Chapter 3
Open-Source Agriculture Initiative—Food for the Future?

Caleb Harper

Abstract In the 10,000 years of agriculture's history, advancements have enabled three society-altering revolutions. We believe that food computing, an alternative, distributed farming system based on new methods of communication, sensing, data collection, and automation, will enable network-effect advantages in the next generation of food production and give rise to the Internet of Food and the next agricultural revolution. At the MIT OpenAG Initiative, we are working on building this new digital-plant-recipe-centric network, a database of "climate recipes" for achieving the desired phenotypic expression of the plant in question. The food computer, or FC, that we are developing is a term for an agricultural technology platform that creates a controlled environment using robotic control systems and actuated climate, energy, and plant sensing mechanisms, designed to optimize agricultural production by monitoring and actuating a desired climate inside of a growing chamber that in turn creates desired phenotypic traits in plants. With iterative experimentation, we could hypothetically map the entire phenome of a selected plant and correlate certain phenotypic traits with specific environmental stimuli—our Open Phenome Project, a catalog of the epigenetic expression of plant life. Currently, the commercially available systems are being developed as closed proprietary systems noncompatible with other platforms of the same scale or across scales. We imagine a very different future, with open and cross-compatible technology platforms underlying a distributed network of FCs of various scales using digital plant recipes and the controlled environment climate as the scaling factor.

Keywords Food computing • Networked experimentation • Climate recipes • Plant phenomics • Controlled environment agriculture

In the 10,000 years of agriculture's history, advancements have enabled three society-altering revolutions. First came the domestication of plants and the resulting first human settlements in 8000 BC, followed by the horse and plow and the rise of technology-based societies in 600 AD, and finally the vertical integration

---

C. Harper (✉)
MIT Media Lab, 75 Amherst Street, Cambridge, MA 02139, USA
e-mail: calebh@media.mit.edu

T. Kozai et al. (eds.), *LED Lighting for Urban Agriculture*,
DOI 10.1007/978-981-10-1848-0_3

of farming brought on by the mechanization, chemical fertilization, and biotechnology of today (Baker 1996). Agricultural revolution has been a major driving force behind humanity's societal progress. The current industrialized food system feeds 7.3 billion people (United Nations, World Population Prospects 2015), of whom more than half live in cities (United Nations, World Urbanization Prospects 2015) and very few of whom are involved in the production of their own food. The backbone of this system is comprised of large, centralized, chemically intensive single-crop farms. With natural-resource scarcity, flattening yields, loss of biodiversity, changing climates, environmental degradation, and booming urban populations, our current food system is rapidly approaching its natural limit. What will define the fourth agricultural revolution, and how will it impact and shape global societies?

This is the central research question of the Open Agriculture (OpenAG) Initiative at the MIT Media Lab. As we at the OpenAG Initiative and our collaborators develop a greater understanding of the unintended ecological and nutritional consequences of industrialized agriculture—including its contribution to global warming from CO_2 emissions from farming, shipping, and storing food, the pollution of oceans from agricultural runoff, nutrient-depleted produce and resulting malnutrition, "food deserts," and obesity and diet-related illnesses such as type II diabetes—we envision an alternative, distributed farming system based on new methods of communication, sensing, data collection, and automation that will enable network-effect advantages in the next generation of food production.

The Internet was built to compute and share information using interconnected open systems and networks. In the same way, this next agricultural revolution will be based on interconnected open food production platforms (food computers) to increase production either by scaling up or scaling out and sharing data to form a new kind of network: the Internet of Food (IoF). This new Internet is a digital-plant-recipe-centric network, a database of "climates" created for achieving the desired phenotypic expression of the plant in question. One can imagine digital plant recipes as the equivalent of "html" in computer networks. The recipes are the logical structured containers of exchanged information within the IoF. We believe that food computing, open data platforms, and networked production communities will each play a pivotal role in the next agricultural revolution.

3.1 Food Computing

Donald Baker, a distinguished fellow in the American Society of Agronomy and the American Association for the Advancement of Science, suggests the following:

> The third revolution may run its course or it may receive a boost from biotechnology. But with or without the application of a new technology, a fourth method of yield measurement may be used in the near future. It is the ratio of yield to a critical factor other than land. As the critical factor in the past has gone from human effort, to the amount of seed sown, to the amount of land used, it may soon change, for example, to the nitrogen, the phosphorus, or

> the energy expended. Perhaps the best one would be an economic one, since it also requires a superior bookkeeping system. Thus, the next yield expression might become yield per dollar spent. (Baker 1996)

It is the premise of the OpenAG Initiative that the "superior bookkeeping system" to which Baker refers could be realized through leveraging the networked and computational power of "food computing" in the fourth agricultural revolution (Harper and Siller 2015).

The food computer, or FC, is a term for an agricultural technology platform that creates a controlled environment using robotic control systems and actuated climate, energy, and plant sensing mechanisms. Not unlike climate-controlled datacenters optimized for rows of servers, FCs are designed to optimize agricultural production by monitoring and actuating a desired climate inside of a growing chamber that in turn creates desired phenotypic traits in plants. Climate variables—such as carbon dioxide, air temperature, photosynthetically active radiation levels, leaf surface humidity, dissolved oxygen, potential hydrogen, electrical conductivity, and root-zone temperature—are among the many potential points of actuation within the controlled environment.

These points of actuation, coupled with the plant machine interface (PMI), are the drivers of plant-based morphologic and physiologic expressions. For example, FCs can program biotic and abiotic stresses, such as an induced drought, to create desired plant-based expressions of color, texture, taste, and nutrient density—vintners often apply the method of inciting a strategic vineyard drought, implemented by analog means, to sweeten grapes, but this technique has not been applied to the much broader variety of food that can be grown in FCs, with exponentially greater control. Operational energy, water, and mineral consumption are monitored (and adjusted) through electrical meters, flow sensors, and controllable mineral dosers throughout the growth period. When a plant is harvested from the FC, a digital plant recipe is created based on the corresponding data.

Digital plant recipes are composed of layered data that includes operational consumption data, plant morphology and physiology data, and a series of climate set points. Such points read like machine code and include a time stamp, an environmental control code, and a value associated with that environmental control. For example, a single climate set point reading of "00:00:00 SAHU 60" would set the air humidity to 60 % at time 00:00:00 h or 12:00 am. All of these layers of data are collated to form a repeatable digital plant recipe with known inputs and outputs. The goal is to create a genuine cyber-physical system in which each attribute has a closed feedback loop from sensor, to actuator, to biologic expression. With iterative experimentation, we could hypothetically map the entire phenome of a selected plant and correlate certain phenotypic traits with specific environmental stimuli.

With sophisticated correlation, we anticipate building digital plant models based on real-time data that can rapidly carry through iterative experimentation and suggest new digital plant recipes without having to grow each individual permutation. We are interested in a paradigm shift from simple controlled environments to adaptive environments where knowledge gained in process is feedback continuously based on the desired attributes of the product.

The human plant interface (HPI), a combination of the user experience and user interface, is a software layer that lets a human operator monitor sensors and actuator systems; browse and predict inventory; and load, override, or create derivative digital plant recipes. The HPI abstracts the operator from the mechatronics and reduces the biological or engineering expertise required to operate the system. Most importantly, the software is being designed as hardware agnostic enabling the development of a modular hardware ecosystem. This is crucial for enabling FCs to integrate easily with rapid advancements currently being made in the control environment agriculture space (sensors, LEDs, actuators, etc.).

There are currently three scales of control environment platforms being developed globally. The consumer electronic scale is a product scale (2–10 ft^2 or 0.18–0.93 m^2) designed for an at-home user, hobbyist, or student (see Fig. 3.1). The boutique production scale is a shipping container scale (200–500 ft^2 or 18.6–46.5 m^2) FC designed for owners/operators or franchisees to sell small amounts of high-value produce into local markets, restaurants, or cafeterias (see Fig. 3.2). The factory farm is a light industrial scale (+10,000 ft^2 or 929 m^2) designed to operate in urban or peri-urban environments and distribute fresh produce into a regional supply chain or produce a large quantity of a very high-value crop (see Fig. 3.3).

Currently, the commercially available systems are being developed as unique, closed, and proprietary systems that are noncompatible with other platforms of the same scale or across scales. CAE environments are being designed as static control systems, set points are created once, and an agricultural product is created. Knowledge is being developed locally on closed platforms, and questions remain unanswered regarding the functionality, scalability, economic viability, safety, and environmental sustainability of these systems.

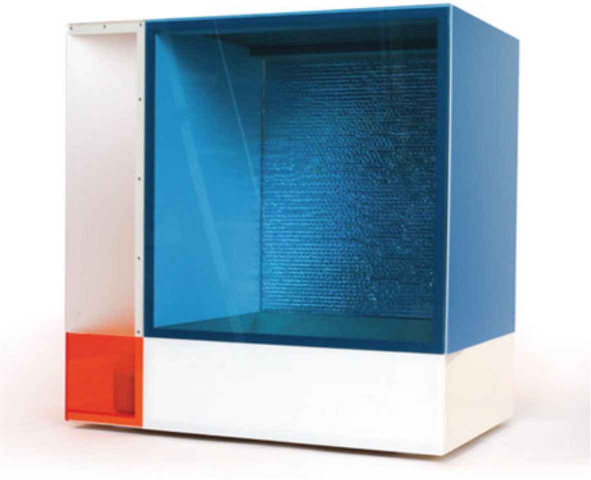

Fig. 3.1 The new FC (food computer) prototype

Fig. 3.2 The MIT OpenAG FC (food computer), built against the façade of the Media Lab and designed to be shipped anywhere in the world

Fig. 3.3 The view from within a farm factory scale FC, with multilayer design

3.2 Open Platforms and Open Data

We, at the MIT Media Lab OpenAG Initiative and our collaborators, imagine a very different future. This future is one where open and cross-compatible technology platforms underlie a distributed network of FCs of various scales using digital plant recipes and the controlled environment climate as the scaling factor. Conventional agricultural data has been difficult to export and use to replicate plant growth and output, because the growing conditions are dependent on the idiosyncratic variables created by the time of year, regional climate, and local resource availability.

FCs operate autonomously of local climate. Therefore, creating an agricultural product in one FC can easily be shared as a digital plant recipe and recreated, almost identically, in another compatible FC anywhere in the world, greatly expanding the concept of agricultural exports. We have begun piloting this concept through collaborations among boutique FCs at MIT, Guadalajara, and India.

This cross-platform compatibility would create the framework for rapid scalability of valuable discoveries. For example, innovations made at the personal scale could be quickly tested and verified across a network of compatible FCs and then deployed at the boutique or light industrial scales. FCs, then, could be imagined as networked cores of agricultural experimentation and production, capable of responding to local or global environmental, cultural, or market demands.

As the global network of FCs begins to create, iterate, and deploy digital plant recipes, we imagine these recipes would be open-source licensed and hosted on a public forum, modeled after Wikipedia, and downloadable as an executable file. Similar to the Human Genome Project, we envision the Open Phenome Project to be a crowdsourced cataloging of plants and their phenotypic traits correlated with the causal environmental variable. Over time, recipes would be optimized to decrease water, energy, and mineral use, while increasing nutrient density, taste, and other desirable characteristics. This database of functional plant phenomics would be the basis for scientific discovery, interdisciplinary collaboration, and new methods of efficient and distributed food production.

We believe this database could eventually impact conventional farmers by simulating a change in future climates to simulate future productivity and by using FCs to “climate prospect” which areas in the world would be best for a particular crop and its desired attributes—thereby rendering climate as a useful tool, by providing access to a catalog of climates and allowing farmers to make more informed, articulate choices about where and what they plant globally.

3.3 Integrating Artificial Intelligence Experimentation

The ultimate goal of the Open Phenome Project is to serve as a comprehensive catalog of epigenetic plant data, but the compilation thereof will rely entirely on crowdsourced and iterative experimentation. We have recently taken that idea further with experimentations in artificial intelligence (AI) and machine learning applications. To that end, we are collaborating with Rene Redzepi, renowned chef and owner of Noma, the molecular gastronomy restaurant in Copenhagen, and Sentient Technologies, an artificial intelligence program most commonly used for stock prediction.

Though our plants are already two to three times more nutrient-dense than those conventionally grown on farms, grow three to five times faster, and use 50–90 % less water, we are not limited to optimizing nutrition—we can also use our climates to enhance or change the phenotypic expression that results in flavor. For example, much of what humans perceive as flavor in herb plants like basil derives from molecules classified as secondary metabolites. These are referred to as “metabolites” in the sense that they are the result of living cellular processes and as “secondary” in the sense that they are not directly involved in the growth, development, or reproduction of the plant, but serve as enhancements to one or more of these, or to survival more generally. Secondary metabolites are involved in protecting the plant against environmental stresses, such as drought, UV light, and predation from herbivores. When exposed to different combinations of these stressors, basil has been shown to increase the concentration of these volatile secondary metabolites by up to an order of magnitude as compared to unstressed plants.

This means that it is possible to grow more intensely flavorful basil by stressing the plant in specific ways. With Noma’s flavor chemist, Arielle Johnson, we have designed an experiment relating input data on basil-growing conditions (including main effects such as light source, chitosan addition, and UV supplementation and secondary effects like temperature, nutrition, water EC, and pH) to output data on markers for basil flavor and quality, for various volatile-increasing stress conditions.

The experiment involves the testing of three common types of light fixtures (fluorescent, Philips LED, and Illumitex LED), as well as supplementation with UV-B light and chitosan. UV-B has been shown to increase production of basil trichomes, the gland-like structures on the surface of the leaf that store most of the volatiles, and boost essential oil/volatile output. Chitosan, a polymer modified from the exoskeletons of crustaceans, confuses the plant into thinking that insects are in its vicinity or eating it and has likewise been shown to increase volatile output. This plant defense mechanism renders basil offensive to insect predators by yielding increased pungency, which makes such stressed basil ideal for culinary purposes.

We are using the MIT OpenAG boutique FC, partitioned into three rooms, each with three trays, such that potential interactions between light source and stress can be evaluated. Each tray within a room will receive one of the three light sources (fluorescent, Philips, or Illumitex), and each room will feature one of three stress treatments—UV-B addition, chitosan addition, or a control (no added stress). Within the nine trays, we will grow the basil to at least five leaf pairs—about 5–6 weeks total, including germination—and then analyze for dry weight, fresh weight, and volatile profile. The GC-MS volatile analysis is performed by pooling the first four leaf pairs on a basil plant, grinding them with liquid nitrogen and extracting the volatiles from this homogenate.

Once we have the nine experimental conditions' volatile profiles and other metrics, we will run the information through Sentient Technology's neural network AI algorithm, which will begin to generate suggestions about optimal growing conditions for essential oil yield. From there, we plan to design further experiments to vary nutrition, levels of different stressors (such as chitosan concentration, the time course for adding chitosan, or other "volatile elicitors" such as methyl jasmonate, UV light exposure times, and others), microbial profiles, temperature, and water availability.

Other experiments we have already completed include culturing the water within the MIT OpenAG boutique FC in order to study the microbiome of our plants. Ultimately, the goal is to understand the microbiota of root structures, stalks, and leaves peculiar to each plant such that we can mimic microterroirs from all over the world by introducing different cultures of bacteria to the water. Soon, we will also have the benefit of an additional experimental space in Middleton, Massachusetts, currently under construction; a 5000 foot^2 or 464.5 m^2 shipping container which we will divide into four boutique FCs; and one factory farm FC—the largest open-source vertical multilayer farm in the world.

3.4 Building the IoF and Enabling Communities

As the IoF develops, we look to the development of the Internet for useful guiding principles for adaptation—specifically flexibility, diversity, and openness. These guiding principles enable user-driven development, which has characterized the Internet's history (Abbate 1999). The IoF design is based on the premise of abstracting the information we share and its logical distribution algorithms from how we implement and interconnect physical things. In other words, the logical definition of the information is conceived in a different plane from the physical implementation. Therefore, the physical implementation is left open and enables the desired versatility, flexibility, and easy management of the IoF.

This openness would also allow for FCs customized in size and design, according to their application. For example, a research lab design (such as the MIT OpenAG boutique FC) might be different from a restaurant implementation. Imagine retailers in different locations designing a custom "case," similar to a custom iPhone case, for their FCs to coordinate with local décor, marketing, and regional aesthetics, while still not altering the core functionality of the FC. FCs might also have customized HPIs according to farming expertise: new, amateur, expert, or research farmer.

Because we recognize that due to lack of expertise, some farmers will not be able to construct their own PCs using the OpenAG schematics, instructional videos, and readily available materials—and might therefore not become involved due to the daunting sense of frontloaded effort, while they might otherwise have become active contributors to the IoF—we are working on the design of the next generation of in-home FC kits, which will be available for market purchase in 1–2 years.

The combination of open-sourced digital plant recipes, open technology platforms, and the IoF will lead to the democratization of food production enabled by massive communities of users. Social communities will be formed by users according to interests, preferences, levels of expertise, and so on. These communities will be comprised of the usual features: chats, forums, wikis, social networks, and blogs. We have recently launched a community at forum.openag.media.mit.edu that now has over 100 users building platforms on six continents—all but Antarctica—in more than 20 countries. Recipes will be quickly shared, validated, and customized. The recipes and FC hardware and software customization will become the center of the socialization process. The sharing of recipes (data) will allow a knowledge base to develop new plant data and technological setups, creating more accessible food production methods and meeting the everlasting demand for optimized food growth.

Open communities of food innovators, drawn together by collaborative and readily accessible technology platforms, will form the foundation of the next agricultural revolution. These communities will yield a diversity of thought and solutions and will nurture new connections between people and their food. The more ubiquitous the tools and knowledge of production systems become, the more informed, innovative, and empowered the average person can be in contributing to the global future of food. The accessibility of data, hardware, software, and, most importantly, food and nutrition for the projected nine billion people of 2050 hinges on fostering a creative, interdisciplinary forum of thinkers and doers on collaborative platforms today.

3.5 A Platform for Expression

Such collaboration on the IoF also creates a natural platform for expression, not necessarily or exclusively food-centric, on the personal, corporate, educational, governmental, and global scales. On a personal level, the in-home FC will allow hobbyist farmers to grow their own nutraceuticals, geared toward the specific requirements of their own genetics and physiology—or even for aesthetic, decorative effect. With resources like the Svalbard Global Seed Vault, we can resurrect more nutritious and flavorful cultivars that fell out of favor due to the difficulty of their production and inhospitable climates, providing the individual with greater diversity in both palate preference and personalized health—and without the attenuation of nutrition brought about by degradation of produce shipped great distances and stored for long periods of time.

From a corporate standpoint, the shift from an emphasis on abundant cheap food to better, more sustainable food is driving corporations toward seeking tools for providing transparency. With the accessibility of the Internet, the consumer has come to demand more transparency and food education from retailers and food producers, and companies must respond by transitioning to open, objectively healthier offerings.

Not only can the FC be turned to increasing adult literacy in food, it can also be used to bolster educational curriculums with an emphasis on science, technology, engineering, and mathematics (STEM) for children. We already have seven FCs in schools all over Boson, with children using an interactive, three-dimensional interface, generating modifications, and emailing recipes to each other. Teachers can use their classroom FCs to teach coding, chemistry, biology, or data science. Of course, every experiment they run will also serve as an additional core of processing for the Open Phenome Project as students upload their recipes.

Alternatively, some corporations and restaurateurs simply wish to integrate FCs into existing or imminent operations. Finally, on a governmental or global level, FCs can also be used to boost the economy by creating jobs in a clean, high-tech field. Ultimately, we are aiming to build an interdisciplinary, agile platform able to empower the collective of its users by capitalizing on their particular skills, lending them instant access to the aggregate wisdom of experts in other fields and meeting their unique needs.

Acknowledgment The author is thankful to Lana Popovic for her editorial support.

References

Abbate J (1999) Inventing the internet. MIT Press, Cambridge, MA, 275 p.p

Baker D (1996) A brief excursion into three agricultural revolutions. Keuhnast Lecture, University of Minnesota. http://climate.umn.edu/doc/journal/kuehnast_lecture/l4-txt.htm

Harper C, Siller M (2015) OpenAG: a globally distributed network of food computing. Pervasive Comput 14(4):24–27

World Urbanization Prospects: The 2014 Revision. United Nations, Dept. of Economic and Social Affairs, Population Division, ST/ESA/SER.A/366, 2015; http://esa.un.org/unpd/wup/Highlights/WUP2014-Highlights.pdf

World Population Prospects: The 2015 Revision, Key Findings and Advance Tables. United Nations, Dept. of Economic and Social Affairs, Population Division, working paper no. ESA/P/ WP.241, 2015; http://esa.un.org/unpd/wpp/Publications/Files/Key_Findings_WPP_2015.pdf