1965). It has been expanded mathematically and theoretically to track resource use and emissions embodied in supply chains serving cities, resulting in different types of environmental footprints (Chavez and Ramaswami 2013), such as those for resource use (water, land, nutrients) and environmental emissions (pollution, greenhouse gases [GHG], waste). The transboundary framework shown here integrates both metabolism and footprint concepts, and further incorporates FEW linkages.[4]

Figure 1 shows the administrative boundary (dotted circle) of a city or urban area with homes, businesses, and industries that collectively exert community demand for FEW. This demand is shaped by local household diets and socioeconomic status, FEW requirements of exporting industries, and consideration of pre- and postconsumer wasted food. Only some of the local FEW demand is locally produced; the rest is imported from regional and larger supply chains (outside the circle).

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[4] The framework in figure 1 can be expanded to include material flows, which intersect with the food and forestry systems. For example, research has shown that platform chemicals, biobased plastics, and other construction materials can be produced through food waste valorization technologies (Lu et al. 2018).

These supply chains include water embodied in the production of food and energy, energy embodied in the production of water and food, and second-order effects (e.g., energy used to provide irrigation water for agrifood production, and water for the energy used to operate farm machinery).

The systems framework enables quantitative evaluation of in- and transboundary linkages across the FEW sectors, from farm production to consumption.

The systems framework enables quantitative evaluation of in- and transboundary linkages across the FEW sectors, from production at the farm level to consumption in urban homes and businesses. Mapping these flows and associated footprints is important for assessing the potential and sustainability of the resource circularity pathways.

Analysis of Circularity Potential and Sustainability

Circularity Pathways

Opportunities for a circular economy can be identified by quantifying the different flows in figure 1 to explore actions that can be taken by society. For example, application of the framework to Delhi, India, has yielded several insights (Boyer and Ramaswami 2018; Ramaswami et al. 2017a). First, the water embodied in food production was found to be a factor of five greater than direct water requirements in the community. This information highlights that dietary shifts (e.g., see the impact of rice in figure 2), opportunities to reduce wasted food, and ways to reduce wasted water in irrigation are larger "reduce" levers compared to other actions in the municipal water sector. Second, knowing the amounts of cooking fuel and gas used in the energy sector makes it possible to match food waste–to-energy projects with local energy requirements to help create a local circular economy. Knowledge of the magnitude/acreage of local agriculture is also useful for assessing the nutrient mass that can be recycled from wastewater treatment to local farms (Miller-Robbie et al. 2017).

Thus the urban FEW metabolism model with in-boundary detail and transboundary supply chains enables assessment and prioritization of the most significant circularity options.

Environmental Impacts, Trade-offs, and Cobenefits

The systems framework in figure 1 also enables assessment of the baseline environmental footprints of urban FEW provisioning by combining the mass of urban FEW demand with life cycle analysis of FEW production across the supply chain. Multiple environmental impacts (see figure 2) can be assessed—for example, on water resources, energy, GHG emissions, and land—relevant to SDGs 6 (clean water and sanitation), 7 (affordable and clean energy), 13 (climate action), and 15 (life on land). Figure 2 illustrates quantification of the multiple environmental impacts of various foods consumed in Delhi, in the base case. Methods are also evolving to quantify nutrient footprints of urban FEW provisioning by assessing nitrogen and phosphorus flows (Leach et al. 2012; Singh and Bakshi 2013).

Such baseline data on environmental impacts enable quantitative assessment of potential future circular economy interventions, as shown in figure 3 for Delhi, including the impact of household dietary shifts, urban agriculture, and technologies that reduce, reuse, or enable recycling and valorization of food waste (Boyer and Ramaswami 2017).

As seen in figure 3, there often are trade-offs among the different environmental outcomes (water, GHG, land), requiring prioritization by decision makers.

Supply Chain Vulnerability, Climate Risks, and Resilience

Supply chain analysis, aided by spatial delineation (figure 1), enables assessment of the resilience of FEW supplies to cities. For example, spatially delineated supply chains in Delhi (Boyer et al. 2019; Ramaswami et al. 2017b) revealed the high-water vulnerability of all transboundary regions supplying food to the city as well as local agriculture, all occurring in conditions of severe ground water overdraft. And supply chain analysis during drought events in the United States over a 200-year period found that urban areas with diversified food supply chains were more resilient (Gomez et al. 2021). Similar supply chain analyses have been developed to

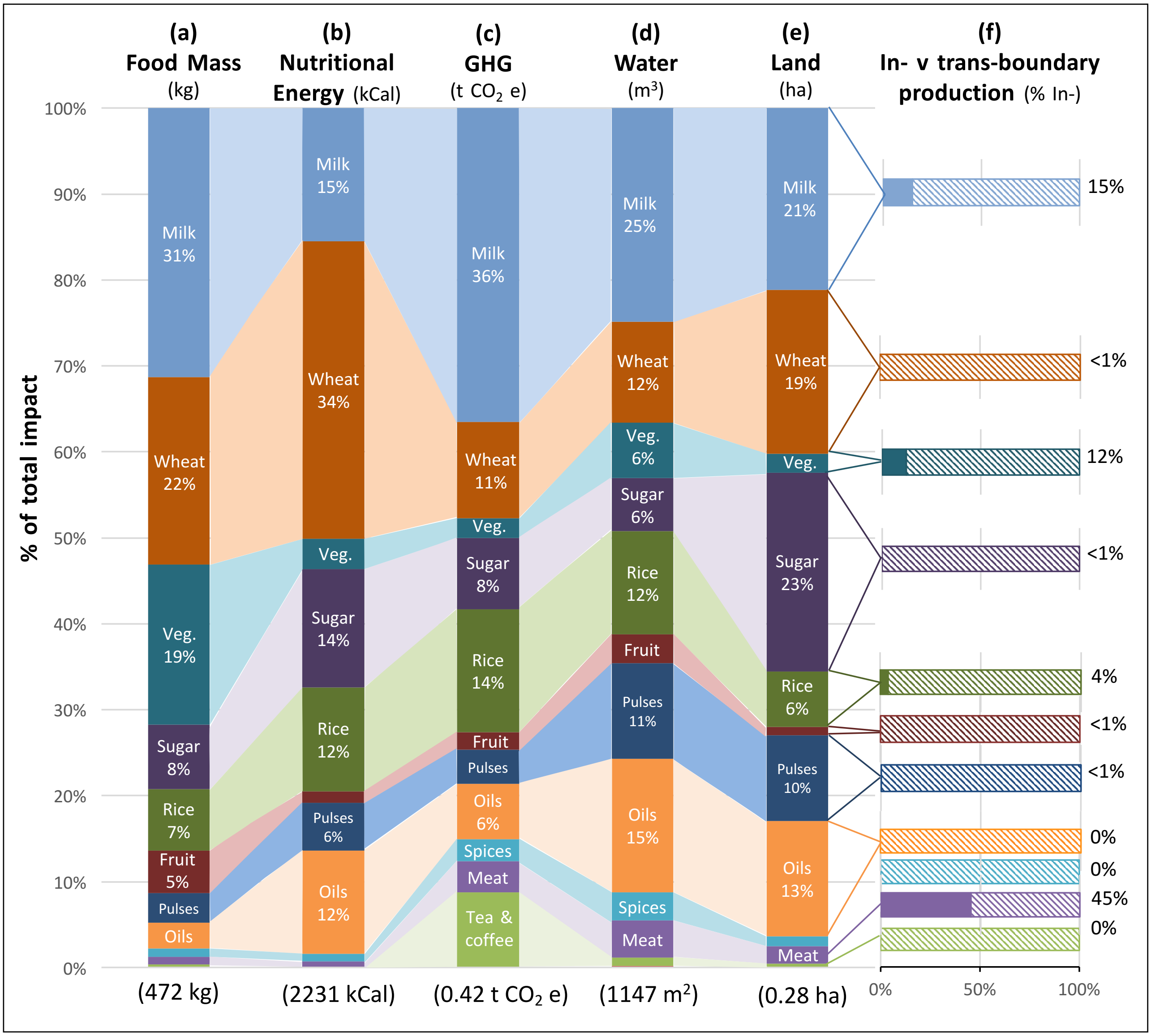

FIGURE 2 Mass, nutrition, and environmental dimensions of annual food supply to Delhi, India, derived from the systems framework in figure 1. Distribution of various foods by (a) food mass, (b) nutritional energy (calories), (c) greenhouse gas (GHG) footprint (including energy use and agriculture-based emissions, tons of CO_2 equivalents), (d) consumptive water-loss footprint (cubic meters), (e) land footprint (hectares), and (f) distribution of these impacts as in- or trans-boundary (in, solid; trans, shaded). veg. = vegetables. Reprinted with permission from Boyer and Ramaswami (2017). © American Chemical Society.

assess the vulnerability of energy supplies to cities in light of projected climate change, which affects precipitation patterns relevant to hydropower generation and cloud cover relevant to solar power generation (Miara et al. 2019). Such analyses are critical to SDG 11, which calls for developing sustainable climate-resilient cities.

Inequality, Health, and Equity

The urban metabolism model illustrated in figure 1 enables assessment of multiple dimensions of inequality. For example, in many Indian cities, dietary intake represents a high level of inequality and deprivation relevant to the UN's SDG 1, zero hunger: the percentage of urban populations with protein- and calorie-deficient diets is as high as 70 percent and 90 percent, respectively, in some cities (Boyer et al. 2019). Future scenarios therefore not only explore more equitable diets that enhance nutrition for the underserved but also reduce environmental impacts by both switching to low-intensive yet nutritious crops like sorghum and managing

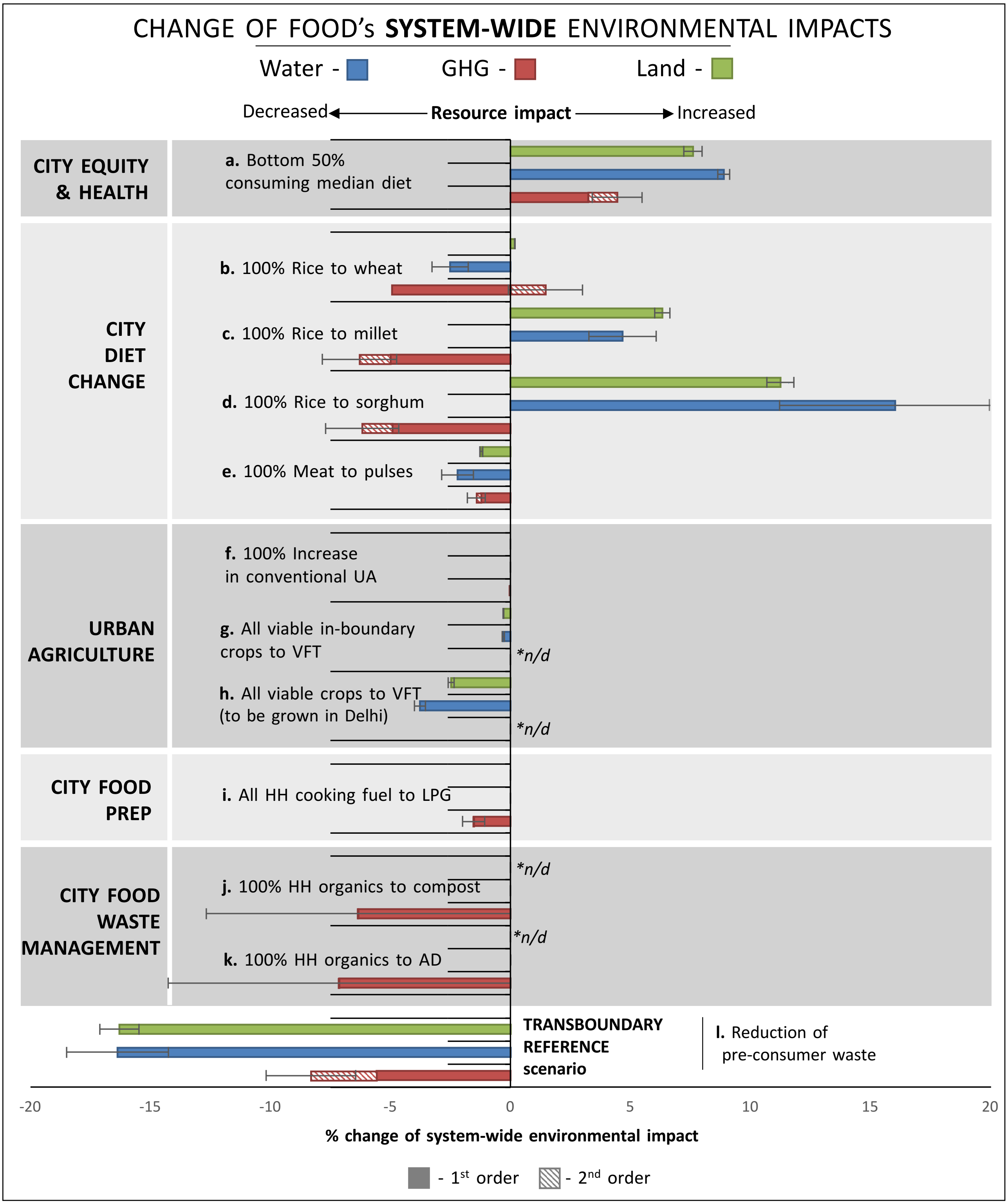

FIGURE 3 Scenario analysis of several circular economy "4R" interventions in Delhi's food system, showing impacts on various environmental outcomes. Percent reduction of annual systemwide food-related water (blue), greenhouse gas (GHG; red), and land (green) impacts shown as a result of 100% adoption of food system scenarios. Expressed in terms of 1st order (solid bars) and 2nd order (shaded bars) impacts. *n/d = insufficient data to determine a result. Error bars represent range of intensity factors and technologies for each scenario. AD = anaerobic digestion; HH = household; LPG = liquefied petroleum gas; VFT = vertical farming technologies. Reprinted with permission from Boyer and Ramaswami (2017). © American Chemical Society.

irrigation and food waste (Boyer and Ramaswami 2017; Davis et al. 2018).

Larger-scale models in the United States have tracked county-level farm fertilizer application, associated transboundary windblown air pollution emissions, and premature disease burden and mortality, finding substantial inequality across counties by income and race (Tessum et al. 2019). By assessing the distribution of burdens across social strata, the studies cited here provide the criteria for designing more equitable interventions that reduce burdens on the most vulnerable in society.

Designing a sustainable circular economy calls for careful consideration of equity. In addition to unequal air pollution exposure and access to nutritious food, who gains from new employment generated through resource circularity technologies? Who loses jobs? What is the quality of jobs lost—and created? What are the trade-offs with the increasing use of robots and artificial intelligence in precision agriculture? Will indoor agriculture displace (often lower-income) farm workers? How many jobs may be generated in other sectors, such as construction or AI?

BOX 1 Eight principles for a sustainable circular economy at the urban-regional food-energy-water nexus

1. Connect consumption, production, and waste across supply chains to get a systemwide perspective of resource circularity options.
2. Evaluate opportunities for resource circularity at societal scales, both within and across sectors and city boundaries.
3. Use per capita or regional analysis to assess potential for circularity, matching magnitude of resources from one application to another.
4. Consider sequential resource circularity processes that can create opportunities for virtuous cycles.
5. Pair technoeconomic analysis with evaluation of multiple sustainability outcomes.
6. Recognize that trade-offs and cobenefits may occur within and across sustainability outcomes.
7. Develop multiscale nationwide models of resource circularity to identify the most suitable spatial scale for operationalizing the circular economy.
8. Engage in multiscale cross-sectoral knowledge coproduction to help design sustainable and equitable circular economy transitions.

Eight Principles for a Sustainable Circular Economy

Based on the concepts and case studies summarized in the figures, we delineate eight principles to design a sustainable circular economy at the FEW nexus (box 1), with some examples to highlight these points.

1. *Connect consumption, production, and waste across supply chains to get a systemwide perspective of resource circularity options*. Such a systemic approach can demonstrate the combined impacts of behavioral changes, adoption of economically viable vertical farming technologies, and food waste valorization technologies (figure 3). These areas represent the spectrum of 4R strategies involved in circularity, with the systems framework explicitly connecting consumption in cities to transboundary agricultural production.

2. *Evaluate opportunities for resource circularity at societal scales, both within and across sectors and city boundaries*. In many cases transboundary nexus linkages, though not directly visible within cities, can contribute to better urban sustainability outcomes. For example, transboundary irrigation management with solar-powered pumps that feed excess electricity back to the grid can be very effective in advancing energy conservation, water conservation, and decarbonization in India. Likewise, application of food waste nutrients and biochar may be limited to the fewer and smaller farms in dense urban regions (e.g., Miller-Robbie et al. 2017), but can be maximized when applied regionally to farms with greater land area for regeneration.

3. *Use per capita or regional analysis to assess potential for circularity, matching magnitude of resources from one sector to another*. Recycling requires matching waste quantity and quality with suitable reuse, often with further treatment or valorization to useful products. The maximum potential for reuse and valorization requires a combination of material-energy flow analysis with life cycle assessments. Currently, life cycle analysis of food waste technologies is conducted per unit of waste to choose among valorization technologies and pathways (e.g., Hodge et al. 2016), and requires data on the mass of virgin resources that can be substituted to maximize circularity. Studies have demonstrated ways to match the supply and demand of waste heat across sectors in cities (Ramaswami et al. 2017a; Tong et al. 2017).

4. *Consider sequential resource circularity processes that can create opportunities for virtuous cycles*. Biochar from

wood and food waste (Lehmann and Joseph 2021), for example, can be a net carbon negative due to post-pyrolysis production of fuel (oil and gas); the impact can be multiplied by beneficially applied biochar at suitable rates to selected soil types to enhance plant growth (Guo 2020). Another example of sequential circularity (being quantified in the Urban Nexus Lab at Princeton University) is the upgradation of spent coffee grounds to grow mushrooms (Dorr et al. 2021), followed by substitution of mushrooms for beef in hamburgers, significantly reducing GHG emissions (Waite et al. 2018). These virtuous cycles have a cascading effect that reflects the power of the circular economy.

5. *Pair technoeconomic analysis with evaluation of multiple sustainability outcomes*. Outcomes should include environmental impacts, vulnerability/resilience, and multiple dimensions of equity, using a metabolism approach with spatially delineated supply chains (figure 1 and accompanying text).

6. *Recognize that trade-offs and cobenefits may occur within and across sustainability outcomes*, including environmental and equity dimensions. For example, figure 3 illustrates that certain dietary shifts may reduce GHG emissions while increasing land or water impacts. Trade-offs can also affect equity dimensions such as nutrition access, pollution exposure, and/or employment.

7. *Develop multiscale nationwide models of resource circularity to identify the most suitable spatial scale for operationalizing the circular economy*. The most suitable scale for implementing a circular economy can be determined only by modeling exchanges at multiple scales and comparing them. For example, resource use occurs in cities, at a regional scale, and at state and national scales based on both the value added of the product and the economy or ease of transporting materials over large distances. Multiscale modeling is essential to help identify the most suitable scale for achieving a sustainable circular economy.

8. *Engage in multiscale cross-sectoral knowledge coproduction to help design sustainable and equitable circular economy transitions*. Given the unequal impacts of circular economy transitions on society, with implications for equity, the design of sustainable circular economy transitions cannot be done by scientists or researchers alone. A combination of technical analysis combined with democratic deliberation is needed (Stern 2005), enabled by the practice of coproduction (Norström et al. 2020). Coproduction—defined as meaningful, context-specific, iterative, and goal-oriented collaboration among researchers and a broad swath of decision makers (Norström et al. 2020)—can provide a framework to engage stakeholders important to enable sustainable circular economy transitions at the FEW nexus. The actors must themselves transcend scale and be appropriate to the FEW nexus context.

Conclusion

Together, our eight design principles can advance sustainability at the urban-regional FEW nexus, addressing environment, supply chain resilience, health, economy, and equity. Real-world codesign of solutions with multiple stakeholders in communities is essential to realize the potential of a sustainable circular economy at the urban-regional scale.

Implementing the eight principles will require concerted action by all sectors of society. Starting with individuals, consumer behaviors profoundly shape the metabolism of cities through dietary changes. For example, reducing meat consumption can dramatically reduce environmental burdens at the FEW nexus. To design systemic solutions, both academic units and professional societies should teach, research, practice, and disseminate the systems concepts outlined in the framework (figure 1) underlying the principles. Collaboration among researchers, policymakers, and industry practitioners is essential to develop practical metrics for sustainable and equitable resource circularity. Community groups must be engaged at every level to ensure that metrics relate to equitable outcomes. Engineers and scientists must embrace multisector partnered projects that transcend disciplinary boundaries, sectors, and spatial scale to harness opportunities at the urban-regional FEW nexus.

Acknowledgments

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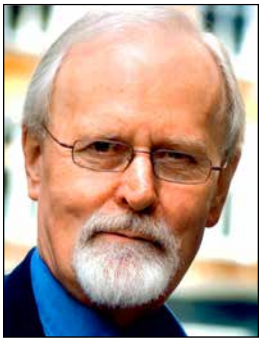
A facilitating policy framework is essential to capture the benefits of science and engineering for improved food systems.

Science and Engineering to Transform Food Systems:

The Role of a Facilitating Policy Framework



Per Pinstrup-Andersen is professor emeritus, Division of Nutritional Sciences, Cornell University, and adjunct professor, Copenhagen University.

Per Pinstrup-Andersen

As discussed in this issue of *The Bridge*, science and engineering offer tremendous opportunities for reforming food systems to improve human and ecosystem health. Impacts are likely to be enhanced if food system interventions are undertaken within facilitating policy frameworks. In this article I consider how government policy may facilitate innovation, technology development, knowledge creation, and their application to improve food systems.

I begin with a brief definition of what is generally meant by the term "food systems." Then I survey some of the major current and future challenges confronting food systems, and suggested goals, to provide the background for a discussion of a facilitating policy framework.

What Is a Food System?

A clear definition of a food system is critically important before embarking on its transformation. Unfortunately, there is no agreement about such a definition, either among the relevant major players or in the literature. The definitions and descriptions of food systems vary from a narrow focus on food and agricultural supply chains to inclusion of virtually all aspects of a national economy. The former is likely to miss important opportunities for improvements, while the latter basically calls for an overall economic transformation in the name of a food system transformation.

I define a food system as a dynamic system comprising all food-related activities and the people who participate in them (Pinstrup-Andersen and Watson 2011). The system operates in natural, political, and socioeconomic environments and is affected by social and economic changes brought about by public policy and action by the private sector and civil society as well as forces such as globalization, urbanization, climate changes, and technological advancement. Thus, efforts to transform food systems may aim at changes within or outside the systems themselves.

I define a food system as a dynamic and behavioral system comprising all food-related activities and the people who participate in them.

Challenges Confronting Food Systems

Challenges confronting food systems are context-specific and policy interventions should be tailored to the relevant contexts. From a global perspective, the following four challenges appear to be of greatest importance in terms of both current threat and a worsening trend:

- widespread and increasing food insecurity, nutritional deficiencies, and obesity in large segments of the world population, and related premature death, poor health, reduced labor productivity, and increasing international and national instability
- deterioration of the stock of natural resources, including water, soil, and biodiversity, needed to ensure future productive capabilities for food as well as the maintenance of nature for its own sake (e.g., undeveloped forests, marshlands, prairies, rivers, and coasts)
- climate change, which both influences and is influenced by food systems
- the rise of antiscience sentiments and rejection of science-based evidence in decisions related to food systems.

What Should Food System Transformations Achieve?

The United Nations' Sustainable Development Goal 2[1] provides an overall answer to the question above: End hunger and malnutrition, and double sustainable agricultural production among smallholder farms by 2030. In its *Voluntary Guidelines on Food Systems and Nutrition* (CFS 2021, p. 13), the UN Committee on World Food Security suggests that policies and actions to transform food systems should

- "enhance the livelihoods, health, and wellbeing of populations";
- encourage "sustainable food production and responsible consumption of safe, diverse, and nutritious foods to enable healthy diets";
- "protect and promote sustainable use of natural resources, biodiversity, and ecosystems"; and
- "support mitigation of and adaptation to climate change."

I suggest that a more specific and operationally useful set of goals for policy and other action to transform food systems, in all contexts, might consist of

- a significant increase in the percentage of the population, covered by the food system in question, that consumes a healthy diet;
- a significant increase in the capacity of the total resources available, both natural and human-made, to meet future demand for healthy diets; and
- no significant damage to the intrinsic value of nature (i.e., independent of its value for productive purposes).

These goals would focus on trends (rather than quantitative goals), while (i) taking into account both human and environmental health, sustainability, and opportunities for trade-offs and substitutions between natural and human-made resources and (ii) recognizing the intrinsic value of nature (as explained above). Context-specific policies, projects, and actions could then replace "significant" with quantitative goals and timelines.

A Suggested Facilitating Policy Framework

In a market economy, food systems are influenced by decisions made by millions of consumers, traders,

[1] https://www.un.org/sustainabledevelopment/hunger/

farmers, government officials, policymakers, and a variety of other agents operating within and outside the systems. For policy interventions to be successful in achieving their goals, they must fit the reality within which these decision makers operate and their priorities.

Policymakers' Resource Constraints and Decision Space

Decisions related to food systems are facilitated or constrained by the resources available to decision makers, as well as the demand for their resources for other purposes and their goals and relative power. Policymakers' decisions are particularly important because government policy can influence decisions and behavior through incentives, regulations, and sharing of knowledge. But governments are confronted with many demands for policy interventions and those of greatest importance for food systems may not be at the top of the government's list of priorities. Therefore, policy action to improve food systems should be designed with a clear understanding of these other priorities to seek win-win outcomes.

The relative power and decision space available to each decision maker or group can be changed through legislative action and resource allocations. A facilitating policy framework is particularly important to support the impact of science and engineering on food systems.

In some cases, as illustrated by the behavior of many governments toward genetically engineered food and agricultural commodities, government rules and regulations influenced by antiscience and/or antimarket lobbying groups may be a major hindrance to achieve potential positive food system effects from research and development. This has been particularly important in legislation related to so-called GMOs (genetically modified organisms), based on gene transfer between species, while the more recent gene editing within a given species has received less—but nevertheless significant—opposition.

Accounting for Externalities

While the nature and content of policy frameworks as well as the specific policy interventions for food systems are context-specific, the most important role of policy in all market economies is to correct for externalities and other market failures through regulations, incentives, or knowledge creation and dissemination.

Externalities occur when total social costs or benefits are only partially reflected in market transactions. For example, environmental costs embodied in lowering ground water levels, reducing biodiversity, depleting cropland nutrients, or expanding greenhouse gas emissions may not be reflected in the cost of food production and processing. Neither may malnutrition and human health costs associated with obesity, diabetes, and other related chronic diseases.

The most important role of policy in market economies is to correct for externalities and market failures through regulations, incentives, or knowledge creation and dissemination.

Failure to endogenize the cost of natural resource degradation in the production costs and consumer prices in virtually every country is resulting in huge costs to societies and future generations. Similarly, productivity losses and health costs caused by the consumption of unhealthy diets may result in large costs to societies and individuals. Other market failures, such as skewed market power and related lack of competition, may require government intervention.

Policy Interventions

A variety of policy interventions are available to governments, such as commodity-specific taxes and subsidies, public investment in both research and knowledge dissemination related to alternative production and processing methods, and consumer-oriented educational campaigns to promote healthy diets. Public and private investment in innovation and awareness regarding nontraditional foods (such as—in the West—edible insects, seaweed), and policy interventions to facilitate greater availability of nutritious processed foods and reduction of nutritionally harmful foods, may play an important role. Policy to facilitate a shift from animal-sourced to plant-based foods, in societies where the former constitutes a large share of the diet, can incorporate results from science and engineering to improve diets and sustainable management of natural resources.

A policy framework should guide and facilitate research and technology development for the food system through public or private funding and exclusive rights policies, such as patents and copyrights, or open access in the form of public goods.[2] Past agricultural research and technology developments, such as those of the Green Revolution, have been key to the rapid expansion of yields per unit of land and water, unit-cost reductions, and increased production of food staples. Government policy, including investments in road and water infrastructure and market facilities, played a major role.

Governments can facilitate subsidized access to innovation in health care and nutrition for healthy diets for low-income consumers and farmers.

Whereas the research that resulted in the Green Revolution was undertaken primarily by public sector institutions and financed primarily by public sources, recent opportunities for obtaining exclusive rights to research outcomes from genetic engineering and gene editing brought the private sector into play. That led to a need for different types of government policies, and private-public partnerships became more widespread. At the same time, though, antiscience sentiments developed in many societies, in part based on opposition to large corporations perceived as gaining "control" over future food supplies and the misplaced perception that smallholder farmers would be unable to get access to the new technology.

Defining an Effective Policy Framework

Knowledge Dissemination and Use

A policy framework for the food system should facilitate access to knowledge and technology among potential users, including food producers and processors, and promote evidence-based decisions among stakeholders. Government action is needed to negate the impact of misinformation related to food systems, including well-funded campaigns against the use of modern science in agriculture (e.g., genetic engineering and editing [CRISPR] and food processing), and the rejection of science-based evidence. Governments can play a particularly important role by facilitating subsidized access to results from innovation in health care and nutrition for healthy diets for low-income consumers and farmers.

Investment

The benefits of past and current investment in innovation and technology development and dissemination are illustrated by very high social rates of return from such activities. Persistent underinvestment calls for urgent attention by governments. Such attention should focus on either expanding public funding for research and technology to generate public goods (e.g., new knowledge available to all) or protecting the rights of private sector research entities for producing private goods (e.g., improved crop varieties or healthy processed foods).

Public-private partnerships, involving some public funding, may be needed to ensure access to private goods by low-income farmers or consumers.

Incentives

An effective policy framework should be able to change the behavior of various stakeholder groups through changes in relative prices and/or costs, income, and other incentives. Such incentives may be macroeconomic, such as monetary and trade policies, or microeconomic, such as taxes, subsidies, and related fiscal policies. The specific nature of the interventions would depend on government objectives, for example

- substitution of plant-based for animal-sourced foods,
- improved efficiency in input use through the promotion of precision agriculture,
- climate-independent and water-saving production of certain food commodities by means of vertical production,
- enhanced access to water for agriculture through desalination, or
- agroecological or organic agricultural production methods to improve food system sustainability.

[2] A public good is available to all (nonexclusive) and nobody can diminish its availability to others (nonrival).

Support of Healthy Diets

Past single-minded emphasis on increased production of grains, root crops, and other calorie-rich foods, headed by the Green Revolution, was very successful in preventing predicted mass starvation in Asia and elsewhere. It is now high time to address widespread micronutrient deficiencies, excessive calorie intake, and related negative health issues. Efforts are underway but much research and policy are still guided by maximization of the production of calories. A redirection of science, technology, and policy toward the production of a portfolio of foods that provide the foundation for diversified, healthy diets is urgently needed.

Context-based Prioritization

There are, of course, many other priorities for government policy related to innovation and technology development and dissemination, including alternative energy sources (e.g., solar panels, wind, biofuel), reduced food waste and losses, antimicrobial resistance, and animal welfare. All of these have large potential effects on food systems.

Bottom Line

A facilitating policy framework is essential to fully capture the benefits of science and engineering for improved food systems.

Current and future food systems depend on the decisions and actions of a variety of stakeholder groups, including governments, and individuals. Governments have four tools at their disposal to influence decisions and actions by other stakeholder groups: They can change the incentives for stakeholder groups, regulate their behavior, change resource allocation and facilitate investment in research and development, and disseminate knowledge. These tools can be used to enhance innovation, knowledge creation, and technology application for food systems.

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An Interview with . . .

Shahrokh Yadegari, Electrical Engineer and Composer

Photo credit: Erik Jepsen

RONALD LATANISION (RML): Good afternoon, Shahrokh. Thank you for talking with us. I understand you're an electrical engineer, but you've taken tremendous interest in musical production and modern dance, which clearly go way beyond typical engineering. Tell us a little about your history and how you came to study electrical engineering and then how you made the transition from the engineering world to modern dance and music.

SHAHROKH YADEGARI: I'm from Iran. I was in one of the first groups who left in 1979 right after the revolution. I was on the first flight out of Iran because I had all my papers and visa and ticket.

In Iran, in general, you become a doctor or an engineer before you think of anything else. Music is usually not among the professions that you would pick for your life. So music was generally important for me, but I never thought about it in terms of my profession.

After I left, within about 3 years, I earned my bachelor's degree in electrical engineering. One interesting point is that I never finished my high school. Purdue University knew my high school back in Iran and they accepted my 11th grade education for enrollment. It was very kind of them. To this day, I am very grateful to them because at that very difficult time they also provided a scholarship for me.

But when I graduated, I thought, 'What did I do?' Because as much as I am good in math and love engineering, I had this sense of art in me and I wanted something else.

While I was at Purdue I got interested in Unix, the operating system. It was not part of my studies since I was an electrical engineer, not a computer engineer, and at the time software engineering didn't really exist so much. But I got very interested in it, and shortly after I graduated I started working in a computer company.

At the same time my musical interest grew. Maybe 7 or 8 years later, I heard about the Institute for Research and Coordination in Acoustics/Music (IRCAM), in Paris. I was searching for a topic to go back to school and do a PhD with some research in an area that was my passion. This was a way for me to mix my musical interests and my electrical engineering and computer science background. But at IRCAM I immersed myself in the world of music and decided I wanted to make music the center of my life and my profession.

RML: Did you say you practiced as an electrical engineer for 7 or 8 years?

DR. YADEGARI: Yes, although my electrical engineering was in communication, and I worked more as a Unix software kernel engineer. But the electrical engineering helped my process of research in computer music because computer music includes a considerable amount of digital signal processing and requires understanding of the physical properties of sound.

Shahrokh Yadegari is vice chair of the Department of Music at the University of California, San Diego, where he is also associate director of the Qualcomm Institute and director of the Sonic Arts Research and Development group. This interview took place January 12, 2022; it has been edited for length and clarity.

At IRCAM, it became clear that I wanted to follow my passion. Although it was somewhat of a long and slow process to change, I was lucky to meet a lot of fantastic artists. Sometimes I feel my life is more of a nonlinear dynamics process than a single function. At first, it was a matter of connecting computers and algorithmic composition. Over time, that connected me to critical theory, partly because the heart of my search was based on Persian poetry.

In Persian culture, with almost everything you touch, at the end you arrive at poetry. Especially in the arts—even things that you may not imagine, like carpet making, eventually connect to poetry; and Iranian music is fully based on poetical structures. In that sense, the poets of Iran are the philosophers. In the West the separation of poetry and philosophy goes back probably to ancient Greek times. But in Iran, to this day, the poets are revered as people who carry understandings of the culture and the deep ontology of what it means to come from that culture.

I was very attracted to the poetry of Omar Khayyam because he had a very scientific approach to understanding the world. He didn't believe in anything metaphysical. He understood that we come from the earth, and we go back to the earth. In so many poems, he described the fact that, if you are holding and drinking from a cup of wine, you're holding your ancestors and you're holding what you will become. Be respectful of this cup. This is all symbolic as well. The cup comes from the earth which is the bodies of human beings and the wine in it is the soul of human beings.

If you look at the world without metaphysics, nothing exists. You cannot make any statement about anything except the friendship you have for somebody you love. And that love becomes the heart of poetry.

Khayyam left very little poetry. But so many of our poets are inspired by him.

CAMERON FLETCHER (CHF): Shahrokh, many of our readers will be familiar with Omar Khayyam, particularly the *Rubáiyát*. If people go to their shelves and pull out their copy of the *Rubáiyát* or Google it, will they find in it what you are talking about? Are there any particular passages, or any other works of his, that illustrate what you are describing?

DR. YADEGARI: Yes, it is in there, and there is a lot of writing about it as well. In fact, this became the heart of my PhD dissertation, on the union of poetry and philosophy through self-referentiality.

When Khayyam talks about this idea of human beings coming from the earth and the earth becoming us, he is talking about the circulation of matter. His idea of the world, as I said, was very scientific—he was a mathematician and astronomer and extremely precise. He measured the time of rotation of the Earth around the Sun to, I believe, the 16th decimal. He came up with a calendar that is about 2 seconds every 32 years more accurate than the Gregorian calendar. Bertrand Russell said that Omar Khayyam was the only person he knew of who was truly *both* a scientist and a poet.

The connection here is that while I was searching on this path of connecting music and computers and the concept of algorithmic composition, I came across the book *Gödel, Escher, Bach: An Eternal Golden Braid* by Douglas Hofstadter. It talks about recursion and I suddenly saw that this is exactly what Khayyam was talking about. I always thought about the relationship between sound and music, which in the arts generally become the message and the medium, or semantics and syntax, a separation of the content from the message.

All these concepts started me thinking about how I could incorporate the two together. That almost became my thesis work at MIT's Media Lab.

I was searching on a path of connecting music and computers and the concept of algorithmic composition, and found similarities with fractals.

I worked on a synthesis method that did not differentiate between sound and music. I applied certain structures as rewriting rules very similar to the Lindenmayer or L-system, which is used for modeling plants. At the time I didn't know what fractals were, but as I started working on this I learned about them and found considerable similarities.

My search through this musical and then philosophical process connected me to the concept of self-referentiality. Years later I came to a critical understanding of self-referentiality, which I found in the work of Kierkegaard and Nietzsche as well. Kierkegaard wrote a book called *Repetition* that talks about the same structure, same type of understanding of the world, about how we understand God, how we understand faith, and how we engage with it. All of these concepts made sense to me readily.

I followed this on a very intellectual level. At the same time, art was a vehicle for me to engage with the concepts, and I ended up thinking about music as a way of life.

There is a book by Christopher Small, *Musicking: The Meanings of Performing and Listening*, in which he says we should think of music as a verb. It is an action and all those involved in the process of music are making music. He also argues that to be a musician, you have to live music. That became sort of my motto.

The concept of self-referentiality changed mathematics and also applies in music, where you're looking for something that is both deterministic and random.

I was working with nonlinear dynamics and the concept of self-referentiality. I believe one of the first times self-referentiality was found in nature was in the 1960s,[1] and that had a major impact on mathematics. Many people started finding new ways of looking at mathematics. It also had an impact in music, because in music you're always looking for something that is deterministic, but random at the same time. Chaotic behavior is like that, and so is the 1/f noise, which you can find in so many different phenomena—right at the cusp of something being deterministic or completely random.

RML: This is very interesting because you're addressing one of the questions we would have asked you, and that is, How did your training as an electrical engineer or computer scientist inform your interest in music and the arts? You're telling us in ways that are not only palpable, but inspirational. You are remarkable.

DR. YADEGARI: I appreciate that. Thank you.

RML: I want to understand the origin of this intersection for you. Were your parents musicians? Were they poets? How did your interest in putting all of this together come about?

DR. YADEGARI: My mother sang and played music. But in Iran, it used to be hard to find professional musicians. In some sense, everybody is a poet. Poetry is a common tool. You may go to a grocery store and if something happens, the grocer may say something about it in poetry. And sometimes complaints are easier said in poetry because it is a very kind way of mentioning something.

Poetry is everywhere in Iran, not only in high scholarly form but also in a common colloquial format. Poetry lives with you. It's in the music on the radio and television—all from a really vast source of poetry made in the past thousand years.

The interesting thing about poetry in Iran is that the Persian language really hasn't changed much in the past thousand years. One of the well-known poets is Ferdowsi. He lived about 1000 years ago, at a time when the Persian language was in great danger because of the Arab invasion. People were not allowed to speak Persian and the language was dying. Ferdowsi spent 30 years writing an epic poem, *The Shahnameh*, that is the history, the culture, and the mythology of Persia in this one book. It is probably the longest poem in human history—60,000 lines. The language of that poem is to this day alive in Iran. Anybody can quote from those lines and everybody understands.

There is in Iran a culture of revering poetry—it is so treasured that it is the source of many different art forms. Every song in Iran had and still has that kind of poetry connected to it. In that sense, the lyrics of music you might hear have a very long history connected to the ontology of Persians' understanding of where they come from.

Another important Persian poet is Hafez. Even Nietzsche wrote him an admiring letter. Goethe as well wrote to Hafez that 'you understand so much of all human emotions.'

To illustrate how essential poetry is in Iran: Usually, the Bible or the Koran is the most owned book in a culture. Hafez wrote one single book—and in Iran you

[1] Lorenz EN. 1963. Deterministic nonperiodic flow. Journal of the Atmospheric Sciences 20(2):130–41.

will find more copies of that book than of the Koran. For the Persian new year, people create a little altar with items that have meaning for them. Some people put the Koran, but almost everybody puts a copy of Hafez—that's how important his work is in the culture.

Omar Khayyam, too, even though it's not exactly clear how many of the poems in the *Rubáiyát* were written by Khayyam himself. Some scholars argue that only 20 of the quatrains were written by him. That's all we can be 100 percent sure of. Others say 70 of the quatrains were written by him and that other people wrote and put his name on the others.

CHF: This sounds like the arguments about Shakespeare's authorship.

DR. YADEGARI: Yes. We argue sometimes that the role of Shakespeare is very similar to the role of poets in Iran.

RML: I have a bit of an aside. My father-in-law, during the Second World War, flew in B17 bombers and was shot down over Germany, where he spent about a year and a half in a prisoner-of-war camp. During that time, he memorized the *Rubáiyát*. I don't know how long it is, but he memorized it. When I met his daughter and I was courting her, he used to quote from the *Rubáiyát*.

DR. YADEGARI: Fantastic.

RML: I was blown away by this. He was quite a remarkable guy in many ways. I don't know how he got a copy of the *Rubáiyát*, but he had time on his hands and memorized it.

CHF: What an amazing intersection with this conversation, Ron. Shahrokh, I want to come back to your mention of the poet Ferdowsi. Is it his work on which you collaborated with Sia Nemat-Nasser[2] on *The Scarlet Stone*[3]?

DR. YADEGARI: It is, exactly. Just this week I was with Sia's family and we all remembered the soul that he was. But my feeling is that he never dies. He's always in our minds and what we remember of him is part of him. He was larger than life. He had such an effect on me.

CHF: Does his influence continue in your creative work?

DR. YADEGARI: Absolutely. I'm working on the next story by Ferdowsi, called *Siavash* (Sia's full name, Siavouche, is a variant in the spelling of this name). The story of Siavash is the story of a very special human being who was very ethical and understood why he was on Earth. He was a prince, the son of a king, but the character had become to me the ultimate sign of humanity. It's a very old story, about 5000 years old. Ferdowsi found it and included it in his epic poem *The Shahnameh*. Sia was that kind of a person. He didn't really believe in religion that much, but he was an extremely ethical man. He cared deeply about people and he was very active in the process.

We met at the pool at UC San Diego—he was a very good swimmer. We started having conversations and got to know each other. Sia was a fan of *The Shahnameh* and actually translated a considerable amount of it.

There is also a book by a contemporary poet who wrote about what happened in the revolution.[4] He used *The Shahnameh* as both a poetic form and a methodological source to tell his story. He based it on the most famous mythological story of Iran, the story of Rostam and his son Sohrab, whom he killed in battle almost in ignorance, although the judgment is out whether they really didn't know each other in the moment.

RML: I understand that Sia was a major benefactor or sponsor of *The Scarlet Stone*?

DR. YADEGARI: That is correct. I can explain the background of the endowed funds that Sia established. He was the son of Roghieh Chehre-Azad, who was the first woman in Iran to take off her hair covering on stage. Chehre-Azad means "free face," because she freed herself from wearing the veil; she picked this stage name. She faced numerous threats for performing in public without the veil. But Sia's father stood against them and said 'No, she is my wife and she's doing what I am telling her to do and it's completely fine by me.' He truly fought for her to be able to do this.

She became a very important actress in Iran. Because she often played the role of mother, she's understood as the Mother of Theatre in Iran.

Sia wanted to establish a fund for remembering the name of his mother. After coming to one of my performances, he called me. He had heard a comment by one of the UC presidents who said "Our businesses are doing well, but who is going to pay the salary of the English

[2] NAE member Sia Nemat-Nasser (1936–2021)

[3] https://scarletstone.com/

[4] *Mohreye Sorkh* (1995) by Siavash Kasrai.

Photo of *The Scarlet Stone* performance. Photo credit: Jim Carmody.

department?"[5] Sia told me, because of that, 'I want to put money in the arts and support your work.' I was speechless at this generosity. He contributed over the years and eventually we had a discussion with our chancellor and Sia argued for a visiting professorship to be set up. Now it is the Chehre-Azad Visiting Professorship Fund.

RML: I'd like to go back to *The Scarlet Stone*. As I understand, Shahrokh, you directed it and composed the music.

DR. YADEGARI: Yes, and I designed the sound.

RML: I've seen some videos of it and the production is fantastic. But I've seen it described as a "computer-enhanced" rendition of Iranian poetic art. How is it computer-enhanced?

DR. YADEGARI: It's about how the media is delivered, mostly in graphics and in the sound.

The tradition of telling the story of *The Shahnameh* is called *naqqali*, a style that mixes poetry and theater together. It was often done in a very small space like a tea house while people gathered around. There might be a painting at the back, showing one of the stories of *The Shahnameh*. The storyteller, the *naqqal*, would talk about this painting and in the process tell one of the *Shahnameh* stories. The story of Rostam and Sohrab is a very special one, it is very emotional and everybody knows it.

We took the *naqqali* tradition and the plan was to work with the *Scarlet Stone* that was written by the contemporary poet Siavash Kasrai about the revolution. I wanted to connect the old and the new. This is a theme in my work as well as that of my collaborator, the dancer Shahrokh Moshkin Ghalam. I wanted to connect these two traditions together.

The performance is inspired by the old form of performance, with the painting in the background. But now the painting is interactive video, which is connected to the voice of the storyteller. For example, the volume of the storyteller's voice can interactively change the

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[5] UC president Mark Yudof, quoted by Jorge Mariscal in "On the value of a liberal arts education," The Guardian (UCSD), Oct 6, 2011 (https://ucsdguardian.org/2011/10/06/on-the-record-on-the-value-of-a-liberal-arts-education/).

backdrop. This creates a very dream-like space. The set is composed of multilayer screens; sometimes they feature the poetry, sometimes various images—old or new images—to help tell the story. The tradition is similar in the old tradition of one storyteller telling the story, but there are also dancers and changing graphics as parts of the story, so there's some theater in it as well.

I would say different types of arts are mixed in based on the need of the story itself, although almost 90 percent of it is in poetry. The performance is in Persian with English subtitles. I've heard from many colleagues who said that, hearing the language in Persian in poetic form, they hear it as music. The rhythm and the form of delivery really help, so that as you are reading the subtitles you get the emotions of the story. I picked the pitch and the amplitude of the voice, and could adjust and manipulate the material of the background according to the parameters of the voice.

One other element that unfortunately not many people get to experience is the use of spatialization in this work. The audio is immersive in a sense that the music has many different layers, which are curated in the performance space. For example, the acoustic musicians perform a line, I play it back to them, and they react to it. Again, there is this recursive quality. They hear what they have said or played and, through this space, they are able to express the traditional music in a new expression. I hope you will hear that when you see and hear the piece. In performance spaces, those layers that they were hearing would become spatialized in the room and transform the performance space with music and sometimes sound effects.

CHF: I listened to some of the pieces—"Vidya," "Nirvana," and "Harmony," from *Green Memories* and *Migration*. They're fascinating. I'm glad you mentioned that it's both traditional and new. Actually, the word that came to mind when I was listening was "experimental," but maybe you wouldn't use that word. I wondered, Are these pieces scored? Are they actually written as performed, or are they created afterward on the computer, or are they made up ad hoc by the violins and string players and then remixed? How is the music made?

DR. YADEGARI: I appreciate the amount of time you have put in before this interview and that you've listened to these. I'm truly grateful.

The two works, *Green Memories* and *Migration*, I call them structured improvisation. They are very similar to traditional Persian music. Generally, Persian music performance, especially in its urban form, is based on what is called the *Radif*, meaning "sequence." There are, according to various accounts, between 200 and 450 different melodies; these are very old melodies that have been classified in a hierarchical model. Professional musicians know these melodies and they know the space of these melodies. The performance is often defined as picking a sequence of these melodic patterns.

So they are composed in that sense—we know where we start, what are the different grounds we hit, what are the emotional spaces that we go through—but everybody is open to express themselves in the way they like.

The heart of these productions is also my computer music instrument called Lila, which I created for exactly this call and response process. I can tell you the story of how this instrument came about.

I created a computed music instrument called Lila for a call and response process.

The word *Lila* is an old Sanskrit word, it is the concept of circular re-creation, the idea of us becoming one and the same, the same thoughts, the same concepts, talked about in the poetry of Omar Khayyam. It is the concept of the gods dying and being reborn. Circulation is understood as the form of play. If you think of it very dogmatically, that its structures are fixed, you don't have room to play. But it also cannot be completely random. The two have to sort of meet each other. The concept of Lila defines that. It's also the concept and the word used for love.

I will briefly tell you how I picked this name for my music instrument. In the early 1980s when I was living in Santa Monica, a mockingbird made a nest in a jasmine tree next to my house. The tree at night would become intoxicating—this bird would sing the whole night and would keep me up.

CHF: Yes, that's what they do. Did you ever count the variety of melodies from the mockingbird during the night?

DR. YADEGARI: I couldn't, so I decided okay, this is a beautiful musician who is continuing to sing, let me record it. I recorded the bird and listened and then

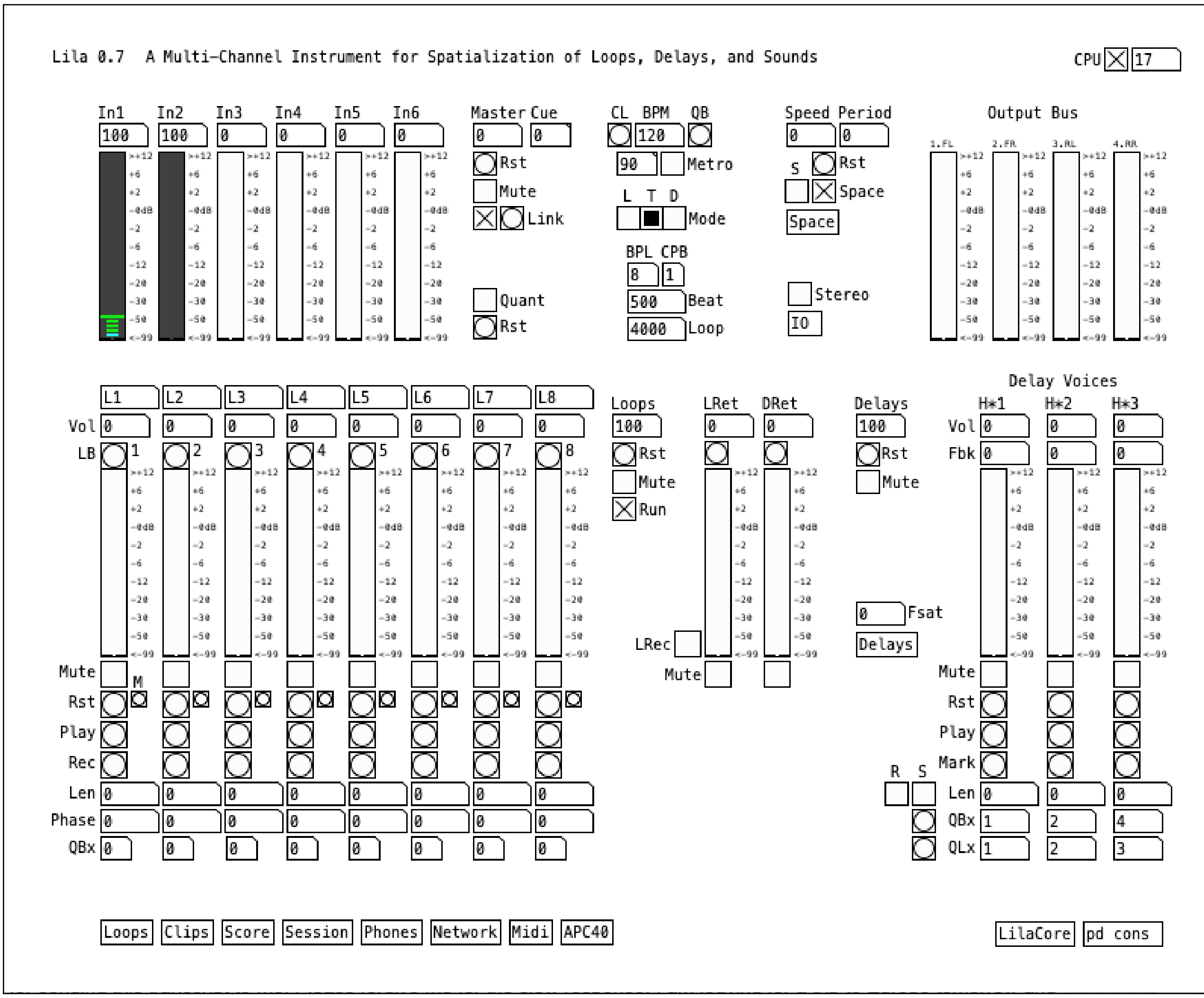

Illustration of Lila interface. Lila is Shahrokh Yadegari's multichannel instrument for spatialization of loops, delays, and sounds.

thought, 'Let me play it back and see what the bird does.' The moment I played back the bird's song, something amazing happened. First, the bird started answering, but more articulately, as though a little competitive. I spent many hours, and the more I recorded, I noticed that the bird would repeat what it heard on the tape. It would do it a few times and then bring in a new theme. But since this new theme was not recorded, the recording wouldn't answer. Sometimes the bird would get upset and I would hear it—*chit, chit, chit, chit*—saying 'This is not the way it goes—you're supposed to answer me.'

[Laughter]

And then I thought, 'If I had a computer, I could do that. I could respond right at that moment.' This is how Lila got created. And now this is the same thing that happens with acoustic musicians that I work with. When I play back their own sound in recording spaces to them right then, the articulation changes. There is a bit of a sense of karma, that if you play something, it is going to come back to you. To an extent, I'm controlling the form of the music and what the musicians are hearing. I also control the number of layers, so I control the intensity and I can also shape the path of the music.

Going back to your question about *Migration* and *Green Memories* and pieces that you will hear in *The Scarlet Stone*: for a number of the pieces that have been recorded, the musicians know the spaces that we are going to hit, they know the landscape. But as I am playing with them through Lila, I can kind of direct them into different paths. Then there is a bit of post-production, mostly to map the multichannel sound into the stereo format to make it sound right. I have taken the Lila instrument to many performances and places, both live and in recording.

CHF: Do you play other musical instruments?

DR. YADEGARI: My main instrument is the santur, which is the Persian hammered dulcimer. I play a little bit of ney as well, the Persian cane flute.

RML: We're reaching the end of our hour but I want to ask, Where can folks who read this interview see performances?

DR. YADEGARI: *The Scarlet Stone* will hopefully soon be available in streaming format on Amazon. It is available as Blu-ray now.

I worked with theater director Peter Sellars recently—I did the sound design and produced the audio track for his film called *This Body Is So Impermanent*. It is based on an ancient Buddhist text, the Vimalakirti text.

And as I mentioned I'm working on a new piece, *Siavash*, that I hope will have performances in about a year.

RML: I want to conclude by saying that you have truly added a new dimension in terms of our interviews. This has been, as I said earlier, inspirational. What you are doing involves very sophisticated engineering and technology, but it also reaches into the heart of cultures and music and poetry in ways that are fascinating. I want to thank you for taking the time to talk with us today.

CHF: I also heard a dimension of spirituality in the undertones and overlays of both poetry and philosophy. I felt transported listening to you, Shahrokh.

DR. YADEGARI: Those are all very kind comments. I thank you for giving me the opportunity to talk to you at this level.

At heart, I'm still an engineer—even in the world of art, similar to Khayyam, I think of the world with a scientific eye. And I think that has been applied to my performances and on the level of spirituality. I'm not really religious in terms of a regular form of religion. What you heard as a form of spirituality is exactly that.

I really appreciate again the time and the quality and precision of attention you've given this interview and the attention that you've given to my work.

CHF: It's a pleasure for us too. And now, how do I say "thank you" in Persian?

DR. YADEGARI: You could use the French *merci*. Or you could say a very old Persian form: *Sepas*.

CHF: *Sepas*, Shahrokh.

DR. YADEGARI: Same to you. Thank you so much for taking the time. It has been a great pleasure for me to talk about this with you.

NAE News and Notes

NAE Newsmakers

NAE president **John L. Anderson** has received the **2022 Distinguished Career Award in Engineering** from the Washington Academy of Sciences, "in recognition of lifetime national leadership in advancing the engineering profession." The award and fellow certificate were presented at the academy's annual banquet, May 11 in Reston, VA.

Daniel E. Atkins III, W.K. Kellogg Professor Emeritus of Information and professor emeritus of electrical engineering and computer science, University of Michigan, is the recipient of the College of Engineering's **Edward Law Emeritus Outstanding Service Award** for 2021–22.

Jonathan D. Bray, faculty chair, Earthquake Engineering Excellence, University of California, Berkeley, was selected for the **2022 H. Bolton Seed Medal** at the 2022 Geo-Congress held in Charlotte, NC, in March. The medal is awarded for outstanding contributions to teaching, research, and/or practice in geotechnical engineering. Dr. Bray was honored for advances in geotechnical earthquake engineering, including liquefaction ground motions, seismic site response, seismic slope stability, soil-structure-interaction, and surface fault rupture.

Emery N. Brown, Edward Hood Taplin Professor of Computational Neuroscience and Health Sciences and Technology, Picower Institute for Learning and Memory and the Institute for Medical Engineering, Massachusetts Institute of Technology, received the **2022 Pierre M. Galletti Award**, the highest honor of the American Institute for Medical and Biological Engineering (AIMBE). It was presented to Professor Brown for his "significant contributions to neuroscience data analysis and for characterizing the neurophysiology of anesthesia-induced unconsciousness and demonstrating how it can be reliably monitored in real time using electroencephalogram recordings." The award was presented during AIMBE's annual event March 25.

Wilfried H. Brutsaert, William L. Lewis Professor of Engineering Emeritus, Cornell University, has been awarded the **2022 Stockholm Water Prize** by the Stockholm International Water Institute. He was honored for his groundbreaking work in quantifying environmental evaporation. The announcement was made March 22, World Water Day, and the prize—widely known as the Nobel Prize of Water—will be presented to Professor Brutsaert by the king of Sweden in Stockholm on August 31 during World Water Week.

Wei Chen, Wilson-Cook Professor in Engineering Design, Northwestern University, has been selected to receive the **2022 Engineering Science Medal** from the Society of Engineering Science. Professor Chen was chosen for her seminal contributions to design under uncertainty, in particular for establishing formalism and developing robust design methods to accelerate the use of physics-based simulations in design. She will be formally recognized during the SES 2022 annual meeting in October.

Jack J. Dongarra, University Distinguished Professor, Innovative Computing Laboratory, University of Tennessee, Knoxville, is the winner of the **2021 A.M. Turing Award**, the Association for Computing Machinery's highest honor. Professor Dongarra was chosen for his pioneering contributions to numerical algorithms and libraries that enabled high-performance computational software to keep pace with exponential hardware improvements for over four decades. The award was presented June 11 in San Francisco.

Ashok J. Gadgil, professor and faculty senior scientist, Civil and Environmental Engineering, Energy Technologies Area, University of California, Berkeley, is the inaugural recipient of the **Zuckerberg Water Prize**. The Zuckerberg Institute for Water Research of the Jacob Blaustein Institutes for Desert Research chose Dr. Gadgil for his "outstanding leadership, vision, innovation, and lasting global impact in the field of water." The award ceremony took place during the biannual International Water Summit held May 22–23.

Ashok Jhunjhunwala, Institute Professor, Department of Electrical Engineering, Indian Institute of Technology, was awarded the **V&D Lifetime Achievement Award**. The award was presented during the 21st Voice&Data Telecom Leadership Forum March 22.

Jay D. Keasling, Hubbard Howe Jr. Distinguished Professor of Biochemical Engineering, University of California, Berkeley, is the recipient of the Science History Institute's **2022 Othmer Gold Medal**. The award was presented May 11 as part of the institute's annual Heritage Day celebration.

Nicky C.C. Lu, CEO, chair, and founder, Etron Technology Inc., was invited to join the **Committee of 100**, a group of Chinese Americans who are "pioneers in their respective fields across the arts, science, technology, business and finance." They work to advance the committee's dual missions of "promoting the full participation of all Chinese Americans in American society" and "advancing constructive dialogue and relationships between…the United States and Greater China."

Sandra H. Magnus, AstroPlanetview LLC, has been elected to the **US Astronaut Hall of Fame**. Dr. Magnus has spent 187 days in orbit; she flew aboard Space Shuttle Atlantis in 2002; in 2008 she flew to the International Space Station, where she lived for 4½ months; and she was aboard the final Atlantis launch in 2011. The ceremony at the Kennedy Space Center, in Cape Canaveral, FL, was held June 11.

Kiran Mazumdar-Shaw, executive chair, Biocon Limited, has been elected a **fellow of the Royal Society of Edinburgh**. Dr. Mazumdar-Shaw's impacts as a leading woman in science, committed to equitable access to health care through affordable innovation, have made her a role model globally.

Marcia McNutt, president, National Academy of Sciences, has been selected to receive the National Marine Sanctuary Foundation's **Lifetime Achievement Award**, which recognizes individuals who make an "exceptional impact on ocean science and research, conservation, or policy." She is recognized for her contributions to ocean science and conservation throughout her career—from groundbreaking discoveries at the Massachusetts Institute of Technology to the development of cutting-edge technologies at Monterey Bay Aquarium Research Institute to her work at the US Geological Survey responding to the *Deepwater Horizon* oil spill. The award was presented June 7 at the Ocean Awards Gala in Washington.

Julia M. Phillips, retired vice president and chief technology officer, Sandia National Laboratories, has been appointed by President Biden for a 6-year term as a **member of the National Science Board**, which establishes the policies of the NSF and serves as advisor to Congress and the president. The board approves major NSF awards, provides congressional testimony, and issues statements relevant to the nation's science and engineering enterprise.

Ares J. Rosakis, Theodore von Kármán Professor of Aeronautics and Mechanical Engineering, California Institute of Technology, is the recipient of the 2020/2021 **Horace Mann Medal** from Brown University. The medal is given annually to a Brown Graduate School alumnus or alumna who has made significant contributions in his or her field, in or outside of academia. Professor Rosakis is recognized for his research and mentoring skills, and for championing the role of the sciences in societal impact.

J. Marshall Shepherd, Georgia Athletic Association Distinguished Professor of Geography and Atmospheric Sciences, University of Georgia, was selected for the **2022 SEC Faculty Achievement Award** for his outstanding commitment to his students and research contributions in hydrometeorology and the intersections of atmospheric sciences with society.

Doros N. Theodorou, professor of chemical engineering, National Technical University of Athens, is the recipient of the **2022 FOMMS Medal**, which honors "profound and lasting contributions…to the development of computational methods and their application to the field of molecular-based modeling and simulation." Professor Theodorou's research focuses on the development of new computational techniques for understanding and predicting properties of materials based on their chemical constitution, with emphasis on polymers, amphiphiles, and nanoporous materials. The medal will be presented in July during FOMMS 2022 in Delavan, WI.

G. Paul Willhite, Distinguished Professor Emeritus, University of Kansas, received the **Distinguished Engineering Service Award** from the university's School of Engineering, its highest award. Professor Willhite is recognized as a remarkable educator and researcher who served the academic community, university, state, nation, and international societies with the utmost distinction.

James C. Wyant, emeritus professor and founding dean, College of Optical Sciences, University of Arizona, has been named to receive the **2022 Frederic Ives Medal/Jarus W. Quinn Prize** from Optica (formerly OSA). Professor Wyant is recognized for pioneering contributions in advancing the science and technology of quantitative interferometric metrology, his leadership as an educator and entrepreneur, and his visionary service to the global optics and photonics community.

Roe-Hoan Yoon, University Distinguished Professor and Nicholas T. Camicia Professor, Department of Mining & Minerals Engineering, Virginia Polytechnic Institute and State University, was selected for the university's **Lifetime Achievement Award**, with appreciation for "[embodying] the cooperation between academic research and innovation."

At the National Academy of Sciences annual meeting in April the following NAE members were **elected to NAS membership**: **Alfred V. Aho**, Lawrence Gussman Professor Emeritus of Computer Science, Columbia University; **Angela M. Belcher**, James Mason Crafts Professor and head, Department of Biological Engineering, MIT; **Juan J. de Pablo**, Liew Family Professor in Molecular Engineering, University of Chicago; **Leonidas J. Guibas**, professor, Computer Science Department, Stanford University; **Craig J. Hawker**, director, California Nanosystems Institute, and director, Dow Materials Institute, University of California, Santa Barbara; **Julio M. Ottino**, Dean, R.R. McCormick Institute Professor and Walter P. Murphy Professor of Chemical and Biological Engineering, Northwestern University; **Kate M. Scow**, professor, University of California, Davis; **Barbara Sherwood Lollar**, University Professor of Earth Sciences, University of Toronto; and **Nancy R. Sottos**, Swanlund Endowed Chair and department head, Materials Science and Engineering, University of Illinois at Urbana-Champaign.

The **Computer History Museum**, in Mountain View, California, has announced selection of its **2022 fellows** who have made a "significant and lasting contribution to the advancement of computing and the information age." Two of the four selected are NAE members. **Donald L. Bitzer**, Distinguished University Research Professor, Computer Science Department, North Carolina State University, was selected for "pioneering online education and communities with PLATO and co-inventing the plasma display." **Leonard Kleinrock**, Distinguished Professor, Computer Science Department, University of California, Los Angeles, was selected for "his pioneering work on the mathematical theory of computer networks and roles in the ARPANET and in expanding the internet." The museum will host a gala honoring the new fellows in October.

The **American Meteorological Society** has awarded the **2022 Hydrologic Sciences Medal** to **L. Ruby Leung**, chief scientist, Pacific Northwest National Laboratory, for "ingenious, groundbreaking contributions that enhance the modeling of land-atmosphere interactions and the hydroclimate." The society also elected **Soroosh Sorooshian**, UCI Distinguished Professor and director, Center for Hydrometeorology and Remote Sensing, University of California, Irvine, an **honorary member**.

The **National Mining Hall of Fame** has announced its class of **2022 inductees**, who include **Thomas J. O'Neil**, retired president and chief operating officer, Cleveland Cliffs Inc., and **Syd S. Peng**, Charles E. Lawall Chair Emeritus of Mining Engineering, West Virginia University. They will be honored at the induction banquet October 29 in Lone Tree, CO. Dr. O'Neil is recognized for outstanding leadership throughout his career as a mining industry corporate executive, educator, board member, author, and volunteer. Dr. Peng is a world-renowned expert in ground control and longwall mining and has, with his team, introduced numerous new ground control technologies, many of which have become standards of the industry.

2022 Bernard M. Gordon Prize for Innovation in Engineering and Technology Education

Jenna P. Carpenter, founding dean and professor of engineering at Campbell University in North Carolina and president-elect of the American Society for Engineering Education; Thomas C. Katsouleas, professor of electrical and computer engineering and physics at the University of Connecticut, where he was also the 16th president; **Richard K. Miller**, emeritus president and professor of mechanical engineering, Franklin W. Olin College of Engineering; and **Yannis C. Yortsos**, dean of the USC Viterbi School of Engineering, holder of the Zohrab Kaprielian Dean's Chair in Engineering, and the Chester

L to R: Dianne Chong, Carol Folt, Thomas C. Katsouleas, Richard K. Miller, Jenna P. Carpenter, Yannis C. Yortsos, and John L. Anderson. Gordon Prize photos by Greg Grudt/Steve Cohn Photography.

Dolley Professor, were awarded the 2022 Bernard M. Gordon Prize for Innovation in Engineering and Technology Education on May 6. They received the prize "for creating an innovative education program that prepares students to become future engineering leaders who will address the NAE Grand Challenges of Engineering."

NAE president **John L. Anderson**, USC president Carol Folt, and the 2022 Gordon prize selection committee chair, **Dianne Chong**, retired vice president of Materials, Manufacturing Structure & Support, Boeing Research and Technology, presented the award on behalf of the National Academy of Engineering. The ceremony with students, alumni, faculty, friends, and NAE members took place at the University of Southern California (USC), Epstein Engineering Plaza, University Park Campus. The Gordon Prize public lecture will be presented October 2 during the 2022 NAE annual meeting.

Gordon Prize Acceptance Remarks by Thomas C. Katsouleas

I suppose it is almost obligatory, this close to Hollywood, to begin with "I would like to thank the Academy…." But seriously, on behalf of my colleagues Rick Miller, Yannis Yortsos, and Jenna Carpenter, I would like to thank Dr. Dianne Chong and the prize selection committee, and I would especially like to thank **Bernard Gordon** for his generous gift to establish this prize as one of the premier education prizes in the world. In so doing he uplifts the efforts of all of us who are engaged in the enhancement of engineering education.

Thank you, President Folt and USC, for hosting this lovely ceremony.

President Folt, President Anderson, NAE Executive Director **Al Romig**, distinguished guests, friends, and family, thank you for being here to celebrate this wonderful honor.

There are so many to thank! I will mention a few. First, Prof. **Iraj Ershaghi** for the time and effort we all know it takes to assemble a strong nomination; Amy Trowbridge and your dedicated team who run the community-based GCSP Network; the network's Advisory Council, represented tonight by Al Romig and Andrew Mang; the talented leaders of the original implementation of the GCSP, including Louise Yates, who is here, Monty Reichert and Martha Absher at Duke, and Lynn Stein at Olin College; and two former NAE staff members: BL Ramakrishna, who stewarded the program well, and Randy Atkins, who, with NAE president **Bill Wulf**, first conceived of the Grand Challenges as a way to communicate the importance of engineering.

The history of the GCSP is an LA story. The original "three amigos," Rick and Yannis and I, got to know each other as a result of working together here at USC. Our amiga Jenna was also working in an LA, but in her case it was Louisiana. This partnership has been one of the greatest pleasures of my professional life.

When the NAE came out in 2008 with its list of Grand Challenges for Engineering in the 21st century, we amigos saw this less as a list than a call to action. It prompted us to ask the fateful question: If this is where engineering is going in the 21st century, are we preparing our students for it? Or is there something more they need?

From that the Grand Challenges Scholars Program was born. It received a big boost along the way from NAE presidents **Chuck Vest** and **Dan Mote**, and the biggest boost of all from the White House when Tom Kalil and President Obama offered to host us if we could get 50 deans to sign on. More than 120 did.

From there, it took off and I would say the future of the GCSP Network is now even brighter. We are on track to graduate over 300 GC scholars this year from 68 institutions. We are expanding the focus of the GCSP beyond the original NAE Grand Challenges, to include, for example, the UN Sustainable Development Goals and even such vexing challenges as engineering for world peace.

And we are building on our foundational partnership with the NAE, adding organizations such as the American Society for Engineering Education and National Society of Black Engineers, as well as leaders of industry.

Graduates of the program—as of this month there are over 2000 of them—have taken it on themselves to organize an alumni network and were instrumental in sparking, for example, the NAE's national Covid-19 Call for Engineering Action.

With its growing community-based network, the GCSP is a pathway for capturing the imagination of diverse and talented students and also empowering them to contribute to global solutions, today and in the future.

Thank you again on behalf of the four of us for this tremendous honor!

University of Arizona NAE Regional Meeting: Innovations in High-Contrast, High-Resolution Imaging Technologies

On March 30 the NAE held its first regional meeting since the onset of the covid-19 pandemic: a symposium on Innovations in High-Contrast, High-Resolution Imaging was hosted by the University of Arizona (UA) James C. Wyant College of Optical Sciences (OSC). Dean **Thomas L. Koch** introduced NAE president **John L. Anderson**, who welcomed the meeting attendees after the 2-year hiatus and reflected on the day's remarkable program, with presentations spanning imaging on length scales from submicron to the galactic scale of lightyears. Dr. Koch then gave a short profile of OSC, noting strong impact and support for growth with 14 new endowed chair faculty positions and a new $100M building under construction.

The symposium was organized in two sessions, the first on novel imaging modalities and technologies in life sciences, and the second on imaging advances in astronomy, with a focus on exoplanet science and discovery.

The keynote speaker for the first session was Elizabeth M.C. Hillman, Herbert and Florence Irving Professor at Columbia University, who presented an innovative approach to in vivo imaging of neural and cellular responses in organism-level 3D volumes at high speeds. Swept confocally aligned planar excitation (SCAPE) microscopy has captured

L to R: Ewan Douglas, Charles Beichman, Elizabeth M.C. Hillman, Jennifer K. Barton, Buell T. Jannuzi, and John Anderson.

the attention of scientists worldwide who are working to apply it to innovative methods of study from medical research to volcanology.

Barbara Smith, associate professor at Arizona State University, described the use of novel photoacoustic micropipette probes to study and characterize disease down to the cellular level, with the potential to outperform commonly used patch-clamping techniques. Her talk emphasized the importance of developing and bringing to market technologies for detecting non-invasive cancers and characterizing neurological disorders.

Jennifer Barton, Thomas R. Brown Distinguished Professor of Biomedical Engineering, professor at OSC, and director of the BIO5 Institute at the University of Arizona, shared advances in clinical diagnostics enabled by sub-millimeter diameter endoscopes that are simultaneously capable of direct tissue imaging, subsurface optical coherence tomography, and fluorescence spectroscopy. Target applications include minimally invasive cancer screening using endoscopic imaging of fallopian tubes, which have previously been inaccessible because of their small size.

The session ended with a presentation by OSC associate professor Khanh Kieu, whose research in compact, low-cost, and reliable ultrafast fiber lasers promises to replace the bulky and expensive lasers commonly used today for a variety of broadband and multiphoton imaging modalities. He illustrated the use of these capabilities in applications ranging from mineral studies to pancreatic cancer margin detection.

The keynote speaker for the second session was Charles Beichman, executive director of the NASA Exoplanet Science Institute at the California Institute of Technology. He described the amazing revolution in knowledge about planets in our galaxy thanks to technological breakthroughs in the past 25 years, with over 5000 exoplanets now identified. He conveyed the excitement around the recent launch of the James Webb Space Telescope, emerging extremely large ground-based telescope projects, and potential even larger space telescopes that promise starlight blocking contrast exceeding 9 orders of magnitude. These developments will enable the imaging of Earth-like planets in the habitable zone, with spectroscopic analysis of atmospheres to detect signatures of life.

Olivier Guyon, UA astronomer and professor, joined from Hawaii, where he is principal investigator of the Subaru Coronagraphic Extreme Adaptive Optics instrument on the Subaru telescope on the peak of Mauna Kea, operated by the National Astronomical Observatory of Japan. He discussed the use of state-of-the-art low-light detectors in conjunction with advanced coronagraphs and adaptive optics to suppress interfering starlight and enable direct imaging of increasingly smaller exoplanets.

Transitioning to space-based imaging systems, assistant astronomer and assistant professor at the University of Arizona Ewan Douglas discussed technological approaches to ultra-high-performance coronagraphs and star shades for implementation in space platforms to identify more Earth-like exoplanets in the habitable zone, including the NASA Nancy Grace Roman Space Telescope set to launch by 2027. He pointed out that even space-based systems benefit from adaptive optics to prevent instrument aberrations due to thermal variations and minute fabrication imperfections.

Joining from the Las Campanas Observatory on peak Cerro Manqui in Chile, UA assistant astronomer Jared Males expanded on the search for life using ground-based telescopes. He described the technologies harnessed in his work on the MagAO-X, an "extreme" adaptive optics system for the 6.5 m Magellan Clay telescope in Chile, as well as challenges in system implementation.

The event drew a combined in-person and online attendance of 94 guests. We thank the event organizers at the Wyant College of Optical Sciences as well as the Lunar and Planetary Laboratory for hosting the event in the Kuiper Building.

Planning Workshop: Ways to Move the Needle on Public Understanding of Engineering

A planning workshop, Public Understanding of Engineering: Exploring Ways to Move the Needle, was held as a virtual event April 18, 19, and 21, led by **Leah Jamieson**, Ransburg Distinguished Professor of Electrical and Computer Engineering at Purdue University. Participants and speakers from academia, business, government, professional associations, communications, and the media met to uncover insights and consider guidance to improve public understanding of engineering. Discussions explored multifaceted issues surrounding the problem, why a change in thinking is necessary, timing, and which opportunities to pursue.

There was general agreement that improved public understanding of engineering is critical to meeting the country's future needs. Participants examined what is working or has worked to enhance understanding, current perceptions of engineering's image and role in society, and societal needs that influence engineering's role.

The opening keynote speaker was **Susan Margulies**, assistant director of NSF's Engineering Directorate. Her presentation, "AM/FM Solutions for Expanding Public Awareness and Understanding of Engineering: Turning Up the Volume and Increasing the Frequency," emphasized both the value of and valleys between efforts to communicate with others about the world of engineering. She spoke about the need to engage the "missing millions"—men and women who could contribute to engineering and science if a better path were paved for opportunity and inclusion in the field. Calling for faster progress in diversity to reduce a significant talent gap, Margulies observed that there is no single pathway to success; engineers need to engage communities broadly and share the responsibility for expanding public awareness. She said her personal approach is simple: when she meets anyone aged 8–88, she initiates a conversation about the contributions of science and engineering.

In the first session, on Campaigns and Messaging for the General Public, speakers pointed to recent efforts that are reshaping perceptions around what engineers do, their contributions, and ways to communicate their value to specific audiences. For instance, Hayaatun Sillem, CEO of the Royal Academy of Engineering, shared an engaging video and outcomes from the RAEng marketing campaign "This is Engineering," which aims to spark teens' interest in the field by revealing how engineering connects to a multitude of fields and interests. Discussions also explored ways to reframe the benefits of engineering and focus on equitable designs and diversity to create a more inclusive frame.

The second panel, on Prior Messaging Efforts, looked at partnerships with teachers, for example, as an entryway to engineering careers. Other presenters spoke about the effectiveness of the NAE's 2008 consensus report *Changing the Conversation*. They suggested thinking about what engineering is and what it is not, and cited the value of hands-on approaches, including makerspaces, and lesson plans and guides tailored to nurture interest in engineering.

During the second day, participants were challenged to enhance their own understanding of the public, to consider which public audiences to engage, and to start with what those audiences already know about engineering. The session concluded with an interactive exercise where participants shared what they believe are today's most pressing challenges and opportunities.

Nick Donofrio, retired EVP of Innovation & Technology at IBM, delivered the final keynote on the third day and provided an industry perspective. He called on engineers to take responsibility for their designs and to practice ways to promote open dialogue and honesty, to create trust among the public.

In an open mic session at the end participants engaged over strategies and avenues to move forward in efforts to enhance public understanding of engineering. A short questionnaire sent to participants after the event invited their further thoughts on next steps.

More information and recordings from the workshop are available at https://www.nae.edu/270048/Public-Understanding-of-Engineering-A-planning-workshop-to-explore-ways-to-move-the-needle.

NAE Frontiers of Engineering Renamed The Grainger Foundation Frontiers of Engineering

The NAE is pleased to announce the renaming of its Frontiers of Engineering program to The Grainger Foundation Frontiers of Engineering. The renaming honors the financial support and steadfast commitment The Grainger Foundation has made to Frontiers of Engineering throughout the life of the program. The Grainger Foundation has generously committed $10 million to endow the Frontiers of Engineering, building on more than a decade of philanthropic support to the program, totaling more than $19 million since 2008.

"The Grainger Foundation Frontiers of Engineering's goal will remain the same as the current program—introducing outstanding young engineers from different backgrounds and technical areas, expanding their networks, sparking their collaborations, and broadening their perspectives on new approaches to engineering problems," said John L. Howard, chairman of The Grainger Foundation. "The program has proved successful in meeting these goals, helping to build our nation's innovative capacity and enrich our national future."

Frontiers of Engineering symposia bring together a select group of emerging engineering leaders from industry, academia, and government labs to discuss pioneering technical work and leading-edge research in various engineering fields and industry sectors. The symposia facilitate collaboration in engineering, enable the transfer of new techniques and approaches across fields, and establish lifelong contacts among the next generation of engineering leaders. There are five meetings in the Frontiers of Engineering portfolio: the annual US symposium, and a rotating schedule of bilateral symposia with Germany, Japan, China, and the European Union.

"Our focus in education and workforce development in science, technology, engineering, and mathematics has strengthened over the years," Howard noted. "Frontiers of Engineering aligns with our mission, supports our focus, and fulfills our passion by preparing future engineers for a world we have yet to imagine. It is an honor to be a part of this worthwhile program."

A new logo featuring the new name was unveiled at the NAE national meeting May 4–5 in Irvine. The new name and logo will be featured on the NAE and the Frontiers of Engineering websites and in all future outreach.

The Grainger Foundation is an independent private foundation based in Lake Forest, Illinois. Established in 1967, the Foundation provides substantive support to a broad range of organizations including educational, medical, cultural, and human services institutions.

NAE Hires Director of Outreach and Communications

L. EILEEN ERICKSON is the new NAE director of outreach and communications. She began her duties in this newly established role on January 18 and reports directly to the president and executive officer. Her duties include building the NAE's public presence and public understanding of engineering; amplifying NAE program communications to members, stakeholders, and international audiences; boosting the reach and impact of NAE publications; enhancing the NAE website and media outlets; driving communications to engage industry; and collaborating with various communication units of the National Academies.

Eileen is an entrepreneurial-minded strategic communications professional with more than 30 years of experience serving nonprofits. She has a wealth of communications, marketing, and publishing experience as both a consultant and in-house communications leader. She led media and public outreach efforts for the National Council of Teachers of Mathematics during the period known as the "math wars"; oversaw marketing, communications, and publications for the Institute of Transportation Engineers (ITE); and spearheaded the organizational repositioning and rebranding of the Society of American Military Engineers during the global war on terrorism. She also served as editor in chief of the *ITE Journal* and *TME Magazine*. As a consultant, Eileen has provided media training to nonprofit leaders, led event marketing efforts, and was a cofounder of Health21.

She earned an MA in public relations from Ball State University, a BS in journalism and telecommunications from Radford University, and accreditation in public relations and military communication from the Public Relations Society of America. She can be reached at lerickson@nae.edu or 202.334.2233.

NAE Director of Programs Wins AAMI Top Prize

Guru Madhavan, Norman R. Augustine Senior Scholar and senior director of NAE programs, has received yet another honor: the AAMI Foundation's 2022 Laufman-Greatbatch Award. The award honors an individual or group that has made a unique and significant contribution to the advancement of healthcare technology and systems, service, patient care, or patient safety. Dr. Madhavan was chosen for "exemplary leadership in advancing engineering approaches to support patient care, advise health policy, and guide global health interventions." The award was presented at the AAMI Exchange held in San Antonio in early June.

NAE Mirzayan Fellow Wins Award

Dayoung Kim, Christine Mirzayan Science and Technology Policy Graduate Fellow, received a 2022 Outstanding Research Award for Engineering Education from the College of Engineering at Purdue University, where she is pursuing her PhD in engineering education. The award goes to students who have demonstrated excellence and leadership in research through publications, participation in professional organizations, and willingness to mentor others. Dayoung joined the NAE Program Office on March 7, 2022, for a 12-week tenure, working with David Butler on the Cultural, Ethical, Social, and Environmental Responsibility in Engineering (CESER) program. We congratulate her on this accolade and wish her all the best in her continuing research!

New Look for the National Academies

NATIONAL ACADEMIES *Sciences Engineering Medicine*

In April the National Academies of Sciences, Engineering, and Medicine unveiled a new visual identity system to create a stronger presence for the institution, enable improved digital communications, and support greater consistency across publications, advisory activities, and other products. The new design elements are contemporary but also reflect the rich visual heritage of the National Academies. The logotype, for example, echoes script on the historic National Academy of Sciences building on Constitution Avenue, and complements the existing design identities of each of the three academes. The new designs will create a unified identity for the National Academies across all communications vehicles and will also help readers more easily differentiate among types of publications.

Calendar of Meetings and Events

June 13	2022 Charles Stark Draper Prize for Engineering Presentation (by invitation only)
July 18–20	2022 China-America Frontiers of Engineering Irvine, California and Chengdu, China
August 3–4	NAE Council Meeting Virtual
September 21–23	The Grainger Foundation Frontiers of Engineering 2022 Symposium Seattle
September 23–24	EngineerGirl Ambassadors Training Meeting
September 30–October 1	NAE Council Meeting
OCTOBER 2–3	**NAE ANNUAL MEETING**

All meetings are held in National Academies facilities in Washington, DC, unless otherwise noted.

In Memoriam

John G. Bollinger, 86, dean emeritus, College of Engineering, and professor emeritus of industrial and systems engineering, University of Wisconsin–Madison, died April 7, 2022. Dr. Bollinger was elected in 1983 for outstanding research on machine tools, sensors, and controls for manufacturing equipment, and leadership in education and the engineering profession.

Daniel B. DeBra, 91, Edward C. Wells Professor Emeritus, Stanford University, died December 3, 2021. Professor DeBra was elected in 1981 for contributions to theory and design of instruments in space engineering of the first drag-free satellite control system.

George J. Dvorak, 88, professor emeritus, Rensselaer Polytechnic Institute, died April 23, 2022. Professor Dvorak was elected in 1995 for contributions to research on metal matrix composites and micromechanics of materials.

Leroy (Mike) M. Fingerson, 89, retired chair and CEO, TSI Incorporated, died February 10, 2022. Dr. Fingerson was elected in 1993 for contributions to flow instrumentation, including research, development, design, and manufacturing.

Ronald L. Geer, 95, retired senior mechanical engineering consultant, Shell Oil Company, died April 16, 2022. Mr. Geer was elected in 1977 for pioneering development of deep-sea floating drilling vessels, and of associated hydrocarbon drilling and production equipment systems.

Roy W. Gould, 94, Simon Ramo Professor of Engineering Emeritus, California Institute of Technology, died February 19, 2022. Professor Gould was elected in 1971 for pioneering contributions to microwave electronics and plasma physics and distinguished service in higher education.

Marvin E. Jensen, 95, retired director, Colorado Institute for Irrigation Management, Colorado State University, died March 30, 2022. Dr. Jensen was elected in 1988 for development of improved methods for determining irrigation water requirements, and for international leadership in irrigation engineering advances.

Hisashi Kaneko, 86, counselor emeritus, NEC Corporation, died August 8, 2020. Dr. Kaneko was elected a foreign member in 1997 for contributions and management in digital communication systems.

Kaye D. Lathrop, 89, retired associate director, SLAC National Accelerator Laboratory, and professor emerita, Stanford University, died October 23, 2021. Dr. Lathrop was elected in 1986 for seminal work in developing neutron transport methods used worldwide.

Paul A. Libby, 100, professor emeritus of fluid mechanics, University of California, San Diego, died November 2, 2021. Professor Libby was elected in 1999 for contributions as a researcher, author, and educator who advanced knowledge of fluid dynamics, turbulence, and combustion through theoretical analyses.

Robert W. Lucky, 86, retired corporate vice president, research, Telcordia Technologies Inc., died March 10, 2022. Dr. Lucky was elected in 1978 for contributions to the theory and practical development of data communication systems.

Robert F. Mast, 86, senior principal, BERGER/ABAM Engineers Inc., died July 30, 2020. Mr. Mast was elected in 1989 for pioneering design of prestressed transit guideways and floating structures, and for contributions to design and construction codes and standards.

Jerome H. Milgram, 83, professor emeritus, Department of Mechanical Engineering, Massachusetts Institute of Technology, died December 20, 2021. Professor Milgram was elected in 1995 for design of sailing vessels and solutions to such ocean engineering issues as environmental impact and towing dynamics.

Hyla S. Napadensky, 92, retired vice president, Napadensky Energetics Inc., died March 19, 2022. Mrs. Napadensky was elected in 1984 for developing experimental and analytical models of propellant and explosive sensitivity to initiation of detonation by low-velocity impact.

J. Randolph Paulling, 91, professor emeritus of naval architecture, University of California, Berkeley, died November 22, 2021. Professor Paulling was elected in 1986 for internationally recognized research in the areas of ship structures, ship hydrodynamics, and offshore engineering.

Carl H. Rosner, 93, chair and CEO, CardioMag Imaging Inc., died April 16, 2022. Mr. Rosner was elected in 1996 for technical and entrepreneurial contributions to the practical application of superconductivity.

Jörg Schlaich, 86, structural consulting engineer, and professor emeritus, University of Stuttgart, died September 4, 2021. Dr. Schlaich was elected a foreign member in 1994 for leadership in structural engineering practice and advancement of economic, environmental, educational, and aesthetic aspects of civil engineering.

Kenneth Walters, 87, Distinguished Emeritus Professor, IMPACS, University of Aberystwyth, died March 28, 2022. Professor Walters was elected a foreign member in 1995 for viscoelastic fluid-flow calculations, experiments, and numerical simulations.

Invisible Bridges

Engineering for Equity: Factors and Aspirations

Komal Syed

Mary Mathias

Courtney Hill

Komal Syed, Mary Mathias, and Courtney Hill are associate program officers in the NAE Program Office.

Engineers are not the first actors that come to mind when considering social justice issues, but they play an integral role in designing and operating the sociotechnical systems in which we work and live.

Factors of Concern

Decisions of engineers and the social power imbalances that exist around them have significant societal impacts. The twin lacks of education about how engineering and social justice issues are intertwined and of diversity in the field have led to a long history of inequitable engineering decisions made without considering their effects on large groups of people heavily affected by them.

Disproportionately high levels of environmental pollution in poor communities (Katz 2012), algorithmic bias in facial recognition technologies that lead to wrongful arrests of people of color (Najibi 2020), and the increased risk of female injury in automobile crashes because of their inadequate representation in crash testing protocols (Barry 2021) are just a few examples illustrating the critical need to integrate equity in engineering. These technology-based inequities demonstrate the urgent need to prepare engineers who understand the societal implications of their work and can design equitable sociotechnical systems. Such systems promote a healthy society and distribute benefits to the system's users equitably, taking into consideration different stakeholders' requirements of technology (e.g., based on age, physical and mental abilities, socioeconomic or cultural background).

Educators across the country have risen to the task with education interventions, community-building approaches, and design initiatives that incorporate social justice concepts. Even with these efforts, much progress is still needed to integrate these concepts into the mainstream understanding of engineering practitioners.

Historical Context

Merging social justice concepts into the profession is not new—discussions of injustice and industry date back to Adam Smith's writings in the 1700s (e.g., *The Theory of Moral Sentiments*, 1774). During the Vietnam War, engineers who were conflicted by the field's contribution to the design and production of military weapons formed the Committee for Social Responsibility in Engineering, which inspired engineers to use their skills with regard to social context instead of only profit. The resulting publication *SPARK* identified negative applications of engineering skills and opportunities to work toward liberatory ends (Wisnioski 2012).

Since then engineering education scholars have made essential contributions to incorporate social and political-economic context in students' understanding of engineering. Progressive engineering education reform efforts—including educational and professional

Inspired by the name of this quarterly, this column reflects on the practices and uses of engineering and its influences as a cultural enterprise.

community-building interventions as well as scholarly contributions—have been categorized in terms of how they could work at different levels of reform to comprehensively integrate social justice into the field (Nieusma 2013). And studies have examined how engineering could be changed if social justice were a core component of the profession (Baillie et al. 2012; Riley and Lambrinidou 2015).

Scholarship thus laid a critical foundation that engineering educators are using today as they harness students' heightened interest in social justice to develop more "reflective practitioners" (Schön 2017). Yet despite student interest and sound conceptual frameworks, efforts to integrate social justice concepts remain largely in science, technology, and society departments and have not extended into engineering programs' technical core.

Faculty and Student Concerns

The bulk of engineering curriculum in most academic institutions gives little opportunity for students to think deeply about sociotechnical systems (Leydens and Lucena 2016). However, engineering curriculum can make a major difference in whether students feel engaged or disengaged from their professional responsibility to public welfare (Lucena and Leydens 2015). Many universities are trying to include courses and programs (McGlynn 2014) to bring attention to the critical role of engineering in big-picture solutions by focusing on connections between engineering design and impact on local and global communities.

While an increasing number of engineering researchers and educators are trying to integrate social justice into their work, challenges remain. Faculty have noted that one of the main challenges in changing engineering curriculum is accreditation (Lucena and Leydens 2015). Another concern is that adding content to engineering curriculum implies sacrificing other content. Engineering educators are working to address these concerns in a variety of ways, including, for example, the incorporation of social justice concepts in textbook problems in core engineering subjects such as thermodynamics (Riley 2011).

Another challenge in integrating social justice in engineering curriculum is student attitude. While some students welcome the explicit recognition of social justice concerns in the study and practice of engineering, others see the topic as an irrelevant addition to the curriculum or worry about missing technical content by taking courses with social justice topics (Lucena and Leydens 2015). One study found that engineering students' interest in and understanding of public welfare concerns and overall social responsibility may actually decline over the course of their engineering education (Cech 2014).

It is worth noting that, while ABET's accreditation focuses primarily on the technical content, its code of ethics states that engineers should put "the safety, health, and welfare of the public" first and foremost. The ABET code of ethics thus reflects the importance of engineering design in terms of its societal, economic, and environmental impacts (Shannon and Mina 2021). The code in effect calls for the inclusion and discussion of these issues in engineering education so that they translate to the engineering profession.

Engineering for Social Good

The benefits of including and/or expanding the integration of social justice topics in engineering education go beyond the development of more socially aware and engaged engineers in the workforce to bringing in a more diverse group of engineering students. Engineers in the United States are disproportionately white and male: in 2019 only 14 percent were women and 13 percent were from underrepresented racial groups (Wilson 2019).

Engineering has struggled and stumbled in areas of social justice when those most affected by negative impacts are significantly underrepresented in the field.

In any discipline and profession, diversity of thought and experiences enhances the work done, but particularly in a field such as engineering, where the work directly impacts society. As Riley and Lambrinidou (2015, p. 26.322.2) succinctly state, "Social justice is an aspirational value conceptualized in contrast to injustice, and is best defined by those most closely experiencing that injustice." It is not surprising that engineering has struggled and stumbled in areas of social justice when those most affected by the negative impacts are significantly underrepresented in the field.

By integrating social justice and community engagement in engineering education curricula, students can begin to see engineering as a driving force for social good, not just a career for people who like math and science and want to build machines and bridges. Women and those in racial groups underrepresented in engineering are generally more interested in a career in which they can have a positive impact and make a difference (NAE 2018). Courses that combine engineering with subjects like community development and social equity can be especially effective when the curriculum includes hands-on project work. As a student at the University of California, Berkeley, said of her Engineering, the Environment, and Society class (McGlynn 2014), "I didn't even know about engineering until I got here.… This class puts it all together—it gives examples but also includes the science." She went on to study civil engineering in graduate school.

Our Aspirational Look Forward

With the debt that many students accumulate in order to pursue an engineering degree (NAE 2019, p. 35), a career in a socially conscious or community-oriented area may not offer the salary necessary to pay the bills. We are hopeful that as more engineering students are exposed to social justice as part of their engineering curriculum and then enter the workforce, societal and other shifts will occur and more career opportunities will allow engineers to *both* follow their heart and support themselves financially.

The preparation of engineering students with an equity-based approach to design before they enter the workforce will go a long way to ensure that the field moves in a positive direction. Accreditation criteria and faculty investment in these ideas beyond courses on technology and society will need to follow suit.

Fully integrating social justice concepts in engineering education is imperative for the field. We understand that aspects of what we've described here are aspirational, and that additional societal priorities and politics will need to shift before every engineer can be directed by their morals and conscience, but that is a topic for another day. In the meantime, engineering curricula with a foundation of social justice can lead to more diverse, engaged students and in turn more diverse, socially aware engineers, making it much more likely that the world created by engineering functions equitably for all.

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