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RESOURCE

engineering and technology for a sustainable world

Transforming Food and Agriculture to Circular Systems

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A Big Impact from Big Thinking

Our Society and our profession have a long history of increasing agricultural productivity to feed the world's growing population. I have seen firsthand the impact that agricultural and biological engineering (ABE) has had on my family's row crop farm in central Iowa. Growing up, I heard stories about how our farm transitioned from the horse power my great-grandfather relied on, to the early tractors my grandfather used, and now the efficient diesel equipment used today. I helped my father implement precision farming with GPS, grid soil sampling, yield monitoring, and variable-rate application to ensure that every acre received the inputs the crop needed. The improvements in our on-farm grain storage and handling allowed us to better manage grain, reducing post-harvest losses and increasing grain quality. Most recently, I am excited to hear terms like regenerative agriculture, nutritional density, carbon sequestration, and soil health being discussed among Midwestern farmers as we all continue to learn and evolve.

ASABE is now positioned to have an even bigger impact as we face a new set of challenges. The growing population continues to need food to eat and clean water to drink. Our current production systems, as good as they are, can't simply be expanded to accommodate the increasing demand. There are absolute limits to the amount of arable land and fresh water available. And while productivity per unit land area has increased enormously over the past century due to the collaborative efforts of ASABE members, there is more to do. To achieve the needed productivity, to feed the world, while also protecting the natural environment, we must fundamentally transform our global food and agricultural systems. Our current linear systems, in which productivity flows from the producer to the consumer and ultimately to the landfill, must become circular systems, in which wastes and byproducts are captured for reuse and are recycled back into production. The transformation to circularity is a big challenge, and it will require big thinking.

And it's getting started. This special issue of *Resource* presents a new initiative: Transforming Food and Agriculture to Circular Systems (TFACS). As **Sue Nokes** and **Jim Jones** explain in their introductory article, ASABE's involvement in TFACS began with the 2019 Annual International Meeting (AIM) in Boston. One of our first actions was the formation of an expert Roundtable lead by **Brahm Verma** to explore the possibilities for circularity in our current production systems and to define the importance of ASABE in collaborating with the many disciplines, stakeholders, and public and private agencies that will be involved in the transformation to circularity. The articles in this issue present the ideas developed by the Roundtable members on how circularity applies to open-field systems, controlled-environment systems, and livestock systems. These articles are intended to be thought-provoking, even debatable, and they are just the beginning. We will continue the discussion at the ASABE Annual International Meeting being held virtually this July. **Kati Migliaccio** has a led the charge, organizing special sessions focused on the transition to circularity.

Seeing the advancements that past generations have made, I am excited to see what the world of food, fuel, and fiber production will look like in the next 25 years. I encourage you to read on to learn more about how ASABE members, just like you, are coming together to have a big impact on our future—"benefiting people of the world." I hope this issue motivates you to #getinvolved and make contributions toward a more efficient, resilient, and sustainable global food production system. This is a really big deal.

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events calendar

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2021

July 11-14	**ASABE Annual International Meeting.** Virtual.
Dec. 6-10	**6th Decennial National Irrigation Symposium.** San Diego, Calif., USA.

2022

Jan. 9-14	**Soil Erosion Research under a Changing Climate.** Aguadilla, Puerto Rico.
Feb. 14-16	**Agricultural Equipment Technology Conference (AETC).** Louisville, Ky., USA.
May 16-19	**Sustainable Energy for Sustainable Future.** Escazu, San Jose, Costa Rica.

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ON THE COVER:

This special issue focuses on ASABE's national priority to develop circular food and agricultural systems.

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Guest Editors:
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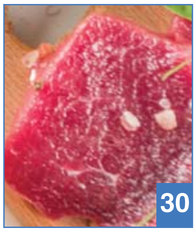

DEPARTMENTS

Transforming Food and Agriculture to Circular Systems: ASABE's National Priority

Sue Nokes, P.E., and James Jones

The involvement of ASABE in prioritizing the development of circular food and agricultural systems began at the 2019 Annual International Meeting (AIM) in Boston. The keynote speech, titled "From Here to Sustainability," was given by Joel Makower, President and CEO of GreenBiz. Joel described several areas that he and his colleagues identified as necessary for achieving a sustainable future, such as regenerative agriculture, walkable communities, and resource productivity, including the use of "stranded resources." The keynote was followed by a panel discussion that was moderated by **ASABE Past President Norm Scott**. In addition to Joel, the panel included a public policy lawyer, a chemical engineer, and an agricultural engineer from the machinery industry.

During the remaining days at the AIM, **Jim Jones** and **Lalit Verma** engaged **Sue Nokes,** the incoming ASABE President, in a persuasive conversation recommending that ASABE assess the feasibility of sponsoring a project to increase the visibility of agricultural and biological engineers (ABEs) both in the U.S. and abroad. At the time, Jim was completing a three-year term as a co-leader of the NSF program on "Innovations at the Nexus of Food, Energy, and Water Systems" (INFEWS), where he found a lack of recognition of ABEs, and of ASABE, in the federal agencies.

Where it all began. Following Joel Makower's 2019 keynote address, these panelists got the conversation started. From left to right, Joel Makower, Amy Stein (Professor of Law at the University of Florida and nationally recognized for her research on energy policy and its implications on the energy and water nexus), **ASABE Fellow Rabi Mohtar** (Dean of the Faculty of Agricultural and Food Sciences, American University of Beirut, Lebanon; TEES Research Professor, Texas A&M University; and an expert in the area of water resources and transdisciplinary research), JoAnn Lighty (Dean of Engineering at Boise State University and former NSF founding co-leader of INFEWS), **ASABE Fellow John Reid** (former Director, Product Technology and Innovation, John Deere), and **ASABE Past President and Fellow Norm Scott,** panel moderator, and a former Director of Cornell University Agricultural Experiment Station and Vice President of Research and Advanced Studies at Cornell, has been active in research on sustainable communities for over 20 years.

As president of the ASABE Foundation, Lalit saw the project as an opportunity to advance the Foundation's mission of helping ASABE become "a world leader in connecting resources for engineering sustainable systems of food, bioproducts, and the environment." Additionally, Jim, who is a member of the National Academy of Engineering and served on the Board of Agriculture and Natural Resources (BANR), recommended that ASABE prepare a proposal to BANR on transitioning from linear food and agricultural systems to circular systems for a consensus study by the National Academies of Science, Engineering, and Medicine (NASEM). At its November 2019 meeting, the ASABE Board of Trustees voted to commit ASABE to this important initiative: Transforming Food and Agriculture to Circular Systems (TFACS).

Immediately after the 2019 AIM, Jim introduced Sue and Lalit to the director of BANR. Jim talked about the powerful session at the 2019 AIM and explained why ASABE was excited about TFACS. He also relayed ASABE's interest in working with other professional societies, including ASA-CSSA-SSSA, chemical engineering, economics, and others, in identifying grand challenges that could help guide currently siloed science communities toward a sustainable future through convergent research. The director of BANR was interested in the idea and suggested that we stay in contact with her.

TFACS is a great fit for ASABE because ABEs work across all the subsystems involved in the complex problem of producing and processing food, feed, fiber, and energy, as well as the ecosystems that support these commodities, and ABEs are adept at integrating work from multiple disciplines to create solutions for improving the quality of life. ASABE members work on engineering and management projects in facility systems, plant systems, animal systems, energy systems, natural resource and environmental systems, machine systems, processing systems, packaging systems, waste management, sensors, big data, and many other areas.

In addition, ASABE members' day-to-day work requires collaboration with individuals in agriculture, manufacturing, processing, basic sciences, and the social sciences. ASABE members also have experience with working in a convergent manner, from a "system of systems" perspective, which is necessary to transform food and agriculture into circular systems and ensure long-term sustainability. The goals of TFACS align with our profession in a way that plays to the strengths of ASABE, providing an opportunity for ASABE to increase its contributions to the nation and to the world.

ASABE Past President and Fellow Sue Nokes

ASABE Fellow James Jones

The continuing dialogue with BANR led to an invited presentation at the February 2020 BANR meeting. ASABE's goals for the meeting were to introduce the TFACS project and build support for it among the BANR committee members. Things moved more rapidly than we expected. At the same meeting, the BANR committee voted to move the project forward. Jim was invited to write a proposal to BANR laying out suggested questions for the project to address. To assist in raising funds, Sue requested that ASABE's E-06 Liaison committee recommend TFACS to the ASABE Foundation as a fundraising priority.

ASABE envisions its role in TFACS as three-fold. First, we want to provide a framework with which ASABE can organize technical sessions and committees, which will encourage our members to work across specialization boundaries within the profession in a new way. Second, we want to facilitate convergence among different disciplines, find others willing to contribute to this effort, and find additional financial support. Every discipline has a specific way of seeing things, so a convergence of disciplines can remove those single-lens views of the problem and its solutions. Third, we plan to take a leading role in developing standards for food and agricultural processes (not just equipment) and work with other organizations to make this happen. Circular systems will need reliable standards for setting quality levels and coordinating advances.

Over the past 160 years, NASEM has gained a reputation for providing objective assessments and recommendations by highly experienced thought-leaders and visionaries across a broad spectrum of disciplines, industries, and agencies. Their assessments and recommendations are used to set national priorities and commit resources to address the complex challenges faced by our nation. For example, the 2019 NASEM study titled "Science Breakthroughs to Advance Food and Agricultural Research by 2030 - NAP 25059" is a primary driver of the USDA's current Agricultural Innovation Agenda, which emphasizes sensor technology, digital agriculture, and systems approaches.

ASABE's TFACS project aims to influence the research and development priorities of federal agencies and lead to innovations and actions for converting our current linear production systems to circular systems. By working with BANR and NASEM in developing a national consensus on how the U.S., and the world, can transition to robust and resilient circular systems, ASABE will benefit by gaining additional resources to support the goals of the ABE profession, and ASABE's longstanding contributions will receive greater visibility.

Many activities within ASABE already support this initiative. One of the first actions was Sue's appointment of a small group of members to serve on a Roundtable, during the summer of 2020, to begin the TFACS discussion. Many thanks to Brahm Verma for his excellent leadership of the Roundtable. The articles in this issue of *Resource*, which were written primarily by Roundtable members, are intended to be thought-provoking, but they are certainly not the whole story. That story is just beginning. We hope this issue will be an inspiration for you to get involved in this exciting new initiative.

See author information for **Sue Nokes, P.E.,** and **James Jones** below.

2020 ASABE Roundtable members

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Darrin Drollinger, ASABE Fellow, ASABE Executive Director, St. Joseph, Michigan.

Candice Engler, ASABE President (2020-2021), Johnson Brothers Farm, Cambridge, Iowa.

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Terry Howell, Jr., P.E., ASABE President (2014-2015), Executive Director and Research Professor, Food Innovation Center, University of Nebraska, Lincoln.

James Jones, ASABE Fellow, Guest Editor, Distinguished Professor Emeritus, Agricultural and Biological Engineering, University of Florida IFAS, Gainesville.

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Kelly Morgan, Professor and Director, Southwest Florida Research and Education Center, University of Florida, Gainesville.

Transforming Food and Agriculture to Circular Systems: A Perspective for 2050

James Jones, Brahm Verma, Bruno Basso, P.E., Rabi Mohtar, and Marty Matlock, P.E.

Food and agricultural systems (FAS) provide food, feed, fiber, energy, and other products, and they are intricately interwoven with human society. FAS are often misunderstood as simply farming systems. In reality, FAS are much more complex because they encompass a wide range of activities—including production, processing, transport, marketing, and consumption—as well as management of the byproducts. In the U.S., FAS constitute more than 22% of the national GDP, employ more than 28% of the national workforce, and are critical to national security.

However, as is evident in the FAS schematic in figure 1, different decision-makers control the various activities along the FAS value chain, and there are no public or private infrastructures for recovering unwanted outputs, which are lost or discarded as wastes. These wastes include the 30% to 50% loss of produced food that is typically dumped into landfills, along with the valuable resources, such as nitrogen, carbon, and other raw materials, that are contained in discarded food.

The impressive improvements in U.S. FAS since 1930, which quadrupled the supplies of food and fiber, were driven by advances in genetics, agricultural sciences, mechanization, and other technological innovations. Simultaneously, government policies provided incentives for innovations, increasing and stabilizing production, and providing affordable food for consumers.

FAS are now at an inflection point because their current incremental rate of improvement is unlikely to meet the anticipated increase in demand by the growing global population

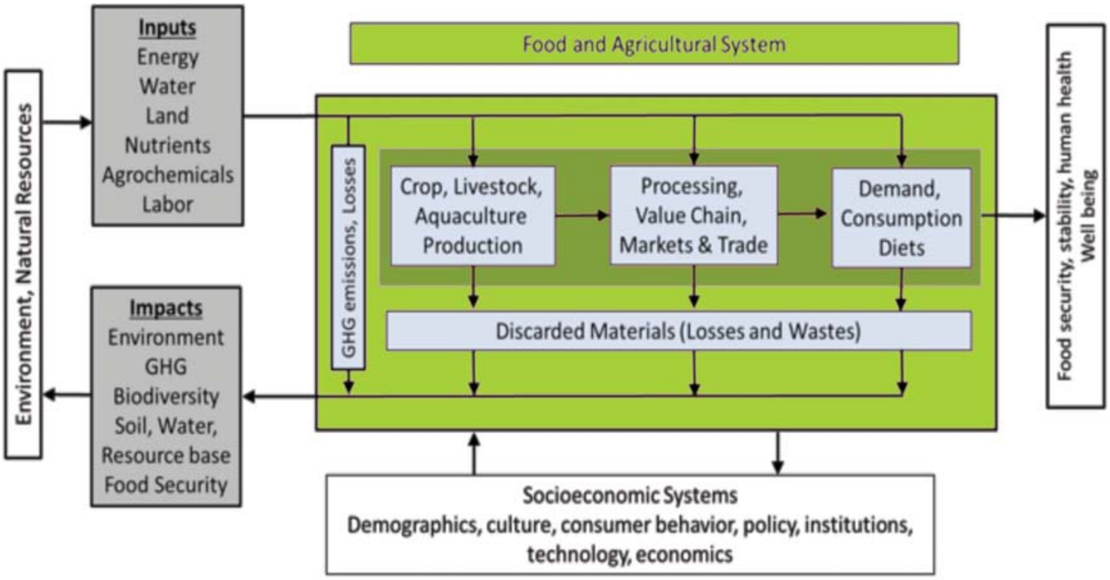


Figure 1. Schematic of a current food and agricultural system (FAS), showing the boundary that encompasses all activities from production to consumption, while losses and wastes have external impacts (adapted from a presentation by C. Rosenzweig at the NASEM workshop on Healthy People, Healthy Planet, 22 July 2020).

(e.g., a 50% to 70% increase in food demand by the year 2050). Additionally, the necessary increase in production must be achieved with fewer resources, declining biodiversity, and increasing risks to ecosystem health. Climate change will further exacerbate the risks to our industrial, traditional, and family-based FAS.

Most of these problems have arisen because our current FAS are linear, that is, they follow the one-way path of take-make-use-dispose, as shown on the left in figure 2.

In the U.K., the Ellen MacArthur Foundation defined food systems as "the full value chain of producing food for human consumption, from agricultural activities and other means, through handling, transportation, storage, processing, distribution, and consumption to organic (including human) waste management and disposal/reintroduction into productive use ('looping')". We can easily extend this definition to include the value chains for feed, fiber, energy, and other FAS products along with their complex interactions with human activities and the environment.

Three reports by the National Academies of Science, Engineering, and Medicine (NASEM) in 2015, 2018, and 2019 highlighted the importance of FAS to the U.S. economy and national security, discussed FAS vulnerabilities, and emphasized the importance of including all components of the FAS value chain, from production to consumption and beyond. The 2015 report developed a scientific framework for assessing the strengths and weaknesses of different FAS approaches to measure the sustainability of U.S. agriculture. The 2018 report indicated that continued incremental changes in current systems will not meet future challenges and recommended redesigning systems to consider tradeoffs among multiple goals. The 2019 report identified five grand challenges:

- Sustainable supplies of food, energy, and water.
- Curbing climate change and adapting to its impacts.
- Designing a future without pollution and waste.
- Creating efficient, healthy, and resilient cities.
- Fostering informed decision-making and actions.

Collectively, these reports provide an excellent assessment of the problem, they emphasize that current FAS are not sustainable, and they recommend using convergent systems approaches. NASEM's Board of Agriculture and Natural Resources (BANR) is now organizing a new consensus study to develop a vision of FAS for 2050 and recommend pathways to address the multiple goals of food security, environmental and natural resources sustainability, economic profitability, and resiliency.

This article presents an overview of transforming linear FAS into circular systems to meet these multiple goals. The later articles in this issue of *Resource* present some of the opportunities that lie ahead if we can rethink and redesign our systems to meet future demands.

Overview of circular systems

Circular systems are not a new idea—they are based on nature. Waste does not occur in nature. One organism's waste is another organism's food, and nutrients and energy flow in closed-loop cycles of growth, decay, and reuse. In contrast to circular systems, our current linear FAS do not include mechanisms for waste recovery and productive reuse. This "looping" of resources, as described by the Ellen MacArthur Foundation, can guide the design and development of future FAS. Studies in Europe show that the make-use-reuse-remake-recycle path of circular systems, as shown on the right in figure 2, can capture the resources that are embedded in byproducts, mimicking the zero-waste efficiency of natural systems.

Circular economies keep products and materials in use, regenerate natural resources, drastically reduce waste and pollution, and increase economic value. However, to ensure their reliability for human societies, circular systems must be resilient and be able to function during unexpected events (such as a global pandemic) as well as during expected chal-

Figure 2. Linear (*left*) and circular (*right*) systems. A 2019 study by the Ellen MacArthur Foundation on implementing circular food systems in urban areas estimated that cities would gain economically, socially, and environmentally, and the economic benefits would amount to $2.7 trillion by 2050.

lenges (such as pest outbreaks and extreme weather). Developing circular FAS for a wide range of products, practices, and conditions will require a convergence of disciplines, practitioners, and agencies.

ASABE has adopted this challenge as its long-term priority. We are now working with BANR to support a proposed study on transforming linear FAS to circular systems. An important goal of the study is to make recommendations for transitioning to circular systems that can double food production by 2050 without the need for additional freshwater, arable land, or other natural resources, mostly eliminating non-renewable energy use, and protecting the health of ecosystems.

The 2020 ASABE Roundtable

As Sue Nokes and Jim Jones explain in their article on page 4, an ASABE Roundtable was convened last summer to frame the problem and support the proposed BANR study. The 23-member Roundtable addressed two objectives:

- Explore the complexity and obstacles in the transition to circular systems using current FAS as examples.
- Identify ASABE's strengths and its role in designing and managing circular FAS.

At its first meeting, the Roundtable members reviewed the concepts of circular FAS, reviewed the draft proposal provided to BANR, and discussed the importance of ASABE in integrating multiple disciplines, practitioners, and public and private agencies for designing circular FAS. In a brainstorming session, the members identified the actions needed to transform a typical linear system into a circular system.

In the next step, the Roundtable formed three groups, each of which focused on a different type of FAS, to identify the critical knowledge and technologies needed for the transformation. The three types of FAS were open-field systems, controlled-environment systems, and livestock systems. These diverse types of FAS present unique challenges and possibilities for transformation. At the same time, many issues (e.g., water and energy) are common to all FAS.

The three groups, each with seven or eight members, refined their chosen FAS. The open-field systems group focused on corn-soybean systems and systems for fresh-market tomatoes. The controlled-environment systems group chose the entire controlled-environment FAS, and the livestock systems group focused on beef systems and pork systems. These systems were selected based on their products (food or nonfood) and the product flow through their value chains.

This approach to FAS based on the entire value chain, rather than just the end products, provided a clearer pathway for tracing, studying, and redesigning the entire FAS. In a month-long effort, the three groups described the value chains of their chosen systems, developed preliminary designs for circular systems, identified gaps in knowledge and technology, and developed first-draft graphical representations of the transformation of the current systems to circular systems.

At the second meeting of the Roundtable, each group refined its graphical representation of the circular system. The pathways to circularity differ depending on the products and processes involved in the value chain, including processes for the looping of losses and wastes. When focusing on circularity in an individual FAS subsystem (such as production), the groups recognized that it was also important to consider the consequences of adjacent subsystems. In other words, the process for making one subsystem circular must be in harmony with the processes for making the other subsystems circular.

In addition to graphical representations of their circular systems, the three groups also prepared written reports on their circular systems and pathways for transformation.

In this issue

The articles in this issue present the work of the three groups. Each FAS varied due to variations in components and environments, and thus the proposed solutions also varied. However, several important considerations were common to all systems:

- Identifying the system's components, boundaries, scale, and environment, as well as its current losses, inefficiencies, wastes, and impacts.
- Considering future environmental and climate conditions.
- Envisioning solutions that achieve circularity, sustainability, and resiliency.
- Using data, models, and other tools to predict system performance, including tradeoffs among the objectives.
- Developing standards for measuring and documenting progress toward the multiple goals.

Each of the following articles describes the characteristics of a selected FAS and the external drivers (such as resource availability, climate, environment, policy, and technological innovations) that can impact the transformation to a circular system. Schematics, conceptual maps, and graphical representations of the envisioned circular systems are included, as well as pathways for completing the transition by 2050 in three phases: near term (2021-2030), intermediate term (2031-2040), and the final phase (2041-2050).

These articles will serve as a basis for scientific papers and other publications to communicate the importance of circular systems to a wider audience. This issue of *Resource* is also an invitation to ASABE members and other professionals to participate in transforming FAS to circular systems.

Transforming Food and Agriculture to Circular Systems (TFACS) is a historic opportunity to meet the increasing demands for food and other products, move toward zero waste, conserve the Earth's natural resources, and protect the health of ecosystems. This is a global challenge, the deadline is 2050, and ASABE has a pivotal role to play.

Author information for **James Jones, Brahm Verma, Bruno Basso, P.E., Rabi Mohtar, and Marty Matlock, P.E.,** is available on page 6.

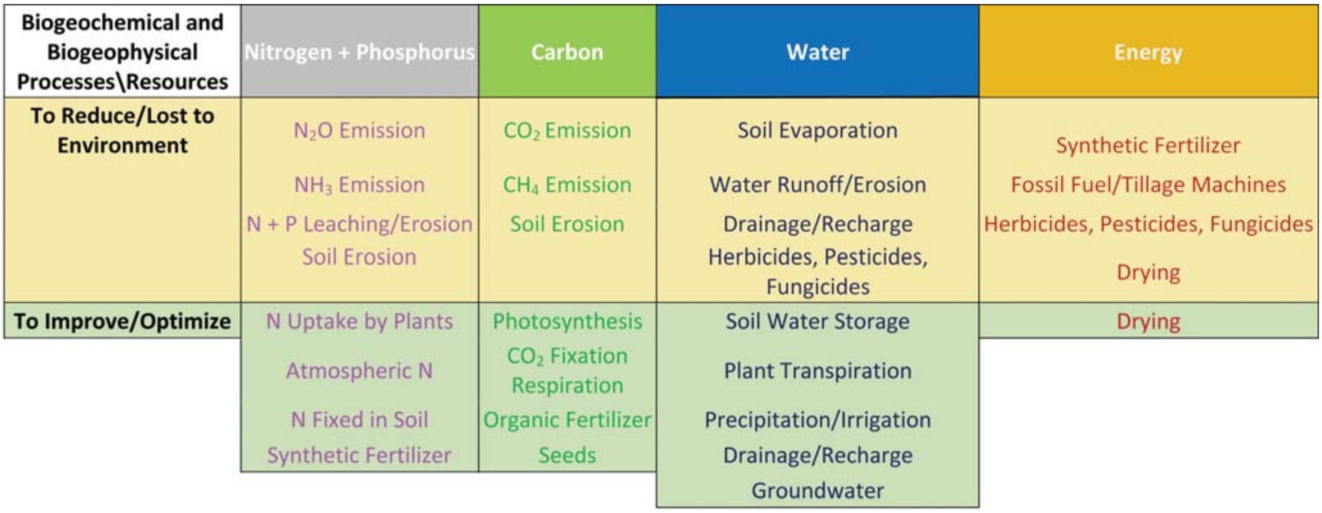
Designing Circularity into Corn-Soybean Systems

Bruno Basso, P.E, James Jones, Tom Richard,
Charles Sukup, P.E., Lalit Verma, P.E., Marty Matlock, P.E.,
Rabi Mohtar, Stephanie Herbstritt, and Rafael Martinez-Feria

Corn-soybean rotations are the predominant U.S. cropping system in terms of land area (92 million acres of corn and 84 million acres of soybeans; USDA, 2020), production (346 million tons of corn and 119.5 million tons of soybeans), and economic value ($75 billion from corn and $21.5 billion from soybean). More than 70% of U.S. corn was used for livestock feed or ethanol in 2019, while only a small percentage went to human consumption. In addition, corn productivity comes with environmental costs, chiefly in the form of greenhouse gas (GHG) emissions and water pollution. In this article, we briefly discuss the steps needed to transform our current linear corn-soybean systems into circular subsystems for open-field production of corn and soybeans in the U.S. Midwest.

Current corn-soybean systems

Two subsystems are considered here: corn production (including crop growth and harvesting) and grain drying. The inputs include land rental, seed, fertilizer, pesticides, labor, equipment, energy (for tillage, planting, treating, and harvesting), irrigation, grain drying and storage facilities, and transportation. Figure 1 is a summary of the biogeochemical processes and resources that are currently lost to the environment or that need to be reduced, improved, or optimized in the corn-soybean systems of the U.S. Midwest.



Biogeochemical and Biogeophysical Processes\Resources	Nitrogen + Phosphorus	Carbon	Water	Energy
To Reduce/Lost to Environment	N_2O Emission NH_3 Emission N + P Leaching/Erosion Soil Erosion	CO_2 Emission CH_4 Emission Soil Erosion	Soil Evaporation Water Runoff/Erosion Drainage/Recharge Herbicides, Pesticides, Fungicides	Synthetic Fertilizer Fossil Fuel/Tillage Machines Herbicides, Pesticides, Fungicides Drying
To Improve/Optimize	N Uptake by Plants Atmospheric N N Fixed in Soil Synthetic Fertilizer	Photosynthesis CO_2 Fixation Respiration Organic Fertilizer Seeds	Soil Water Storage Plant Transpiration Precipitation/Irrigation Drainage/Recharge Groundwater	Drying

Figure 1. The biogeochemical processes and resources that are currently lost to the environment or that need to be reduced, improved, or optimized in corn-soybean systems in the U.S. Midwest.

Plants rely on atmospheric carbon dioxide for photosynthesis, with carbon making up about half of the plant biomass. Carbon and nutrients that are not removed in the grain return to the soil as residue, building up carbon in the soil organic matter. Soil tillage and drainage, which are widely practiced in the Midwest, accelerate the decomposition of soil organic matter, releasing carbon dioxide into the atmosphere.

In addition to the GHGs emitted during fertilizer manufacturing, the use of nitrogen fertilizers can lead to large quantities of nitrous oxide (a potent GHG) and ammonia emissions from crop fields. Fertilizer not taken up by crops runs off the fields and contributes to downstream water pollution, including the hypoxic zone in the Gulf of Mexico. Fossil fuels for crop production, harvesting, drying, and transportation further contribute GHGs.

Resource inputs, flows, losses, and outputs

Figure 2 shows the on-farm processes for corn, including inputs obtained from external sources, on-farm cycling of carbon (C), nitrogen (N), and water, their flows into the surrounding environment, and outputs in the form of grain sales. A circular perspective can identify changes in inputs and operations that could help farms be more productive, sustainable, and efficient users of multiple resources.

Regrettably, current practices are not yet driven by increasing resource use efficiency or by providing ecosystem services, but instead are mostly based on production incentives. Although some resources are recycled on farms, other subsystems (including livestock production, meat processing, sales, and consumption) have losses and wastes that could be recycled or transformed for use as inputs to farming systems.

For example, as one option for increasing circularity, figure 2 shows that production wastes from nearby livestock facilities could be cycled back into the corn system. Other strategies to increase the circularity of farming systems include the choices of inputs, on-farm production of renewable energy, and the use of biofertilizers that are transformed from losses and wastes.

The losses of C, N, and water to the environment are much larger than their outputs in grain sales and thus represent opportunities for increased circularity and resource use efficiency. Significant losses include gaseous flows to the atmosphere (e.g., GHGs and water vapor), losses to landfills (e.g., food waste), and environmental degradation (water pollution and soil loss).

We specifically examined N cycling in rainfed corn-soybean cropping systems for livestock feed in the U.S. Midwest, focusing on N cycling through the return of crop residues to the soil and the application of livestock manure, which together provide the main circularity for N cycling in current systems. The inputs included fertilizer, soybean N fixation, and atmospheric deposition. Undesirable N losses to the envi-

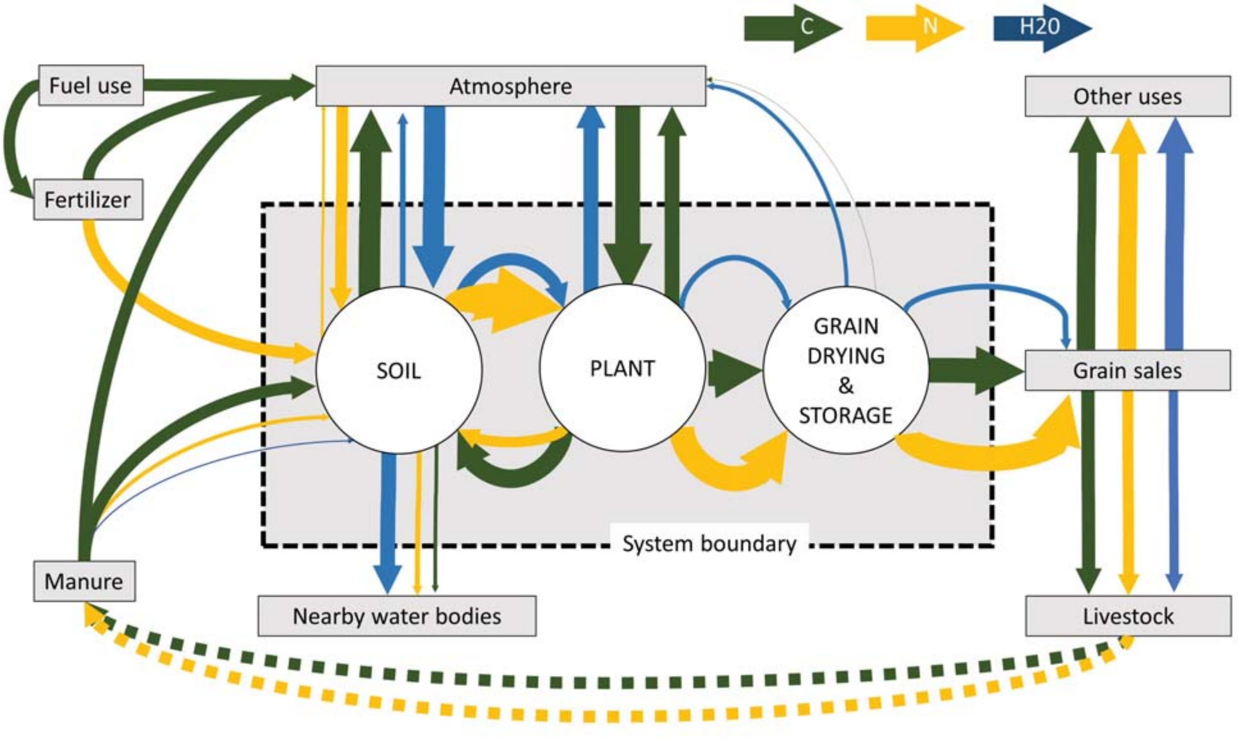


Figure 2. Flows of carbon (C), nitrogen (N), and water (H_2O) in a corn system. The solid arrows represent linear flows among the system components, inputs from fertilizers and the atmosphere, and outputs as grain sales. This diagram includes residue C and N returned to the soil, but it does not show all the losses and wastes from the system components (e.g., grain dryers and storage). The dotted lines show the possibility of reusing manure C and N from nearby livestock facilities.

ronment included gaseous emissions, N transported by water, and ammonia volatilization from manure. The desired N output was the grain sold for animal feed or other uses.

The circularity of N cycling in existing systems (i.e., the proportion of N returned to the soil) was estimated to be about 21%. If N fertilizer use was reduced by 36% (e.g., with more efficient fertilizer application technology) and environmental N losses were reduced by 50%, then the circularity of N cycling would increase to 30%, with dramatic reductions in the N losses to GHGs and environmental contamination. There are many other opportunities to modify current systems to make them more circular and meet multiple goals.

Drivers of change and future scenarios

Multiple drivers of change can make our agricultural systems more productive, efficient, and resilient. These drivers include changes in climate, the cost and availability of natural resources, consumer dietary preferences, government willingness to invest in solutions, traceability of products, technological innovations, and demand for labor along the value chain. The transformation to circular systems will also require tradeoffs among multiple objectives.

In addition to the drivers that affect the entire value chain, those that affect specific subsystems must also be considered. These subsystem drivers will include a continuing strong demand for grain to feed livestock. Corn and soybeans will be used mostly for animal feed, food products, specialty chemicals, and other high-value products, while production of biofuels from grain will decrease. Other subsystem drivers include technological innovations in genetics, automation, management systems, sensors, modeling, and data analytics. The cost of fossil fuel energy will continue to increase, making renewable energy more economically viable throughout the value chain.

Transforming to circular systems by 2050

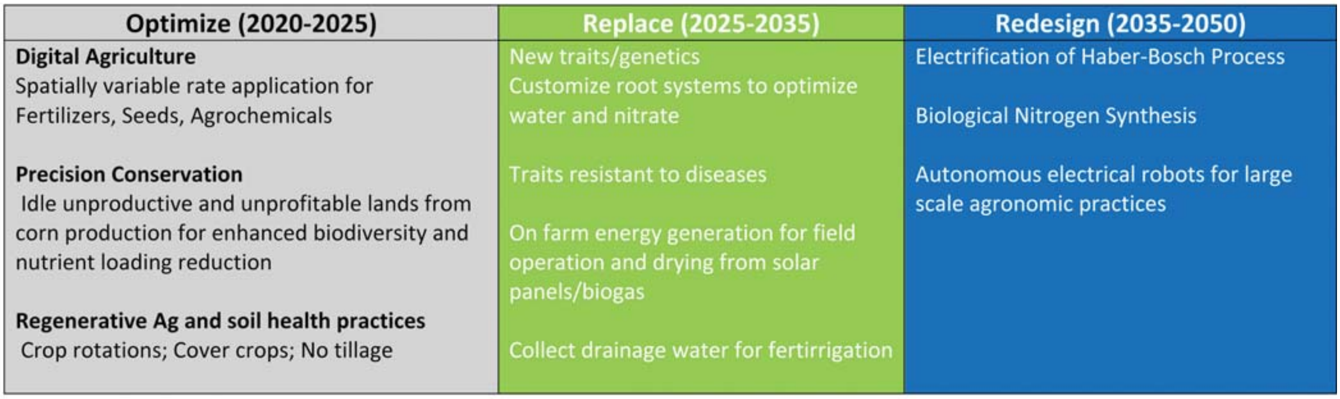
Current food and agriculture systems (FAS) are heavily dependent on fossil fuels to produce inputs, such as fertilizers and chemicals, and for tillage and grain drying. Currently, corn production contributes about 4% of GHGs in the U.S., while the entire FAS from farm to table generates nearly one-third of all anthropogenic GHGs worldwide. However, by increasing the use of renewable energy to manufacture inputs and power farm operations; implementing no tillage, cover crops, and perennial crops; sequestering carbon in the soil; and increasing nutrient and water use efficiencies, agriculture has potential to become the first economic sector to achieve net negative emissions.

When combined, these strategies will reduce agriculture's environmental footprint and increase resource use efficiency and productivity. These strategies also show promise for creating more circular corn systems at the field, farm, and regional scales that can be integrate into circular FAS value chains.

New research agendas and technologies for reducing wastes and enhancing ecosystem services are critical. For example, existing technologies for digital agriculture can determine the precise amount of N fertilizer to apply and identify land that is unproductive and unprofitable. Other examples include broader adoption of digital agriculture, advances in crop genetics, improvements in on-farm renewable energy, electrification, autonomous vehicles, and robotics. Other opportunities include technologies for capturing and reusing discarded resources in FAS value chains and producing affordable inputs that reduce GHGs.

New policies and investments are needed to stimulate the needed innovations. Successful policy changes will enable development of revenue streams that attract private investments for near-term benefits and guide public investments for future improvements. Incentives could include payments for ecosystem services, grain valuation methods, insurance adjustments, interest rates on borrowing, grant support, and renewable energy credits. These incentives will allow producers to adopt beneficial practices while remaining profitable.

Figure 3 illustrates the transition to circularity in three phases. These phases involve reducing GHGs, nitrate leaching, soil carbon losses, and energy use, and improving water



Optimize (2020-2025)	Replace (2025-2035)	Redesign (2035-2050)
Digital Agriculture	New traits/genetics	Electrification of Haber-Bosch Process
Spatially variable rate application for Fertilizers, Seeds, Agrochemicals	Customize root systems to optimize water and nitrate	Biological Nitrogen Synthesis
Precision Conservation	Traits resistant to diseases	Autonomous electrical robots for large scale agronomic practices
Idle unproductive and unprofitable lands from corn production for enhanced biodiversity and nutrient loading reduction	On farm energy generation for field operation and drying from solar panels/biogas	
Regenerative Ag and soil health practices		
Crop rotations; Cover crops; No tillage	Collect drainage water for fertirrigation	

Figure 3. Three phases of solutions for transforming linear corn-soybean systems to circular systems in which waste is reduced and resource use efficiency is enhanced.

quality, irrigation efficiency, and energy generation on farms. Northup et al. (2020) discussed the criteria needed for reducing GHGs from agricultural systems. We expand on their approach to focus on transforming linear systems into circular systems in which multiple resource losses and wastes are considered in order to achieve additional goals.

Eliminating or greatly reducing losses provides benefits for farmers and the environment, because losses cause pollution and reduce farm revenue. The policies and technologies that support the development of circular agricultural systems during the three phases are based on their level of readiness and their potential for adoption. The first short-term phase aims at optimizing current technologies and practices, the middle phase replaces current technologies with new solutions, and the third phase emphasizes redesigning and implementing the system components.

Phase 1: Optimize current technologies

The initial steps toward circular FAS should focus on using existing technologies for reducing GHGs and nutrient losses from areas within fields where yields are consistently low. As shown by Basso and Antle (2020), digital agriculture allows precise quantification of the spatial and temporal variability of environmental conditions. In the U.S. Midwest, about 50% of nitrogen fertilizer is applied at higher rates than the crop needs, with little to no benefit for yield. New geospatial systems can identify zones of varying performance within a field, enabling efficient, variable-rate application of fertilizers and variable timing of harvests.

Figure 4 illustrates the benefits of using the latest sensing technologies for soil, plant, and atmospheric conditions, integrated with artificial intelligence and on-farm tools to optimize the placement of inputs. As regenerative practices

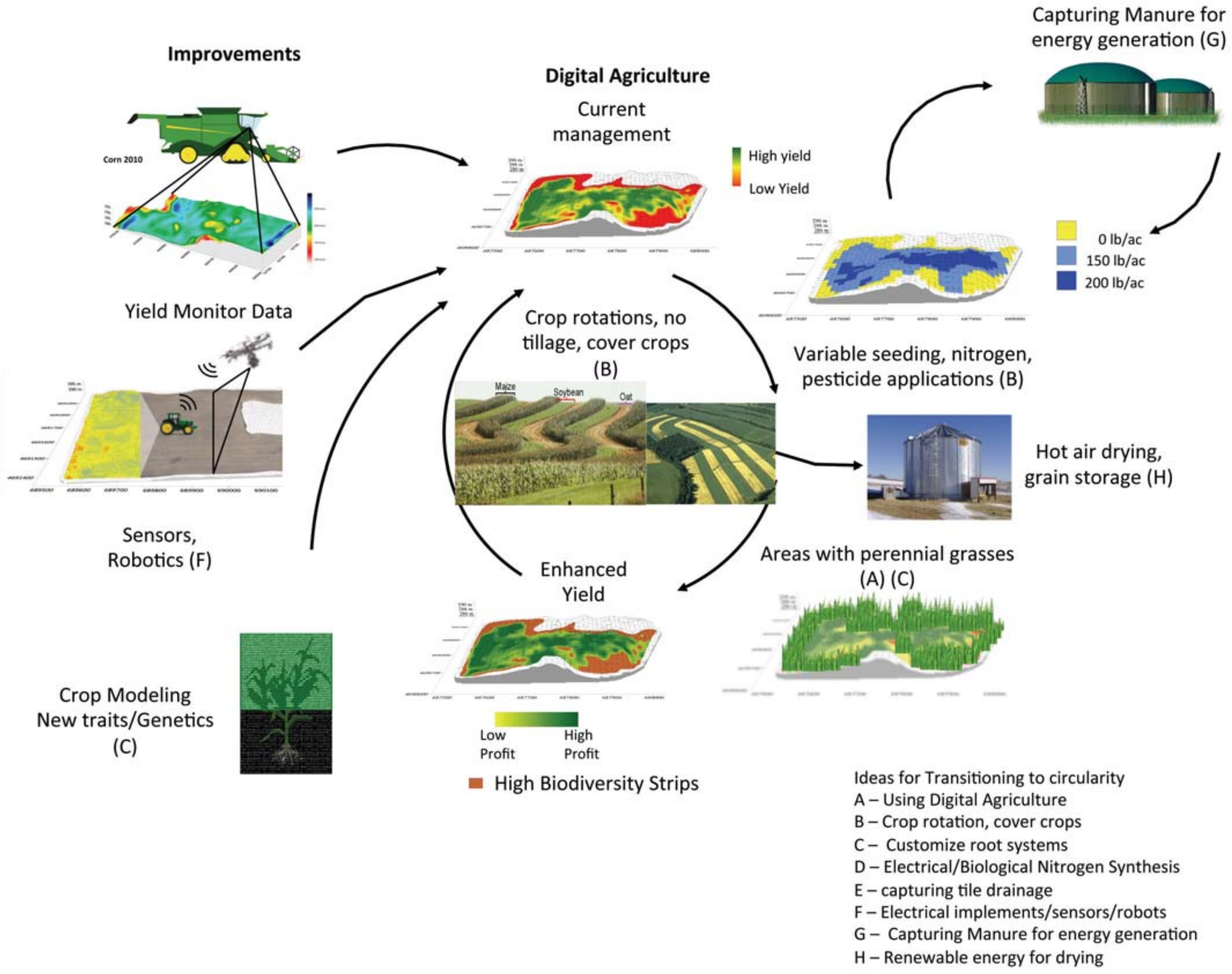


Figure 4. Ideas for transforming current corn-soybean systems to circular systems by combining sensing technologies and big data at the farm and landscape level to inform policy analysis, system design, and implementation.

become more widely adopted, more innovations will be needed for measuring and modeling soil carbon. Unproductive areas with low and unprofitable yields can be used for cover crops or native perennials, enabling farmers to provide additional ecosystem services, such as biodiversity, bioenergy, or alternative markets.

Phase 2: Replace outmoded technologies

In the second phase, new technologies and policies are developed to achieve the multiple goals of productivity, efficiency, and sustainability. We expect that acceptance of new technologies will occur relatively quickly in this phase, including new genetics for disease resistance and other desirable traits, such as deeper root growth. Stronger disease resistance will allow reduced use of agrochemicals for crop protection, while deeper roots will allow more efficient use of resources from deeper soil layers. New genetics could also reduce the moisture content of harvested grain, which would greatly reduce the energy needed for drying. In addition, innovations in fertilizers and application technologies will increase nutrient uptake efficiency and reduce losses to the environment.

On-farm energy generation is already happening, but new resource capture capabilities can be developed for quicker and broader adoption (e.g., large-scale manure digesters, solar panels on unproductive land, and nutrient capture of tile drainage for use in fertigation). Autonomous farm robots are commercially available, and their use will continue to expand. New biological materials and genetics for microbial fixing of N on roots, for species that cannot do this on their own, could reduce chemical fertilizer use.

Phase 3: Redesign system components

In the final phase, we envision electrification of the Haber-Bosch process for producing nitrogen fertilizers using alternative methods, including on-farm production. The use of renewable energy for producing fertilizers and other agrochemicals could reduce current GHG emissions by 75% or more. Sustainable intensification and regenerative practices for livestock and crops can optimize the innovations achieved in phases 1 and 2.

Transitioning to circular FAS requires incentives to inspire investment, design, and adoption of new technologies and practices. A useful approach for resolving the tradeoffs among alternatives and selecting optimum combinations of technologies and practices is the use of a digital twin to model a system and analyze possible solutions. Monitoring of real systems can confirm the model results and prevent problems before they occur.

Conclusions

Achieving sustainable, resilient, and productive circular systems will require significant planning by a broad group of stakeholders to develop appropriate policies and promote investment. By mapping inefficiencies, identifying losses and wastes, and using inputs with small environmental footprints, solutions can be identified, prioritized, and pursued in phases. Technologies already exist that can initiate the transformation or our current corm production and drying subsystems to circularity.

Further transformation can be guided using models that account for cycling and wastes in subsystems and across the entire value chain for the near-term, mid-term, and long-term phases of implementation. Next-generation models are needed to quantify the risks, uncertainties, and tradeoffs in the decision-making process. Ultimately, these innovations will enable agriculture to transition to circularity by 2050, which is the goal that we must achieve.

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Circular Open-Field Systems for Fresh-Market Tomatoes

Kati Migliaccio, P.E., Claudio Stockle,
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Current open-field production of fresh-market tomatoes is mostly linear, resulting in unsustainable and wasteful systems. Opportunities exist to transform these systems to achieve greater circularity, and many of these ideas are applicable to other fresh-market vegetable and fruit production systems. In this article, we discuss a few of these ideas with the aid of a Sankey diagram that shows a 2050 vision for open-field fresh-market tomato systems. This article also describes the process that can transform current linear open-field fresh tomato production toward circularity.

Our diagram of the future (fig. 1), which was created with the help of the d3 Sankey library (https://github.com/d3/d3-sankey), shows the flows of carbon, energy, nitrogen, and water in a circular system, with minimal losses and greater resiliency. The vertical bars represent the nodes in the system (categorized by color) to and from which carbon, energy, nitrogen, and water flow. These flows can vary depending on a particular system's characteristics. The example system shown here represents highly circular, automated open-field tomato production, with primary and secondary markets, and functional and recyclable packaging. The assimilation node (in the upper right corner of the diagram) represents the output of carbon, energy, nitrogen, and water for consumption, by humans or animals.

Automation and robotics

Automation supports circularity by creating more efficient production practices that require fewer inputs and prevent waste. Current production of fresh-market tomatoes is a high-input, labor-intensive process. Robotic harvesting and tomato plants with amenable architecture, aided by breeding and high-throughput phenotyping, could modify production to be less dependent on human labor, which is increasingly difficult to acquire.

Mechanical harvesting of processing tomatoes has existed for many years, with fruit removed from whole plants that have been extracted from the field. Efforts at mechanical harvesting of fresh-market tomatoes are beginning, but further development is needed to produce plant varieties with amenable architecture.

Robots for harvesting and other field activities are being designed with vision systems and artificial intelligence. However, the current technology does not achieve the high throughput of human workers. Robotic harvesting of specialty crops such as tomatoes could be achieved with further investment and focus on key elements, including low-cost navigation and control, more accurate vision using deep learning, and reliable manipulators that protect the product quality required for fresh-market sales. In particular, advances in soft robotics are needed for manipulating fragile agricultural products, such as tomatoes and other fresh produce.

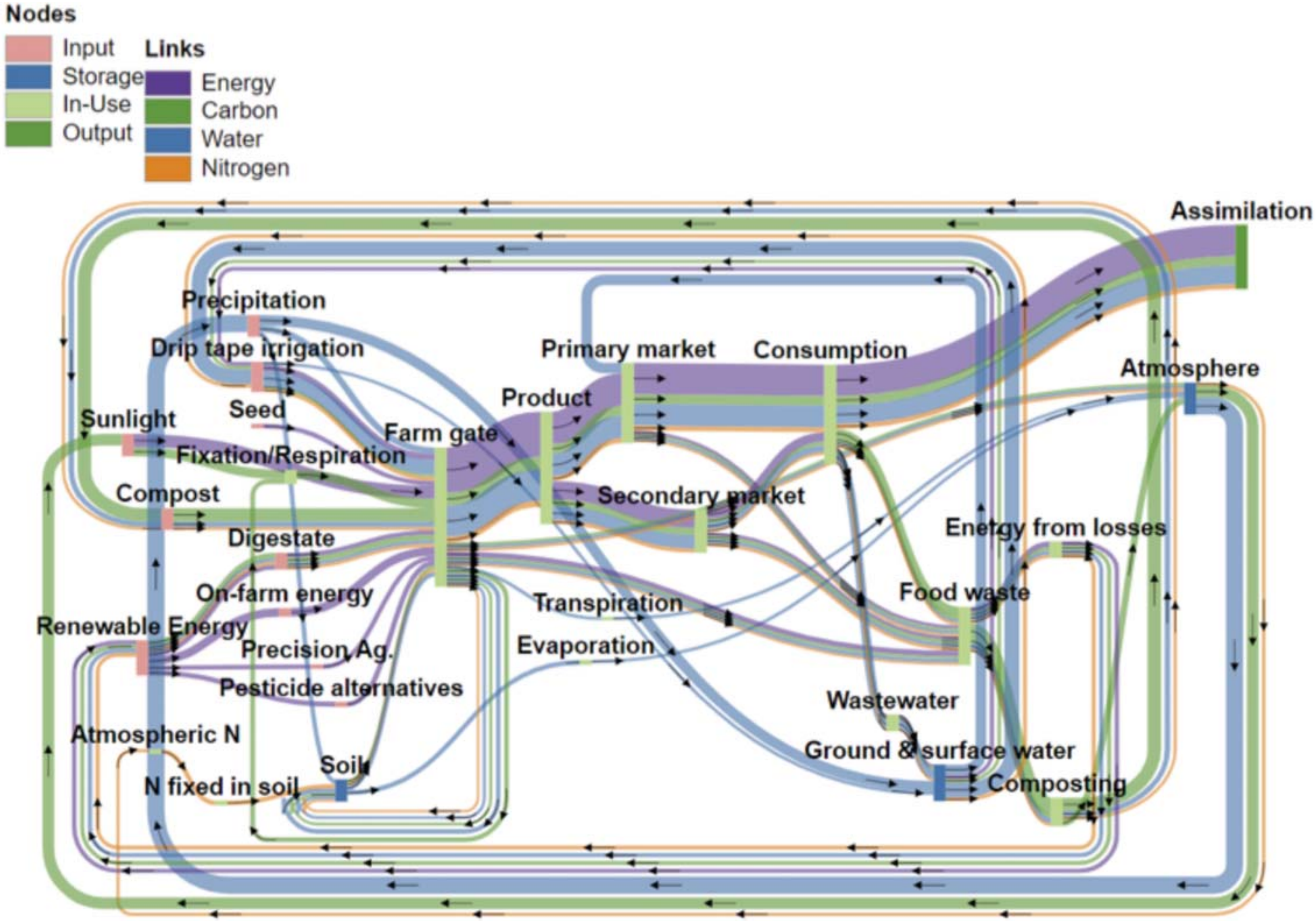

Figure 1. Sankey diagram of a circular open-field fresh tomato system in the year 2050.

Complete automation, from planting to harvest, of open-field systems, is possible by 2050. This vision of "farms without farmers" can be realized with continued advances in robotic technologies and artificial intelligence. The automation of production is represented by the farm gate node in figure 1, although many details are excluded, given the complexity involved. The proposed shift to automated production will change the skills needed in agriculture from predominantly manual labor to operations management and technical expertise. Thus, farm workers will need training to transition to these new roles.

The success of robotic harvesting and other automated processes (such as seeding, weeding, pest and disease detection, spraying, and scouting) in fresh-market tomato systems depends on convergent research among horticulturists, agronomists, breeders, crop physiologists, entomologists, and geneticists, along with agricultural, electrical, mechanical, and computer science engineers. Greater circularity of open-field fresh tomato systems also requires universal access to wireless internet, improvements in edge computing, cyber security, and a workforce capable of managing this advanced technology. With its expertise in agriculture, natural resources, engineering, and technology, ASABE is uniquely positioned to lead this transformation.

Dynamic market systems

Waste of usable product is a substantial loss in open-field fresh tomato systems. An average of 28% of the product is estimated to be lost before it even leaves the farm. Tomatoes are typically grown to meet a particular market and grade. Products that do not meet the desired standard are left in the field, fed to livestock, or discarded. Current production systems operate with a primary buyer in mind, such as grocery stores, restaurants, or institutional users. This type of system is sensitive to disruptions, including pandemics, pests and diseases, new regulations, shifts in consumer demand, changes in transportation, and severe weather. Such disruptions will continue to occur, so greater flexibility is critical for creating more resilient systems by 2050.

Multiple market streams are one way to reduce food waste and provide greater resiliency to system disruptions. Secondary (and possibly tertiary) market streams provide additional buyers in the local or regional market to serve customers who do not require unblemished (and higher priced) products. Local sales also allow a longer shelf-life, reducing waste, lowering transportation costs, and providing increased nutrition.

Another option that reduces waste, compared to current practices, is post-harvest processing. Other alternatives for products that are not suitable for the primary market include supplying emergency food relief, composting for nutrients, and producing non-food bio-products. These options would help transform a less sustainable system toward greater circularity. By 2050, tomato products are expected to be inputs for bio-plastics, 3-D printed food, dietary supplements, and other value-added goods. Another option is renewable energy generation through anaerobic digestion of food waste, which could help power the automation systems and machinery in open-field tomato production systems.

The success of tomato production systems in 2050, whether they consist of multiple markets, post-harvest processing, and/or value-added goods, will depend on the choices of policymakers and corporate buyers, as well as the development of highly integrated data streams with decision support tools.

The success of tomato production systems in 2050, whether they consist of multiple markets, post-harvest processing, and/or value-added goods, will depend on the choices of policymakers and corporate buyers, as well as the development of highly integrated data streams with decision support tools. The complexity of this production will benefit from a systems approach (or a network of networks). No single market system will fit all production situations, and the "best" system may differ for different producers and in different years.

Therefore, knowledge of each farm, including its productivity and its market opportunities, will be needed to identify optimal market streams that lead to greater circularity and less waste. Our example in figure 1 represents an open-field fresh tomato system with two markets, primary and secondary, for which fresh product is produced. By 2050, wastes that cannot be captured in secondary and tertiary markets or that are generated by consumers (e.g., post-retail waste) will be recycled through energy conversion and composting. ASABE's expertise in anaerobic digestion, bio-plastics, and dynamic systems modeling will contribute to these future systems.

Postharvest packaging and distribution

Post-harvest packaging and distribution offer substantial opportunities for achieving greater circularity. We considered two post-harvest process areas: one focusing on post-harvest packaging and recycling of the packaging material, and the other focusing on food traceability and distribution. Further opportunities for a transition to circularity exist in transportation (from field to fork) and in washing and handling practices. Another necessary advance is conversion of the transportation fuel used in post-harvest distribution from today's fossil fuels to renewables by 2050.

Post-harvest packaging

Fresh tomatoes are packaged and sold in various types of plastic and paperboard clamshells, trays, and overwraps. Better performance of the materials used for storage and distribution can reduce food waste, resulting in better product quality and less loss. Packaging designed for recycling also increases circularity through the reuse of materials. By 2050, increasing the recycled material content of the packaging, overcoming the disadvantages of mechanical recycling (such as "downcycling"), and improving the collection and sorting technologies for recycled materials will be central to the post-consumer stage.

Greater circularity in recycling is possible, with different systems likely benefiting from different combinations of solutions. Sensing technologies, such as high-resolution near-infrared (NIR) spectroscopy, can improve the sorting of recycled materials for reuse. Another solution is chemical recycling, in which packaging waste is used to produce refinery feedstock, fuel, and monomers. Thus, "lifecycle thinking" that considers increased quality and reduced losses of the packaged product, as well as increased reuse of the packaging materials, is essential for circularity.

Traceability and distribution

In addition to how a product is packaged from field to fork, tracking of a product in the food system can identify ways to increase circularity through better understanding of each part of the process and through modeling studies to identify alternatives that result in less waste. These analytical tools can be implemented for open-field fresh tomatoes to develop strategies for finding alternate markets and responding to system disruptions. Future food systems will be able to assess their circularity and transition to greater circularity using data-driven solutions.

Data collection methods continue to advance, providing a variety of data streams. Tools such as radio-frequency identification (RFID), near-field communication (NFC), freshness sensors, and time-temperature indicators (TTIs) used with an internet of things (IoT) and internet of packaging (IoP) can provide continuous, geographically referenced data with easy integration into cloud databases. Predictive technologies, block chain, and data sharing for analysis of these data streams will increase the efficiency, trust, and visibility of our food systems and will indicate how modifications throughout the value chain affect circularity.

Post-harvest handling, packaging, and distribution are key elements for meeting the 2050 circularity goals for open-field fresh tomato production. Expertise in sensor development, data management, traceability modeling, and AI tools will be needed to identify paths toward circularity. In particular, finding solutions to the problem of packaging waste is critical. Solving these complex problems will require multidisciplinary expertise to discover alternatives that are beyond the scope of any single discipline, which is another strength of ASABE.

In our Sankey diagram, the conversion of food waste is linked to the renewable energy and composting nodes. However, the diagram does not show the detailed flows associated with packaging reuse. If those flows were added, packaging reuse would flow from consumption to new products. The entire system shown in figure 1 would be traceable to provide the detail needed to assess alternatives and measure the progress toward greater resiliency. Also excluded from figure 1, for simplicity, is the potential to recycle the plastic mulch used in field production of tomatoes, as well as the potential of cover crops to reduce the need for plastic mulch.

Closing thoughts

Fresh vegetable and fruit systems that include open-field production must achieve greater circularity to remain viable in 2050. Significant progress is needed in robotics and automation. Redesigning fresh-market produce streams to include new products and markets and to reduce waste will require the support and cooperation of policymakers, corporate buyers, and consumers. Redesigning packaging for reuse and for advances in distribution will also be essential. The Sankey diagram in figure 1 includes other potential transition points to further explore the mass flows in open-field fresh tomato systems. Although this article does not address post-retail losses, additional improvements are needed to reduce waste in the post-retail stage of the food chain.

Circularity of open-field fresh tomato production in 2050, and the resulting sustainability of this food system, can be achieved, but it will require dedicated researchers, producers, and policymakers. These efforts will rely on industry, stakeholder-respected extension programs, and land-grant universities with their strong interdisciplinary expertise (social sciences, basic research, and applied research in natural resources and agricultural topics). Land-grant resources will be particularly important in developing the educated workforce needed for the transformation to circularity. ASABE is prepared to provide leadership in all these areas.

> Solving these complex problems will require multidisciplinary expertise to discover alternatives that are beyond the scope of any single discipline, which is another strength of ASABE.

Author information for **Kati Migliaccio, P.E., Claudio Stockle, Zynet Boz, Changying Li, Stephanie Herbstritt, and Kelly Morgan** is available on page 6.

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Controlled Biology-Based Indoor Circular Food Systems

Norman Scott and K.C. Ting, P.E.

With projections that the global population will grow to 9.5 billion by 2050, there is pressing concern about how this population will be fed. Can food be produced sustainably, what will constitute a healthy diet, will ecosystems be compromised, will we be able to reduce hunger and poverty, and can we enhance equity and access to food for the global population?

The answers will depend on our food and agriculture systems, but what does that term mean? A report from the National Academy of Sciences, Engineering, and Medicine characterizes food and agriculture systems (FAS) as complex adaptive systems that operate across a broad spectrum of economic, biophysical, and sociopolitical contexts (NRC, 2015).

Our future FAS must also include circularity. The goal of circularity is to minimize waste and pollution, keep products and materials in use, and regenerate the natural systems within FAS. Circularity was introduced by the Ellen MacArthur Foundation as a strategy for achieving sustainable urban food systems by 2050. That report (EMF, 2019) defined three objectives for urban food systems: growing food regeneratively (and locally where appropriate), designing and marketing healthy food products, and making the most of food. Specifically, technologies and systems are needed along the entire food chain to reduce food loss and waste, which are estimated to be as much as 50% globally, with remarkable similarity across regions (FAO, 2011).

We already have a highly advanced FAS thanks to advances in digital agriculture, artificial intelligence, sensors, internet of things (IoT), genomics (such as CRISPR), drones, and robots. However, current FAS depend on land for production. New types of FAS, with reduced land use or even without soil in indoor facilities, are now emerging. We call these systems "controlled biology-based indoor food systems," or CBIFS.

The focus of CBIFS is the development of new food products that mimic traditional forms. Like all materials, foods are an assemblage of molecules arranged in a specific structure. CBIFS represent a significant new effort to build foods from the bottom up, starting with individual plant or animal cells. Because they use biochemical building blocks from plants and animals to create proteins, carbohydrates, fats, and oils, CBIFS are agriculture, but in a new form.

While much of the hype regarding CBIFS has been directed at beef (Purdy, 2020), there has been substantial development of other alternative foods, such as eggs, fish, milk, yogurt, chicken tenders, and chicken wings, to name a few. The development of foods via CBIFS is being driven by several factors:

- Environmental concerns (less energy, water, and land use).
- Removing the effects of weather and weather extremes.
- Lower food loss and waste.
- Shorter supply chains that promote local access.
- Reduced GHG emissions.
- Reduced water pollution.
- Reduction or elimination of pesticides and antibiotics.
- Potential for enhanced micronutrients.
- Elimination of animal welfare concerns, such as growing conditions and slaughter.

At the same time, critics of CBIFS have some legitimate concerns, including:

- The risks of production, particularly the capital cost.
- The time-line to market.
- Food safety and quality, particularly nutritional content and growth hormones.
- The cost to consumers.
- Potential contamination.

- The proprietary nature of the processes.
- The unproven technology.
- Whether CBIFS benefit large-scale economies to the detriment of markets for small farmers (NASEM, 2019; He et al., 2020).

Sustainability is critical for any future food system. Sustainability is typically defined in terms of environment, equity (or social responsibility), and economics. In broad terms, CBIFS seek to produce foods that impose less environmental impact, enhance human health, and reduce the ethical implications of traditional agricultural production, particularly for meat.

Meat consumption is estimated to increase globally by 3% per year to 2040. However, several studies forecast a major disruption of conventional animal agriculture. Foods engineered at the molecular level will increasingly replace meat and dairy products, leading to a reduction of 50% or more in conventional production by 2040 (A.T. Kearney, 2019; Tubb and Seba, 2019).

In this article, we present a brief overview of three types of CBIFS: plant-based alternative foods, cell-cultured food products, and 3D printing of food products. With further research and development, each of these systems has great potential for improving the reliability, sustainability, and circularity of global food production.

Plant-based alternative foods

The development of plant-based alternative foods is an active area, particularly for plant-based meat alternatives (He et al., 2020; Friend, 2019). Among more than 50 current manufacturers, three companies (Beyond Meat, Light Life, and Impossible Foods) are the leading developers of plant-based burgers, and their products are widely available in grocery stores, restaurants, and online.

Current FAS are estimated to generate as much as 25% of global greenhouse gas (GHG) emissions (Tilman and Clark, 2014). The opportunity for plant-based food alternatives to substantially reduce this environmental impact was demonstrated by a life cycle assessment (LCA) of Beyond Meat's plant-based burger and a U.S. beef burger (Heller and Keoleian, 2018). A comparison was also made to an LCA by the National Cattleman's Beef Association (Thoma et al., 2017).

The results were clear: Beyond Burger's production system generated 90% less GHG, with 46% less energy use, 99% less water use, and 93% less land use. Similarly, Impossible Foods commissioned a study which found that their burger uses 96% less land, 87% less water, and 89% less fossil fuel than a quarter-pound beef burger. Independent LCA studies would be beneficial, given the rapidly evolving ingredients for these plant-based alternative foods.

Plant-based protein sources, such as legumes and cereal grains, are an important alternative for both vegetarians and traditional meat consumers. However, challenges remain for developing plant-based proteins that provide nutrition as well as quality attributes (flavor, aroma, texture, and appearance) compared to traditional foods. In some ways, a comparison is a mixed story because plant-based meats provide about the same number of calories with more sodium and more potassium (Bohrer, 2017).

Plant-based protein sources, such as legumes and cereal grains, are an important alternative for both vegetarians and traditional meat consumers.

Further research on plant-based alternative foods is needed, including:

- Further evidence on environmental benefits, using LCA
- Further evidence on health benefits, nutrition, and safety
- Advances in developing new plant protein sources
- Reductions in the number of non-protein ingredients
- Reductions of cost.

In general, plant-based alternative foods require fewer inputs and shorten the value chain compared to traditional systems. These systems also have inherent opportunities for circularity (fig. 1).

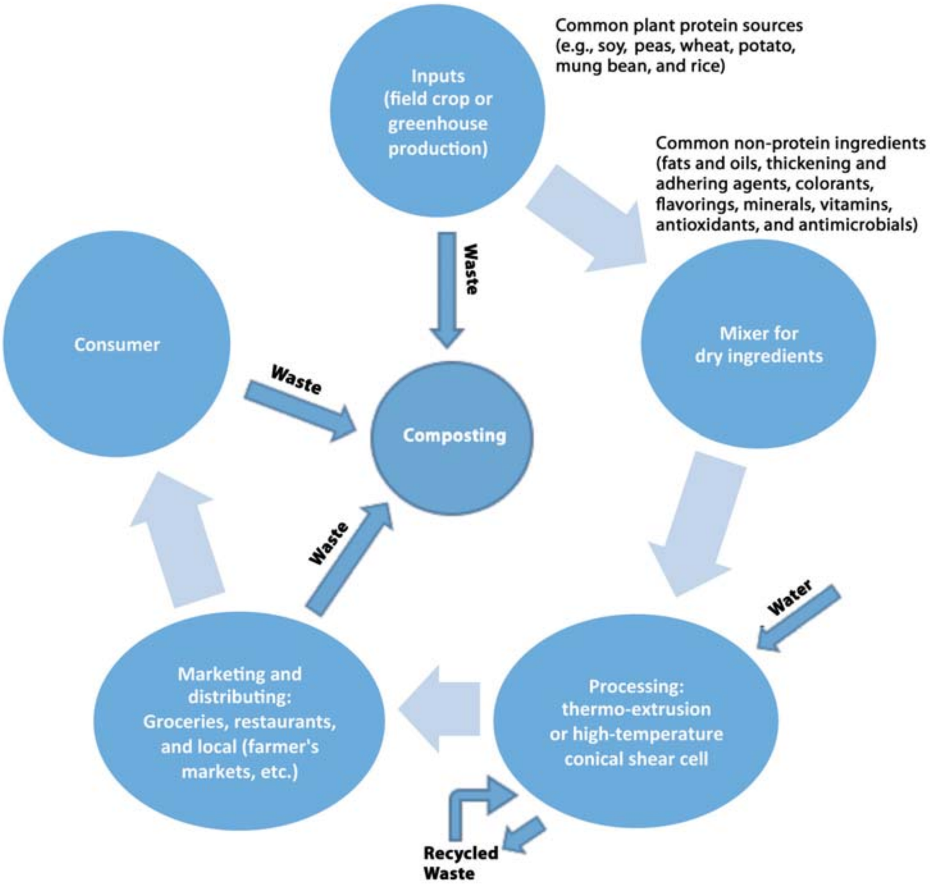

Figure 1. An illustration of a plant-based protein system with potential areas for circularity.

Cell-cultured food products

Over the past 20 years, the technology for cell-cultured meat has advanced at a rapid pace. The concept is simple: animal cells are cultured in a bioreactor to produce food products that mimic traditional meat products (Melzener et al., 2020). Compared to plant-based protein, which is extracted from plants, cell-based meat is created from cells that are extracted from living animals. Specifically, a small piece of fresh muscle, obtained by biopsy from a living animal, is disrupted by a combination of mechanical and enzymatic methods to produce stem cells (Post, 2013).

Using culturing methods, the adult stem cells (called satellite cells) are allowed to proliferate in the presence of high serum concentrations, leading to large populations. Tissue engineering methods are then used to differentiate these expanded cells into muscle and fat, which creates a cultured meat product that closely resembles conventional meat (Melzener et al., 2020). Figure 2 illustrates the process.

It's still difficult to reproduce the diversity of meat products available from different animal species, breeds, and cuts, so there is a great need to improve the cell culture technology (Chriki and Hocquette, 2020). Tuomisto (2019) reported that cultured meat required less energy, less land, less water, and had substantially lower GHG emissions in comparison with conventional meat production, depending on the specific product.

However, Chriki and Hocquette (2020) and Lynch and Pierrehumbert (2019) argued that the comparison is not that simple. They concluded that comparisons with conventional meat production depend on the type of energy generation (i.e., decarbonized and renewable) and the specific production systems. Thus, detailed LCA studies are needed for cultured meat production.

A major challenge is meeting consumer demands for flavor, texture, color, nutrition, and cost. As the development of cultured meat has advanced, its similarity to conventional meat has greatly improved; in fact, many people cannot tell the difference (Purdy, 2020). However, cultured meat systems need further refinement, including:

- Replacement of animal serum with plant materials
- Cost reduction through material substitutions and scalability
- Assessment of the short-term and long-term health effects
- Detailed LCAs to quantify environmental impacts
- Elimination of growth hormone factors
- Development of cell lines that can be propagated indefinitely
- Safety assessment, particularly with respect to contaminants that might enter the process

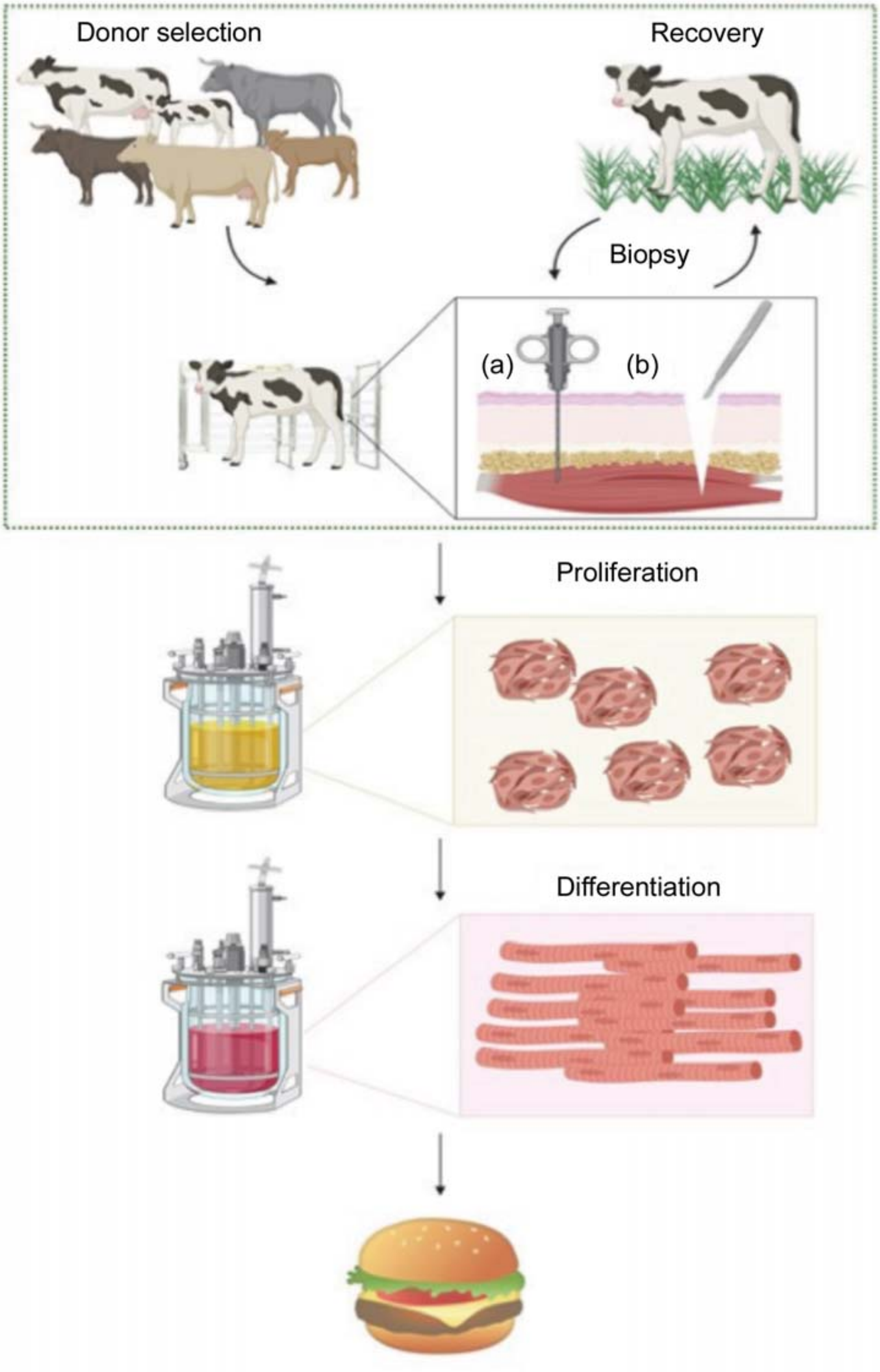

Figure 2. An overview of cell-cultured beef production. The inset compares (a) needle biopsy and (b) incision biopsy for harvesting muscle tissue (from Melzener et al., 2020).

- Replicating the diversity of meat products available from common animal species
- Establishing standards and regulations, particularly in labeling
- Developing standard marketing nomenclature, where there is currently much variation and uncertainty.

A recent study suggests that it may be possible to grow cultured meat with much less dependence on animals by using a soy-based scaffold to support the muscle cells, forming a meat-like 3D cell structure (Young and Skrivergaard, 2020).

Although cultured meat is not yet available at retail or food service outlets, at least 20 startups are operating (A.T. Kearney, 2019). With at least $100 million available in venture capital, this is a major area for development (Purdy, 2020).

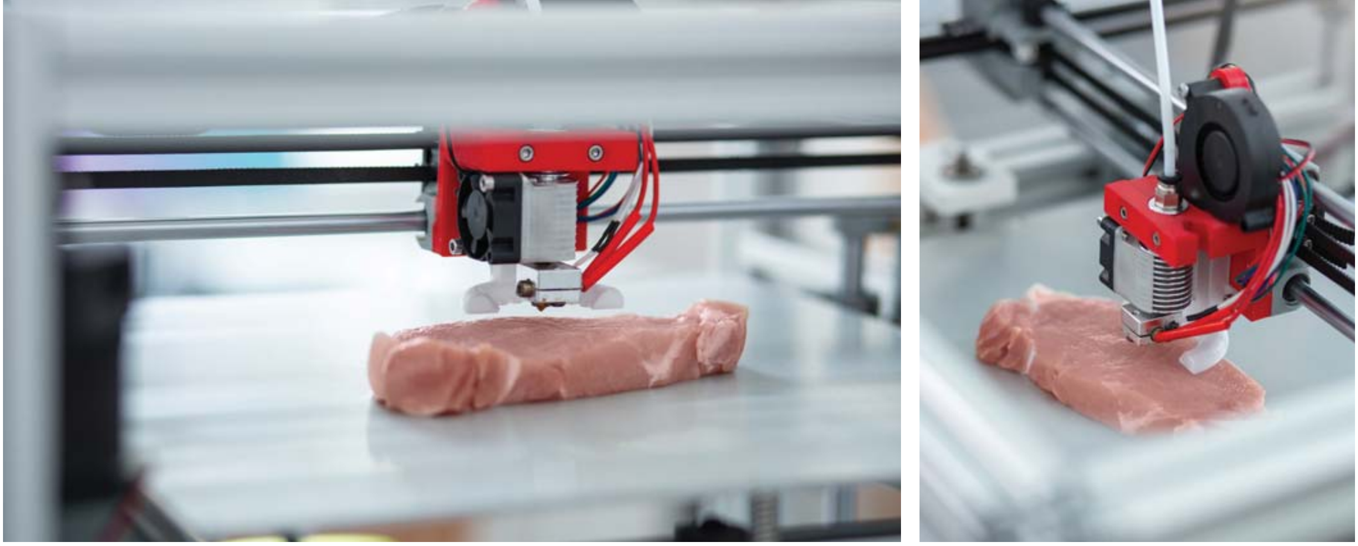

Figure 3. NovaMeat uses biomimetric micro-extrusion technology and custom 3D printing machines to develop plant-based steak and pork.

3D printing of food products

The combination of robotics and software has entered food manufacturing in the form of 3D printing (Dankar et al., 2018), which can create complex geometries, tailored textures, and desired nutritional contents. This technology can provide custom foods to meet specific dietary needs as well as mass production. In Spain, NovaMeat has used 3D technology to produce steaks and other meat products that resemble animal meat (fig. 3).

In the 3D printing process, food ingredients are placed in cartridges, and the product is created layer by layer, similar to the 3D printing of non-food items. Depending on the specific food, the ingredients can range from processed components (sauces, dough, etc.) to more elemental ingredients such as sugars, proteins, fats, and carbohydrates (Dankar et al., 2018). Some foods may require further processing, such as some form of cooking or specialized storage. The process is controlled by parameters related to the printing process and by parameters related to the food materials (fig. 4).

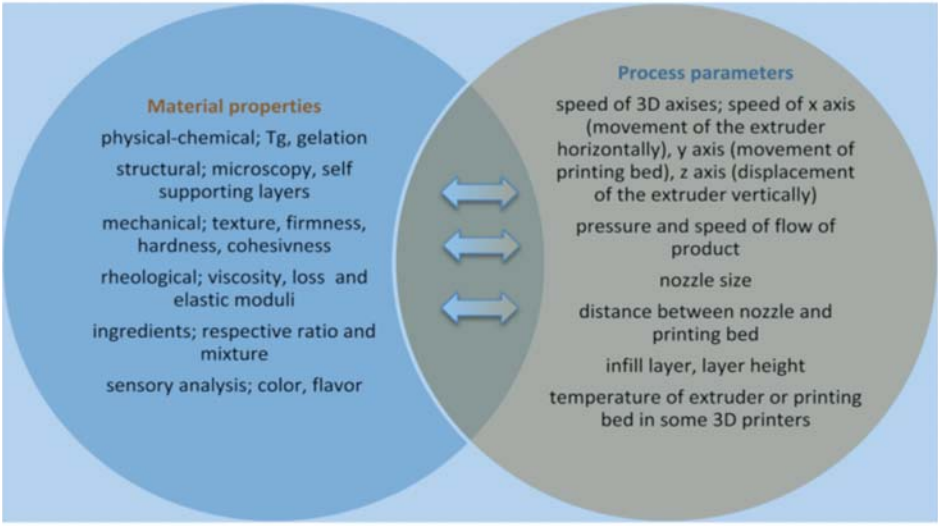

Figure 4. Material properties and process parameters for 3D printing of foods (from Dankar et al., 2018).

In Switzerland, Jungbunzlauer AG is providing recipe cards to guide consumers in the use of bio-based ingredients for dairy and meat alternatives, such as non-dairy ice cream and plant-based burgers. These recipe cards are available online (Jungbunzlauer, 2020). Each recipe card provides a detailed list of ingredients, suppliers, and quantities, together with directions for creating the specific food product and the nutrition information. This information could easily lead to 3D printing of highly specialized foods.

The 3D printing process compresses the value chain to a highly local system of inputs (the ingredients), a single controlled process (the 3D printer), and a single output (the food product). Recycling of wastes, if any, from the processing phase would provide circularity.

Conclusion

Meeting the food demand of the growing global population will require both conventional land-based agriculture and controlled biology-based indoor food systems (CBIFS). CBIFS will greatly reduce the land area required for agriculture, and they also include completely soilless production methods. CBIFS can produce foods that enhance human health, with less environmental impact, while avoiding the ethical concerns of traditional production methods, particularly for meat.

CBIFS should be viewed as complementary to traditional agriculture. Because they use biochemical building blocks, including proteins, amino acids, sugars, carbohydrates, fats, and oils from plants and animals, CBIFS have an agriculture origin and are therefore supplementary to conventional agriculture.

The development of biology-based food products that are as healthy, nutritious, safe, and appealing as conventional foods can help ensure the resilience, sustainability, and circularity of our food and agricultural systems. This is an outstanding opportunity for agricultural and biological engineers. The convergence of biotechnology, nanotechnology, information science, and cognitive science will be a useful interdisciplinary approach for this development (Scott et al., 2015).

In the meantime, CBIFS entrepreneurs, startups, and established companies already have products on the market. In most cases, these foods are more expensive than the equivalent traditional foods, but the cost difference is decreasing. As these efforts advance, it is likely that costs will further decrease and the market will continue to grow, with new players, new processes, and new products.

Author information for **Norman Scott and K.C. Ting, P.E.,** is available on page 6.

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Circular Controlled-Environment Plant Production Systems

K.C. Ting, P.E., Norman Scott, and Rabi Mohtar

Our food and agricultural systems (FAS) are a multi-scale, bio-based economic engine. To ensure the long-term viability of our FAS, the cycles of that engine need to be productive and sustainable. Historically, the FAS issues that have drawn the most attention include effectively managing the resources used to produce food, feed, fiber, and fuel, along with the modernization of agriculture using new knowledge and technologies. Today's FAS are the result of impressive advances in addressing those issues. However, our current FAS are still linear systems that are vulnerable to long-term risks and insecurities.

With the anticipated growth in the world's population, the reality of climate change, the demand for food quality as well as quantity, and limited availability of natural resources, future FAS will need to be vastly more efficient, ideally closed systems. Therefore, the transformation from linear to circular FAS is urgently needed for improving agricultural productivity, quality of life, and ecosystem health.

Greater circularity can be achieved by minimizing the environmental impact of FAS, optimizing the economic return, improving management capabilities, ensuring intelligent use of resources, understanding the desirable objectives and governing constraints, enabling creative productivity, interfacing the various subsystems with each other and with other economic sectors, identifying value-added opportunities, and creating a new circular economy to support circular production.

The FAS value chain, in its generic form, consists of the stages of production, harvest and storage, processing and packaging, sales, and consumption. In addition, transportation, distribution, waste management, and resource recovery are also involved and enable connectivity between adjacent stages and among all stages of the value chain. As a result, many opportunities exist for increasing circularity throughout the value chain.

Controlled-environment food and agricultural systems (CEFAS) are unique FAS because they are fast evolving, more controllable, more adaptive to advances in technology, more attractive to future farming professionals, easier to operate as closed systems, and less constrained by geographic and climate factors. These characteristics make CEFAS excellent candidates for the transformation to circularity. In particular, CEFAS include controlled-environment plant production systems (CEPPS). Opportunities for increasing the circularity of CEPPS, along with the value chain of CEPPS, were explored by our group at the ASABE Roundtable.

CEPPS have evolved from row covers in open fields to highly sophisticated operations, such as vertical farms and plant factories (fig. 1). CEPPS are more sustainable than conventional production systems because they greatly reduce the need for water, land, and chemicals. CEPPS are expected to continue to advance into autonomous, sustainably intensified urban FAS.

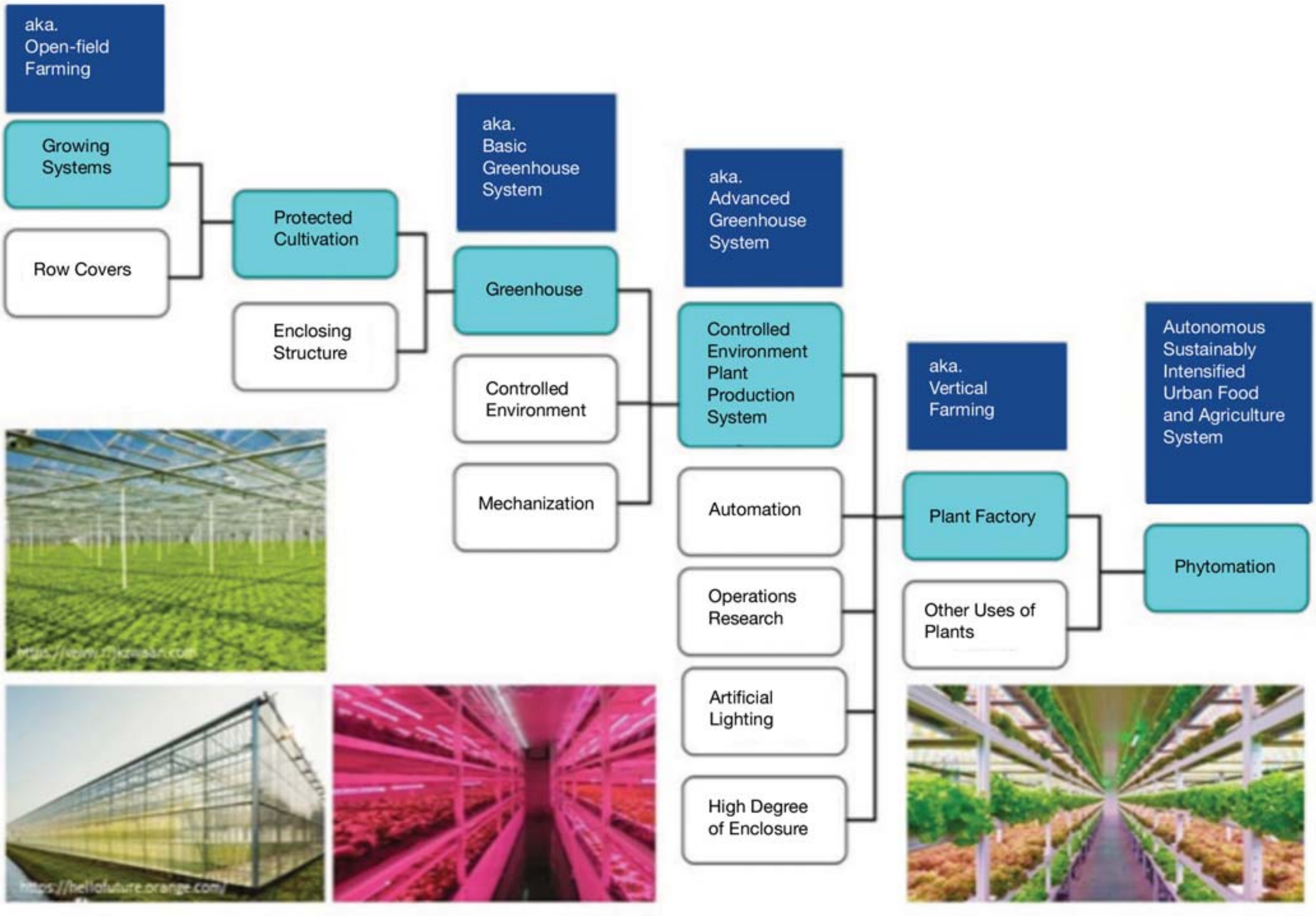

Figure 1. The evolution of controlled-environment plant production systems (CEPPS) from open-field farming to basic greenhouse systems, advanced greenhouse systems, and vertical farms and plant factories.

Three types of CEPPS have evolved sequentially and now co-exist: basic greenhouse systems, advanced greenhouse systems, and vertical farms and plant factories. These three types of CEPPS will continue to co-exist in the future. In addition, the opportunities for transformation to circularity for all CEPPS types are upwardly applicable, i.e., the opportunities for earlier versions will be readily applicable to later versions.

Basic greenhouse systems

Basic greenhouse systems protect crops from adverse weather (such as wind, rain, and snow) and from animal and insect pests, allow timing of the growing season, and improve the quantity (per unit land area) and quality of products. A basic greenhouse system is typically a covered structure that encloses the growing plants, while workers and simple machines perform necessary tasks within this modified environment. The crop growth media inside basic greenhouses are typically soil-based, and movement of individual plants during their period of growth is mostly limited.

Material handling and cultural tasks are primarily performed by human workers assisted by simple devices and equipment. Modification of the plant growth environment typically includes insolation through the translucent cover, heating with circulated air or water, and cooling with a combination of shading and natural or mechanical ventilation, and in some cases evaporative cooling. The low initial cost makes basic greenhouses an attractive investment for crop production. Improvements that can transform basic greenhouses from linearity to circularity, along the value chain and at the system level, are shown in figure 2.

Advanced greenhouse systems

Advanced greenhouse systems enhance the productivity of the crops, the human workers, and the entire facility through better management and operation than is possible with basic greenhouses. These enhancements involve the structural configuration, environmental control, crop production, material handling, labor utilization, resource allocation, and return on investment.

The improvements to the system, including computer control of the environment, innovative crop growing systems (such as nutrient film, ebb and flood, deep flow, and non-soil

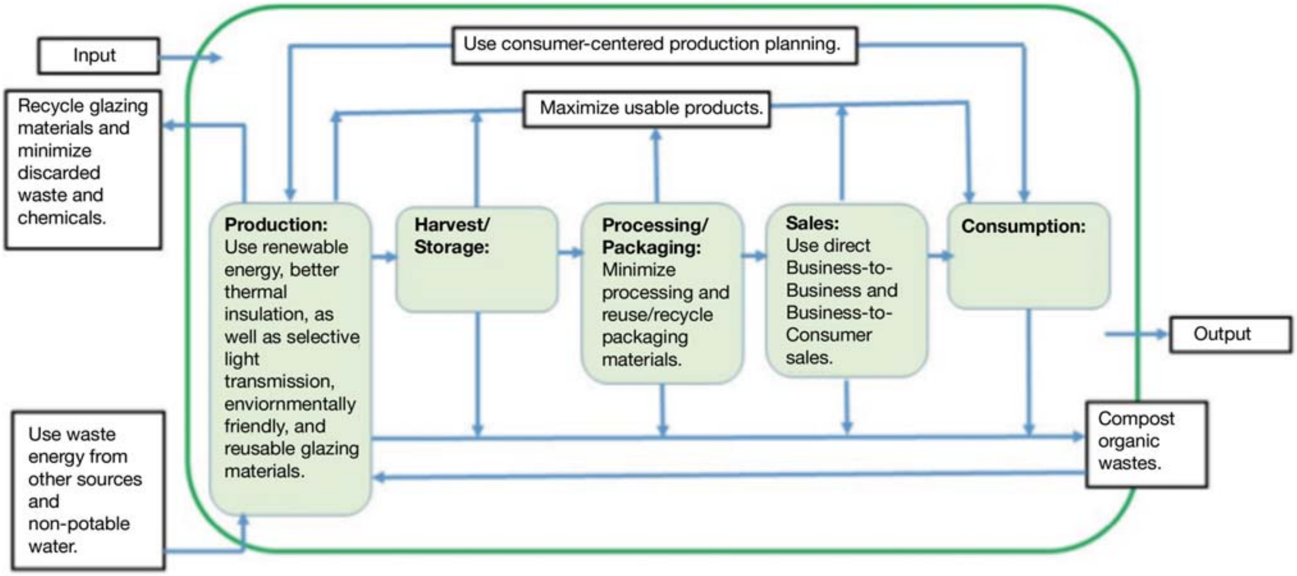

Figure 2. A basic greenhouse system with circularity. System-level opportunities include integration with open-field production systems and better planning throughout the value chain.

growth media), operations research, and greater mechanization and automation, distinguish an advanced greenhouse system from a basic greenhouse system. The system design emphasizes the integration of automation, crop culture, and controlled environment, a concept known as "automation-culture-environment systems," or ACESys.

Supplemental lighting is frequently used where natural light is a limiting factor. The lighting may be computer-controlled based on the daily photon requirements of specific crops. The CO_2 level is often enriched to complement the enhanced lighting level. Hard floors (typically concrete or porous concrete) are used for walkways or the entire greenhouse for easy movement of crops, equipment, and workers, and to facilitate the use of embedded heating systems. Opportunities for increasing the circularity of advanced greenhouse systems are shown in figure 3.

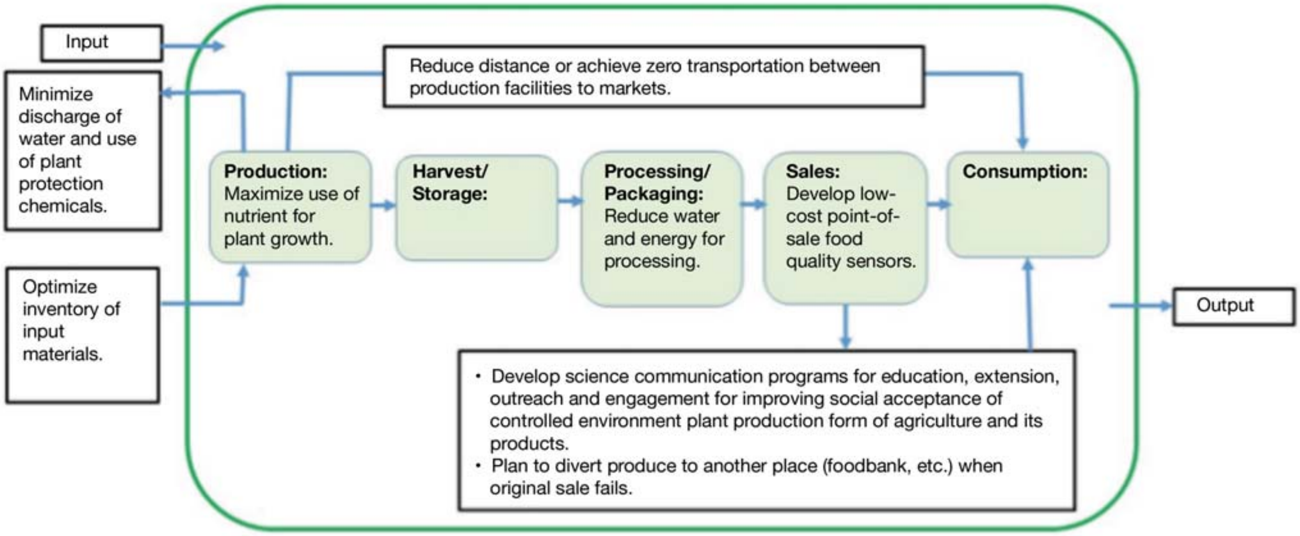

Figure 3. An advanced greenhouse system with circularity. System-level opportunities include setting quantitative goals for reductions of water, energy, and land use; making home composting easier, developing an infrastructure for community composting, and offering incentives for composting of food waste; contracting for continuous supplies of uniform quantity and quality products with individual customers, restaurants, wholesalers, and retailers; and processing wastes into valuable biochemicals.

Vertical farms and plant factories

Vertical farms and plant factories adapt advanced manufacturing concepts to the production of plant-based materials for food and other uses, such as pharmaceutical and chemical feedstocks. Vertical farms and plant factories are well suited for integration into urban food systems, as part of the movement toward smart cities. They are also suitable for areas that are not conducive to conventional food production and in locations impacted by disasters. Building on the advances made in transforming basic greenhouse systems to advanced greenhouse systems, plus recent achievements in science, engineering, and technology, vertical farms and plant factories have emerged as a completely modern form of agricultural production.

The unique features of these systems are their high degree of closure and their integration of sophisticated components, similar to the well-structured production lines and automated warehouses used in advanced manufacturing facilities. Some vertical farms and plant factories make use of both sunlight and supplemental lighting. The latest versions have moved toward total supplemental lighting and climate control within opaque buildings. The energy requirement is a major challenge for this kind of facility.

Vertical farms and plant factories are drawing interest from many organizations, including research and educational institutions, governments, real estate developers, construction companies, venture capitalists, the HVAC industry, the electronics industry, lighting (notably LED) manufacturers, supermarkets, restaurants, media, and consumers. Vertical farms and plant factories have already achieved a high level of technological sophistication. Further opportunities for improving their circularity, beyond those listed for advanced greenhouse systems, may be applied to all CEFAS (fig. 4).

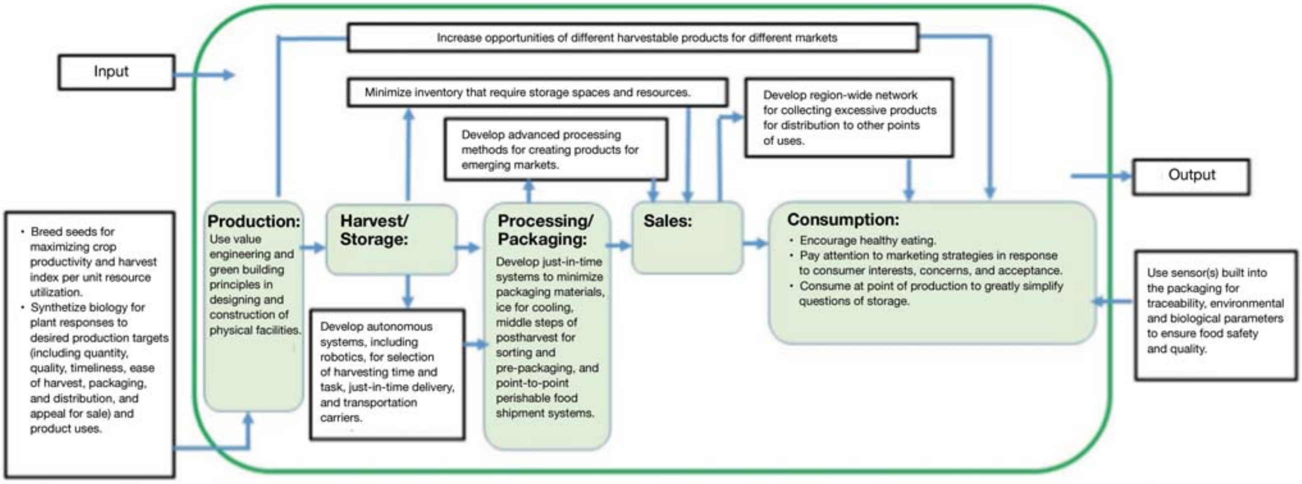

Figure 4. A controlled-environment food and agriculture system (CEFAS) with circularity. System-level opportunities include streamlining of production, harvesting, and shipping; precise monitoring and control of water, nutrients, light, CO_2, temperature, humidity, ventilation, and other parameters to maximize productivity; developing cloud-based platforms for monitoring and control of plant growth, environmental parameters, crop production tasks, data collection, system modeling and analysis, AI development, and decision support; using controlled-environment production as a model for circular FAS, including resiliency, sustainability, adoption of technology, and intelligence-driven and empowered agricultural systems (IDEAS); and integrating CEFAS into urban planning for efficient use of resources (including energy, water, and labor) as well as improving the local quality of life (including human health, employment, and community).

Conclusion

Estimates are that 70% of the global population will be concentrated in urban areas by 2050; therefore, CEFAS will be critical to sustain these future communities. This article briefly covered the challenges and opportunities for three types of CEPPS, including the opportunities for increasing the circularity of these systems. The short-term and long-term opportunities for transforming CEPPS to higher levels of circularity are summarized in figures 2, 3, and 4.

A systematic approach and multi-disciplinary teamwork are needed for pursuing these opportunities. There are also close interactions between specific CEPPS and the larger CEFAS and FAS, as well as with the broader social and economic sectors. For example, food safety analyses of each type of CEPPS need to be conducted based on the specific conditions. Costs and economic analyses are also important considerations; they are interrelated, but not exactly the same. A high net economic return may require a high investment cost, while cost reductions can make food more affordable.

CEPPS will continue to evolve into a major contributor to our future circular FAS, and ASABE is well positioned to lead this circularity initiative. We need to call all stakeholders to action, including scientific research, engineering advances, technology development, industry and business adaptation, decision support for policy-making, marketing, consumer inclusion, and education. Our hope is that the opportunities we recommend in this article will inspire further research.

Author information for **K.C. Ting, P.E., Norman Scott,** and **Rabi Mohtar** is available on page 6.

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Circular Systems for Animal Production and Processing

Mark Riley, Angela Green-Miller, Mary Leigh Wolfe,
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and Sue Nokes, P.E.

As the global population and personal incomes rise across the globe, the demand for high-quality protein and fat-soluble vitamins, such as those found in meat, milk, and eggs, will also increase. According to the USDA Economic Research Service, 19.9 billion kg of poultry, 12.3 billion kg of beef, and 12.5 billion kg of pork were generated in the U.S. in 2019. A wealth of other bio-based products, such as feathers, hides, and related products, were made from animals as well. The OECD estimates that global meat production will expand by nearly 36 million metric tons by 2029, reaching 332 million metric tons, with 80% of this growth attributed to meat consumption in developing regions (fig. 1). In the U.S., per capita consumption of pork and fish has been consistent, but beef consumption has declined and is now surpassed by poultry (fig. 2).

Current animal production and processing systems have benefitted from vast improvements in efficiency to meet ever-growing consumer demands. Production systems for meat, milk, and eggs have innumerable variety in the designs of their facilities and operations, and highly specialized systems have been developed for each animal species. These production systems are also distinctly different across the U.S., especially as related to feed availability and distance to processing facilities.

However, production and processing of animal-based protein has faced serious challenges in recent years, especially in 2020, which exposed the flaws in our highly centralized meat processing industry. The spread of COVID-19 closed several processing facilities in the Midwest. The reduced capacity necessitated euthanizing animals that could not be processed, resulting in lost revenue for producers in addition to sparse product availability and price spikes for consumers. Meanwhile, dairy farmers were forced to dump milk due to the decreased demand that resulted from the slowdown of the National School Lunch Program, which is the largest fluid milk buyer in the U.S. Limitations in processing and distribution facilities restricted this milk from being packaged in the small containers necessary for retail sale.

The fragility of our animal production and processing systems creates weaknesses, mostly due to the high degree of centralization and the rigid supply chain. Future pressures to change the systems will likely come from a variety of directions, but it is obvious that the systems need to change to become more robust (i.e., to withstand more pressure before

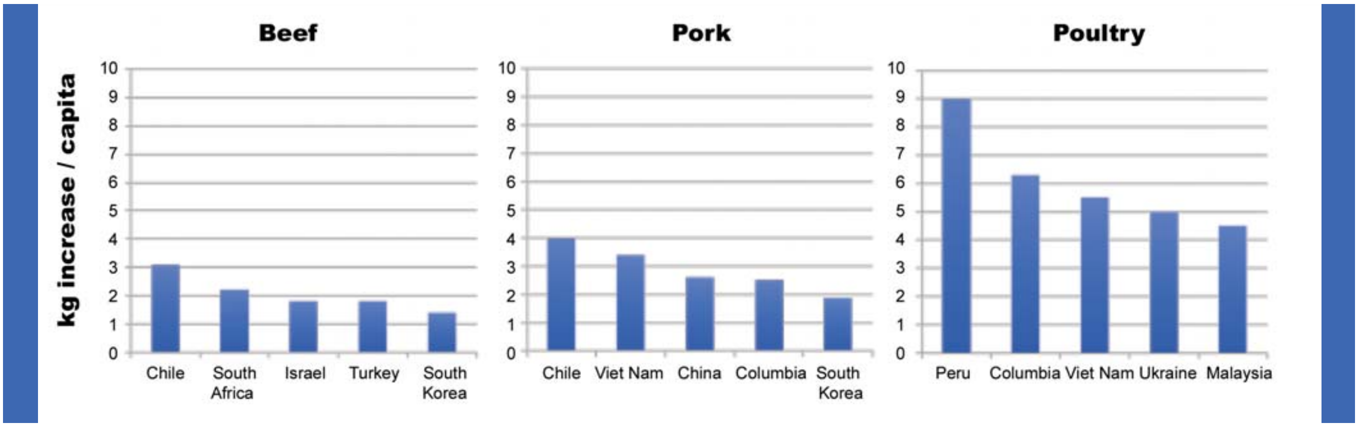
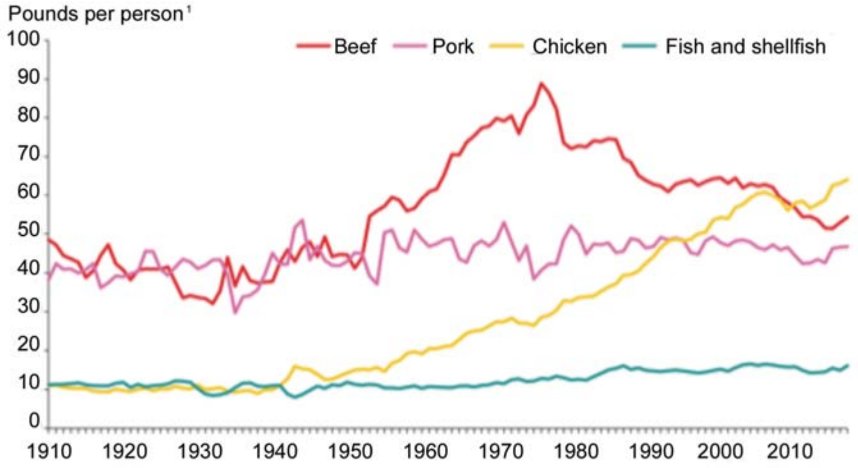


Figure 1. Increases in beef, pork, and poultry consumption for the countries that are predicted to have the largest increases from 2019 to 2029 (data from OECD, 2020).



[1] Calculated on the basis of raw and edible meat in boneless, trimmed (edible) weight. Excludes edible offals, bones, viscera, and game from red meat. Includes skin, neck, and giblets from chicken. Excludes use of chicken for commercially prepared pet food.
Source: USDA, Economic Research Service, Food Availability Data.

Figure 2. U.S. per capita availability of beef, pork, chicken, and fish.

failing) and more resilient (i.e., to require less time to recover from a disruption).

The recently released USDA 2020 Science Blueprint encourages the development of animal production systems that maximize the health of animals, humans, the environment, and economics while maintaining sustainability. This can be achieved through innovations in automation, precision management, and biotechnology, among other steps. These steps align with building circularity into our animal production and processing systems.

The evolution to circular systems

While animal producers and processors have made great strides toward circularity through increased utilization of byproducts, conversion of resources to higher-value products, and reduced environmental impact, evolving our current systems fully into circular systems will require redesign and redeployment of many of the foundational elements. Areas of opportunity include:

- Increased robustness and resilience
- Using all parts of the animal
- Finding alternative uses for wastes, thus minimizing pollutants and landfilling
- Applying transparency in costs (including externalities such as insurance, waste mitigation, and infrastructure)
- Incorporating a sharing economy, in which resources can quickly move to where they are most needed.

These transformed systems would demonstrate the key characteristics of circularity: designing out waste and pollution, keeping products and materials in use, regenerating natural systems, providing economic benefits, and designing in resiliency. This circularity can extend beyond animal producers and processors, and other industries may emerge to add value to the products and reduce food losses. Some opportunities for increasing circularity in the producer, processor, and consumer sectors are described in the following sections.

Producers

A great opportunity for repurposing wastes is to source feed alternatives locally using wastes from other agricultural industries and from human food waste. This opportunity could be enhanced by the development of geographic-specific animal production systems that are optimized for the local climate and locally available resources, as long as the animal feeds are closely balanced for nutrition and growth.

Another opportunity is to capture and return heat, water, and gases into the production system. Technologies for automation, robotics, sensors, and controls are required, as well as provisions for data privacy and security. Monitoring of feed, air, water, animal health, and other production parameters could increase efficiency, aid in waste management, and support animal welfare. In particular, processes are needed that reduce animal stress, and thus reduce production losses due to stress.

Processors

Losses due to catastrophic events, such as the COVID-19 pandemic, could be greatly lessened with modifications to the supply chain. The current system is highly specialized and not equipped to shift quickly between distribution channels, for example to adjust from meeting the needs of restaurants to meeting the needs of grocers, or vice-versa. On-demand communication could be used to better connect resource availability with demand and ultimately connect outputs (including potential waste) with those that can best use them (thus avoiding waste).

Development of edible and inedible value-added products from trim and other byproducts would reduce waste from animal processing, although a vast majority of beef byproducts are already used. Some non-cost-effective byproducts could be composted, converting them to soil amendments for field crops or for controlled-environment production systems.

Consumers

U.S. consumers throw away approximately one pound of food per person per day, and the greatest economic loss is for uneaten meat, poultry, and fish. Recently, the National Academies of Science, Engineering, and Medicine commissioned a study on reducing food waste (NASEM, 2020). The report recommends several innovations to reduce food waste and reduce the physical and psychological distances between food production and consumers. For example, improved date labeling and new packaging, such as chemically responsive packages that provide up-to-the-minute freshness monitoring and materials that improve shelf-life, could reduce food waste.

The NASEM report suggests a coordinated transition from "a society in which attitudes and habits facilitate the wasting of food to one in which the consumption and management of food consistently reflect its value and importance." In other words, consumers should become more engaged with food production.

Safe ways to put the remaining food waste back into the system should be developed, such as conversion of food waste to animal feed or composting of meat and scraps, possibly using the Bokashi fermentation process. Methods should be developed for restaurants and homes to recover nutrients while managing problems of odor, pathogens, and vermin. Successful implementation will require large-scale coordination and will likely require different strategies in different regions.

Specific opportunities for reducing food waste are detailed in the Restaurant Food Waste Action Guide (Cochran et al., 2018), which lays out preventive solutions, recovery solutions, and recycling solutions. The most promising approaches include menus with customer choices for portion size, waste tracking analytics including inventory planning, tax incentives for food donations and storage, and centralized composting and anaerobic digestion along with cooking oil recycling.

U.S. consumers throw away approximately one pound of food per person per day, and the greatest economic loss is for uneaten meat, poultry, and fish.

Adoption of new practices

To reap the benefits of circularity, these ideas, and others, must be put into practice. Most animal systems operate on thin margins with high market risk, and producers and processors would not welcome regulatory approaches for new practices solely for the purpose of improving circularity. However, incentive programs have been shown to be very effective in changing behavior, and the market for value-added products can also be a strong driver. The industry can find a balance between maintaining its current efficiencies and adapting to improve its robustness and resilience.

Opportunities for improving circularity exist in all animal production systems. The characteristics of large-scale systems can be represented by two examples, pigs and beef cattle. Pig production is highly integrated, with a limited number of large entities controlling most major decisions, and little interaction occurs between the pigs and the natural environment.

Given its high concentration of decision-makers, the pork industry could more readily adopt innovations in circularity in the near term than other animal production systems. This opportunity is discussed in in the next article in this issue, "Opportunities for Circular Pork Supply Chains."

In contrast, beef production has large and small operations in different parts of the production system, many different entities make major decisions across the system, and there is much greater interaction between the cattle and the natural environment. Larger animals also remain in the system longer, so beef production facilities face different challenges. For example, periodic cleanouts of the facilities occur at much wider intervals. Longer lifespans also increase the potential welfare challenges for the animals.

Much progress has been made in developing regenerative systems that lessen the environmental impacts of agriculture and integrate the various production activities into a long-term plan. These regenerative systems provide periods of rest from farming by returning the land to its natural state with native plants. Cattle can be fed low-opportunity-cost feedstocks that are grown on land not used for crops, thereby avoiding the food-feed competition and resulting in some aspects of circularity.

Summary

While advances in animal production and processing systems have led to greater efficiencies in resource use, there are still many opportunities to capture and repurpose underused resources across the supply chain. Several technologies have been developed for reuse of wastes as value-added products, but new technologies are needed, as well as broader adoption of existing technologies. Connections to other supply chains would provide opportunities for circularity to keep more resources in the system and reduce the amount of waste released as pollutants.

Completely new approaches carry a heavy risk, but they also offer financial rewards from reusing captured resources in new ways. A thorough analysis is necessary to determine which opportunities are most viable, most practical, and will yield the greatest benefits. ASABE members can contribute to increasing the circularity of animal production systems in several ways, including the development of new robotic and sensing technologies, the design of facilities that collect and reuse heat, water, and gases, and the implementation of models to assess the environmental and economic benefits of new production practices.

Author information for **Mark Riley, Angela Green-Miller, Mary Leigh Wolfe, Manuel Garcia-Perez, Terry Howell, Jr., P.E.,** and **Sue Nokes, P.E.,** is available on page 6.

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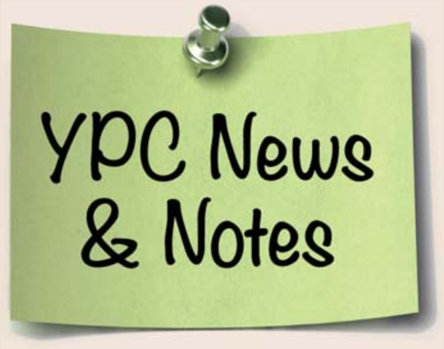
Circular economy: A sustainable solution to the plastics problem



"One word: plastics." This was the unsolicited advice that an unnamed party guest gave to Benjamin Braddock (played by Dustin Hoffman), the protagonist of the classic 1967 film The Graduate. While Benjamin's kind companion thought a career in plastics was the answer to all the problems of the restless sixties (and, by extension, modern civilization), in reality, plastics have proven to be a big headache. Almost 80% of all plastics ever produced have ended up in landfills or nature, with recycling and incineration accounting for the rest. Although plastic packaging materials, which constitute 95% of all plastics, have a service life of less than a year, they remain part of the environment for decades.

Clearly, the conventional management plans for plastics, based on the use and abuse principles of linear economic models, are unsustainable in the long run, especially because plastic consumption will double in the next twenty years. This is why circular economic models have emerged as a potential game-changer, aiming to address the plastics issue head-on by using intelligent product design, retaining products in use, and regenerating natural systems.

The underlying principle of a circular economy is simple: maximize the product's service life by retaining product value and reducing waste. The circular economic model has been around since the seventies (although economist Kenneth Boulding, the so-called father of the circular economic model, preferred the term "open economy"). However, sustainability-conscious companies have embraced circular economies only in the last couple of decades. Today, the circular economic model is in action in cutting-edge products infused with novel sustainability features, such as:

- Innovative designs to reduce waste and pollution, such as biodegradable, fully compostable packaging made from mushrooms.
- Longer service life, such as providing commercial lighting systems as a subscription rather than a transactional purchase.
- Regenerative properties, such as using biopolymers that can be chemically recycled to recapture the monomeric units or to transform the waste into value-added materials.

Even though the COVID-19 pandemic has resulted in a drastic surge in single-use plastic items, there has been significant progress in embracing more sustainable practices. The reuse of items ranging from designer jeans to metal straws to headphones is now a global phenomenon. We also have improved metrics for measuring gains in the transformation pathways, including the World Business Council for Sustainable Development (WBCSD) circular transition indicators (CTI), the Cradle-to-Cradle Products Innovation Institute (CCPII) standards for products, and the Global Reporting Initiative (GRI) sustainability reporting standards for wastes. These tools and standards have ensured a more data-driven approach in developing and implementing actionable targets.

ASABE is playing a vital part in implementing a sustainable, restorative, circular economic model. The recently appointed 23-member ASABE Roundtable has identified three subsystems within the food and agriculture nexus with high potential for circular transformation: open-field systems, controlled-environment systems, and animal production systems. In addition to continuing the investigation of these subsystems, the Society is also offering various resources related to circular economic systems, including a dedicated mini-symposium at the 2021 AIM, a forthcoming white paper, and other outreach activities.

We certainly hope that these initiatives are successful and transformative in the long run. Maybe then, in a future remake of The Graduate, a kindly older gentleman will offer this advice to a young person looking for a promising career: "One word: circular."

ASABE Member and YPC Member at Large Ekramul Haque Ehite, Graduate Research Assistant, Department of Biosystems Engineering and Soil Science, University of Tennessee, Knoxville, USA, eehite@tennessee.edu.

Opportunities for Circular Pork Supply Chains

Angela Green-Miller, Mark Riley, Mary Leigh Wolfe, Candice Engler,
Manuel Garcia-Perez, Terry Howell, Jr., P.E., and Sue Nokes, P.E.

Each year, approximately 200 million pigs are produced for consumption in the U.S., yielding 12.5 billion kg of pork products. A transformed pork supply chain could achieve the key characteristics of a circular economy that would design out waste and pollution, keep products and materials in use, regenerate natural systems, provide economic benefits, and increase resiliency. As animal systems have evolved over time, motivated by economic efficiencies and environmental regulations, considerable progress has been made in practices throughout the supply chain that contribute to circularity. Even so, many opportunities exist to further improve the pork supply chain.

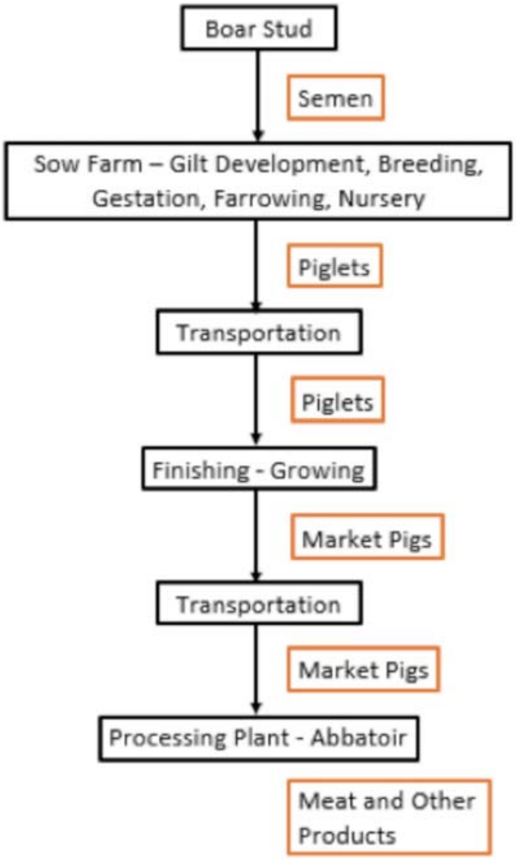


Figure 1. The current pork supply chain represented as a linear system. The stages of the supply chain can be highly integrated or loosely connected, depending on the ownership of the various facilities. Not included in this example are the post-processing activities, including marketing, distribution, and consumption.

The current system

The pork supply chain described in this article is composed of two main production stages (sow farm and finishing) with specialized facilities, transportation systems, and finally a processing facility that produces meat and other products for distribution to consumers. The current pork supply chain is most often organized as a linear system with a strongly linked structure, as shown in figure 1. In this system, the integrator, who typically owns the animals as they move through the chain, contracts with growers who own and manage the production facilities and provide basic animal care.

Management strategies vary based on the ownership arrangement in the supply chain. In one arrangement, the sow farms, finishers, transportation, and processing are all owned by separate companies, and each company is the primary decision-maker for its part of the process. Another arrangement consists of one company that owns all the facilities, controls all decisions, and contracts for support services. With this vertically integrated arrangement, the top-down management can increase the adoption of circularity, or circularity can be more difficult to implement if the management does not value such practices.

Opportunities to reuse resources in the current pork supply chain exist in the selection of feed and energy inputs, environmental management, animal care, manure and waste handling, transportation, and processing. While figure 1 does not include the stages of the supply chain that follow processing, i.e., marketing, distribution, and consumer behavior, there are opportunities in those parts of the process as well, as described in the preceding article, "Circular Systems for Animal Production and Processing."

A pork supply chain with improved circularity is shown in figure 2. While some improvements in circularity result from recycling resources, such as manure and gaseous emissions, back into the system, the improved circularity in this example is mostly driven by better connections with other industries for both inputs to and outputs from the pork production system.

Opportunities for increasing circularity

Feed inputs

Improved feed conversion efficiency through genetic selection, specialized feed mixes, and precise

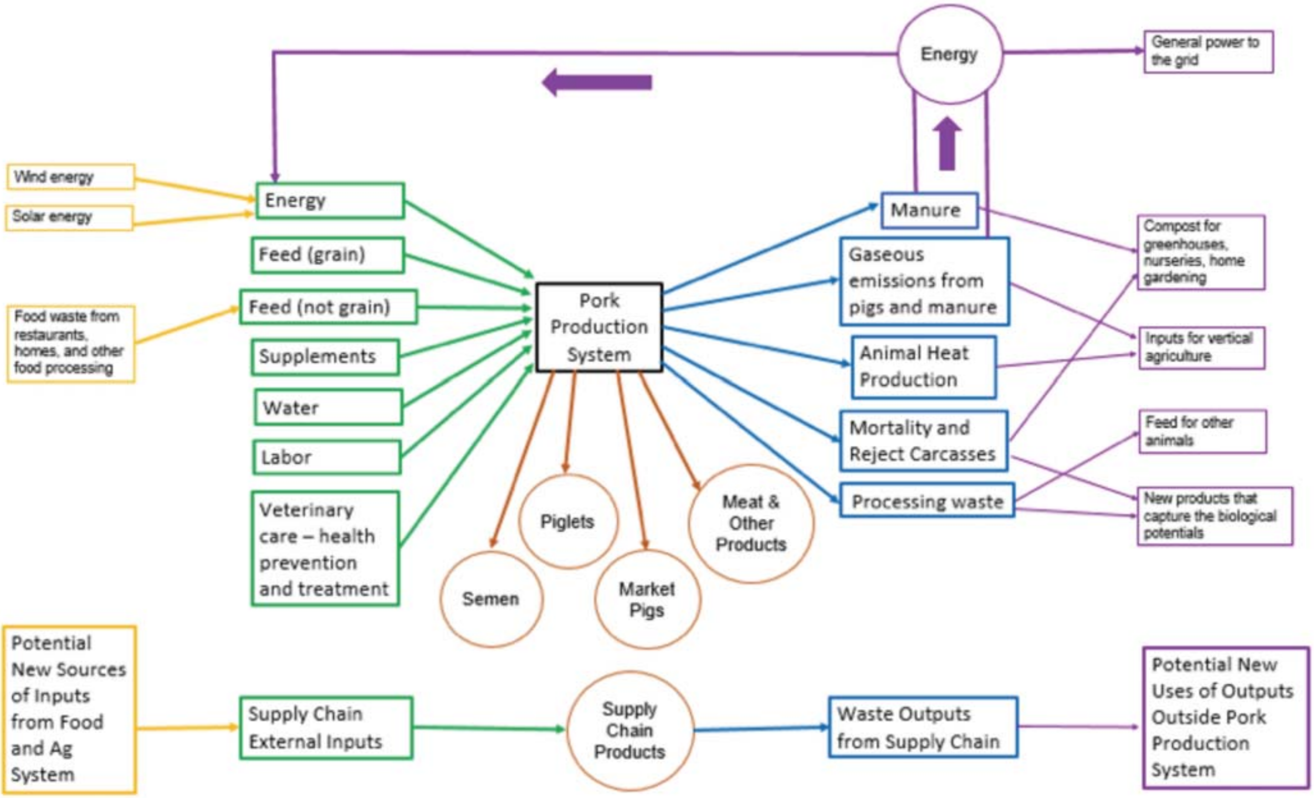


Figure 2. The pork supply chain reimagined, with opportunities for increased circularity.

environmental control have yielded great improvements in nutrient inputs to pigs, in addition to incorporating agricultural residues, such as dried distiller's grains (DDG) instead of milled corn. Additional opportunities exist to capture nutrients from alternative sources, such as locally derived food wastes from industries and consumers.

Using human food waste for animal feed is a great opportunity for simultaneously reducing waste in another supply chain. This long-standing practice can be upscaled after the unwanted food undergoes heat treatment and dehydration. The U.S. alone has potential to capture 44 million kg of food waste per year from restaurants, homes, grocery stores, and other sources. Making the collection and stabilization of food wastes cost-effective will require new technologies, financial incentives, and policies that support the increased value of this underused resource.

Energy inputs

Energy usage on pig farms is primarily in the form of electricity for ventilation, lighting, and feeding equipment and the gas or electric energy used for heating. Opportunities for reducing energy consumption include more effective heating and ventilation systems and high-efficiency lighting products, such as LEDs. Targeted management, considering the thermal needs of the animals at different stages of production, microclimates in the barn, and rapid changes in ambient temperature and humidity due to weather events, could further improve energy usage.

Renewable energy is another opportunity for increasing circularity. Anaerobic digestion (AD) is a mature technology that recovers energy from organic wastes and can be operated successfully in a decentralized production system, such as on-farm. The methane-rich biogas from AD can be burned to generate electricity or provide heat. There is also potential for upgrading the methane into market-grade biogas.

However, other sources of alternative energy are rarely used in current production and processing facilities. Solar and wind power can support or even offset current fossil-based energy requirements. A shift in perspective, as well as financial incentives, may be required to increase the use of these technologies.

Environmental management and animal care

Systems and processes that reduce animal stress and support animal welfare have been shown to reduce production losses. Emerging technologies for automation, robotics, sensors, and controls for critical production parameters have potential to offset the shortcomings of existing systems. Challenges with implementing these new technologies include the practicalities of deployment in pig facilities, the costs of installation and maintenance, and the burden on the personnel who will use the technology.

Manure and waste handling

The use of manure as a fertilizer for land application is a standard practice in cropping systems; however, some locations in the U.S. have insufficient land on which to apply the excess nutrients in manure. Proper management of these nutrients can be a large expense in animal production. Pig manure is commonly collected and handled as a liquid slurry, and the solids can be separated from the liquid. Some pig producers process their manure solids into value-added products, such as compost or pelleted fertilizer. However, due to transportation costs, these bulk products are limited to local markets.

Additional technologies, such as bioconversion, can be developed to convert the nutrients, proteins, and other resources in manure and other animal wastes, including carcasses, into value-added products. As noted for the energy inputs, manure gases can be captured and converted into biogas by anaerobic digestion (AD). However, while AD converts organic waste into methane, the main nutrients (nitrogen and phosphorus) remain in the effluent. Nutrient recovery technologies need to be developed to complement AD and other bioconversion systems.

An advantage of AD is that other agricultural wastes, such as food waste and crop residues, can be co-digested with manure. The European Biomass Industry Association claims that less than one percent of the potential benefits of AD have been achieved. The feasibility of digesting waste on-farm depends on the size of the operation and its waste-handling technology. Small-scale, economically viable AD systems would increase the adoption of this technology. Ultimately, waste recycling is essential for achieving circularity in the pork supply chain.

Transportation

Transportation losses (including animal mortalities) occur at the end of the production cycle, after the investment of resources for growing the pigs. These losses are particularly costly, both financially and environmentally. The transport vehicle design and animal handling practices impact animal bruising and thus meat quality. The transport duration, environmental conditions, and animal condition also impact mortality rates. More efficient transport systems, possibly including electric and/or autonomous vehicles, could reduce the financial and environmental costs of transportation.

Processing

While processing plants currently use carcasses and inedible materials to produce value-added products, opportunities exist to increase and diversify these byproducts. The reduced amount of remaining wastes could then be composted to produce soil amendments for field crops or for controlled-environment production systems.

New packaging could further reduce processing losses by prolonging shelf-life, and thus reduce food waste. Emerging technologies include chemically responsive packages that provide up-to-the-minute freshness monitoring. Additional technologies are needed for safe, inexpensive, and recyclable packaging materials.

Toward a circular system

While some opportunities for circularity can be implemented piecemeal in the current pork supply chain, other opportunities require grander redesigns. A simple change, such as locating animal production facilities closer to processing facilities, could result in shorter transport distances and thereby reduce costs while improving animal welfare.

More profound changes may lead to greater circularity. For example, combining an animal production facility with controlled-environment vegetable production could capture and reuse the heat and gases from the animals and manure, instead of venting them to the environment as a lost resource and pollutant. When combined with vertical farming, such integrated farms might also allow animal production closer to urban areas, which would reduce the total food-miles by distributing more complete food (plant and animal products) in common shipments.

Another opportunity for circularity involves integrating the current pork supply chain with alternative protein markets, including cell-based animal protein, in a shared-resource arrangement that supports both types of production, because both types of production rely on live animals. Cell-based pork production is still in the research phase. For beef products, cell-based meat-like tissue is generated from isolated bovine myoblasts and potentially other cell types, such as endothelial and fat cells. For more possibilities, see the earlier article in this issue, “Controlled Biology-Based Indoor Circular Food Systems.”

The first cell-cultured beef burger was produced in 2013, but production costs remain high, along with concerns about the high energy inputs and the extensive use of antibiotics in the process. Plant-based meat alternatives were the single fastest growing food ingredient in 2019, and similar non-meat protein products are likely to alter consumer preferences in the coming years. Animal production and cell-cultured meat production require many of the same inputs, creating potential for combined systems in which total food production can increase while adapting to changing markets and consumer preferences more rapidly than either system could alone.

Summary

Opportunities to achieve circularity exist at every level of the pork supply chain, including repurposing of food waste from other supply chains. Connecting with industries outside the pork supply chain will be essential for closing some of these circularity loops. New research and new technologies are needed to achieve the ambitious goals of increasing the resilience and robustness of the system, ensuring its economic sustainability, decreasing waste and pollution, keeping products and materials in use, and regenerating the natural systems on which all life depends.

Author information for **Angela Green-Miller, Mark Riley, Mary Leigh Wolfe, Candice Engler, Manuel Garcia-Perez, Terry Howell, Jr., P.E.,** and **Sue Nokes, P.E.,** is available on page 6.

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From Linear to Circular, An Ambitious but Necessary Goal

Brahm Verma and James Jones, Guest Editors

Our modern food and agricultural systems are impressive achievements that have advanced over time to meet the continuing increases in the global demand for food. However, our current rate of consumption and the losses incurred during production, including waste of nearly half of the produced food along with the embedded materials and resources, cannot last much longer. Continuing on the current path, focusing primarily on production efficiency and profitability while depleting limited natural resources, cannot meet the goal of increasing food production by 60% to 70% by 2050. It also has the potential of irreparably damaging the Earth's resources.

Our current linear systems (that use, make, and waste) may be profitable in the short run, but they are ultimately unsustainable. We must change these systems to reduce losses and recirculate and reuse materials and resources after their initial use. In nature, circularity is a basic structural characteristic for sustainability. The Earth's resources are sustained by nature's cycles—the hydrological cycle, carbon cycle, nitrogen cycle, and others—and they lead us to conclude that sustainable systems are inherently circular.

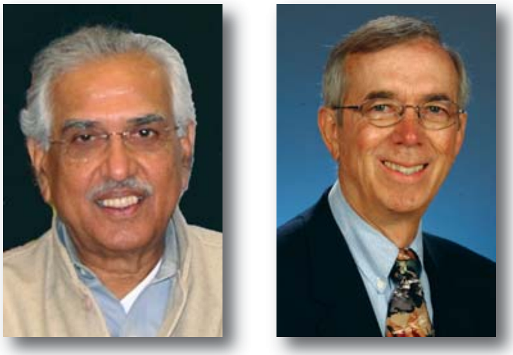
Food and agricultural systems are highly complex, and current paradigms that focus mostly on solutions for individual subsystems do not address the complex interactions and resource circulations with other subsystems. No component of an agricultural system on its own can be circular and thus sustainable in isolation. However, when a system component, such as a production subsystem, is connected to other subsystems so that they are all interdependent for maintaining the flow of materials and resources, then cyclic patterns of use and reuse of resources emerge. The result is that the aggregate interconnected subsystems can attain sustainability through the complex network of pathways for endlessly circulating materials and resources and producing zero waste.

> “**Double helix**, the structure of DNA, sustains information of Earth's living systems.
>
> **Circularity,** the structure of natural processes, sustains the Earth itself.”
>
> *Brahm Verma*

Circular economy concepts can inspire the reimagining and redesign of our current food and agricultural systems, leading to sustainable, conservative, and regenerative systems that are also more efficient and profitable. Achieving this will require in-depth understanding of the complex networks and feedback loops of natural and human processes while simultaneously creating new opportunities for increasing efficiency and profitability, eliminating wastes, reusing resources, protecting the environment, and regenerating natural resources.

The transition to circularity will also require coming together and coordinated efforts by different disciplines and by leaders in the public and private sectors, as well as changing the collective mindset into one that is committed to systems-level approaches. This commitment will create new knowledge, technology, and economic incentives for transitioning to circular food and agricultural systems.

Achieving circularity in food and agricultural systems may be the greatest challenge of our time, and ASABE has adopted circularity as its long-term priority. Through this action, ASABE has become a leading voice in the U.S., enlisting its members for the circularity initiative and building partnerships to work jointly on this effort.



ASABE Fellow Brahm Verma (*left*) and ASABE Fellow James Jones (*right*).

The articles in this issue of *Resource* provide some specific examples of the complexities and challenges involved in transitioning to circular systems. Collectively, these articles also identify the need for building a coalition of professional societies and partnerships with leaders of public and private agencies to answer some key questions:

- What is circularity, and why is circularity important for food and agricultural systems?
- How do we measure circularity? What resources should be monitored? How do we identify metrics and indicators of circularity that are applicable across the value chain, that are comprehensive yet flexible, and that are useful for the full range of decision makers?
- What new knowledge and technologies are needed to achieve circularity?
- What are realistic targets and timelines for transitioning to circular systems?
- How do we monitor improvements, and what indicators and metrics will be needed to measure the progress of the transition?
- How do we build awareness of circularity (Circular Economy IQ) throughout the community of food and agricultural systems?

To inform ASABE members and thought-leaders in other professions and engage them in answering these questions, the 2021 Annual International Meeting will host a virtual mini-symposium with keynote presentations from the Netherlands and the U.S. The event will include a panel discussion and a session with invited presentations, bringing together 13 distinguished leaders of other professional societies and the chair of the National Academy's Board of Agricultural and Natural Resources (BANR) to share their perspectives on developing circular food and agricultural systems. ASABE members and others have been invited to present their work at a poster session and publish papers in a special issue of *Transactions of the ASABE* (see back cover of this issue). We anticipate that these events will grow into a wide range of activities for ASABE and other professional societies.

Additionally, ASABE has made numerous invited presentations on the importance of transitioning to circular systems and has built connections with the National Academies, other professional societies (including crop science, soil science, agronomy, agricultural and applied economics, dairy science, food science and technology, and chemical engineering), stakeholder groups (including Field to Market, and Solutions from the Land), government agencies (including the NSF and USDA), and food-related foundations that have enthusiastically embraced this goal.

We are also engaged in numerous conversations on what needs to happen, when it should happen, and who needs to take action. For example, the Senior Director of Programs of the National Academy of Engineering has invited ASABE to plan a webinar for early fall of 2021 that will inform the wider engineering community about the importance of food and agricultural systems and the challenges that these systems will face in transitioning to circularity in the coming decades.

ASABE has an unique opportunity to be a leader in transitioning our current food and agricultural systems to circular economy principles. Designing circular food and agricultural systems will lead to use-inspired research, development, and education by adopting an interdisciplinary, system-focus paradigm. The new paradigm will also change the priorities of policy-makers and the investments by public and private agencies. In short, we can meet the challenge of 2050 by providing innovative systems-level solutions that ensure productivity, profitability and circularity for the sustainability of global food supply and Earth's ecosystems.

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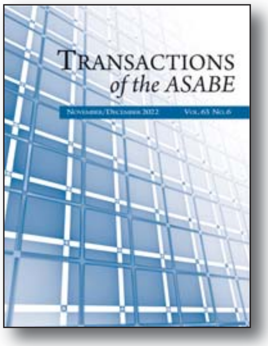

Circular Food and Agricultural Systems (CFAS)

Organizers: Kati Migliaccio, Guest Editor and Coordinator
Garey Fox, Editor-in-Chief

Be a part of this special collection of peer-reviewed articles presenting works that envision, redesign, and/or develop pathways for transitioning current food and agricultural systems into circular economy systems. These articles will present work that: 1) design out waste, 2) keep products and materials in use, 3) regenerate natural systems, 4) provide economic benefits, and 5) are more resilient and in harmony with the Earth's ecosystems. We especially invite manuscripts from all disciplines presenting perspectives and out-of-box, system-level solutions for transitioning to circular systems. Articles will be published in issues of the 2022 *Transactions of the ASABE*. For more additional information:

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Manuscript submission deadline: September 30, 2021