Imagining Science in 2035

Strategies for Maximizing the Value and Impact of Plant Science, and Beyond

Plant Science
Research Network

Contents

Summary.. 1

The Four Scenarios 3

The Four Worlds

Scenario 1: Renaissance Science 4

Scenario 2: Selective Science.............................. 7

Scenario 3: Critical Science 10

Scenario 4: Targeted Science 13

Using These Scenarios 16

Participants and Support... 17

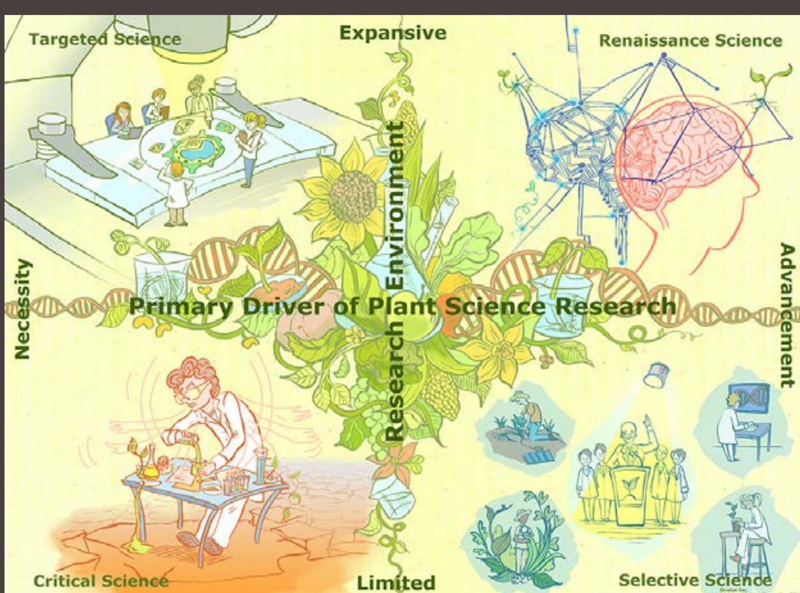


Figure 1.

Illustration by Kristyn Stickley, Kristyn Stickley Illustrations 2016.

Imagining Science in 2035

Strategies for Maximizing the Value and Impact of Plant Science, and Beyond

Summary

Introduction

The Plant Science Research Network (PSRN), funded by an NSF Research Coordination Network grant, consists of fourteen professional societies and organizations whose members are active in plant science research, education, and advocacy. The PSRN's overarching objective is to implement and update the 2013 Plant Science Decadal Vision through engagement of the entire plant science community. PSRN members aim to build consensus around research, education, and training objectives that will promote discovery, broaden participation, and have a measurable impact on pressing challenges around food, agriculture, the environment, and human health. As a key component of its aim to promote engagement and visionary thinking, the PSRN held a workshop to create a set of plausible scenarios to frame the future of plant science research. These scenarios have already been used as groundwork for subsequent PSRN-organized workshops to explore how the plant and broader life science communities might position and prepare themselves in the areas of postgraduate training and cyberinfrastructure. However, the scenarios may also be used in strategic planning activities by other groups or organizations.

Scenarios are stories about the future that encourage us to challenge deeply held assumptions and to chart clear paths forward. Scenario thinking allows communities, groups, or organizations to engage around what is not known and/or cannot be controlled, which includes major external forces that define their respective operating environments. The most relevant and least predictable of these uncontrollable forces are called "critical uncertainties," and they form the foundation upon which scenarios are created. Scenarios also require a focal question, which defines the overall topic and therefore the germane uncertainties.

Scenario-based planning avoids the temptation to choose one assumed future and plan towards it, but instead develops a plan around a set of possible futures that visit the extremes of the identified critical uncertainties. In doing so, it is recognized that the future will never be exactly as described in any one scenario, nor as extreme, but it will be made up of components of all of the scenarios.

The Process

The PSRN began by engaging a trained facilitator, who conducted interviews of strategically selected community members and stakeholders, and followed up with a survey to engage a broader group. Based on that feedback, the following focal question emerged:

How does the plant science community enable plant science research to maximize its value and impact over the next 20 years?

For the purposes of the PSRN workshops, we focused the discussion on how to create value and impact through 1) postgraduate training, 2) cyberinfrastructure, and 3) broadening participation.

Scenarios are stories about the future that encourage us to challenge deeply held assumptions and to chart clear paths forward.

The focal question emphasizes that within the very broad scope of possible avenues for research, there will be a wide range in the value and impact of what is delivered, even though those terms may be used in different contexts with different meanings. The *value* proposition refers to the constraint of resources, while *impact* refers to the importance of discovery itself, including societal impacts contributed in a trained and diverse workforce, as well as in products for health, nutrition, the environment, and agriculture.

Analysis of the interviews and surveys led to an initial list of critical uncertainties surrounding the focal question, which served as background for the in-person scenario planning workshop.The initially-identified uncertainties were:

- Plant Science Research Areas Under Study
- Research Scope and Frame
- Funding and Resources
- Stakeholder Acceptance and Perception (including the public)
- Policy and Regulation
- Enabling Tools & Technology
- Data, Storage, Access, Standards
- Environmental Stresses and Security
- Future Workforce Competencies
- Education and Training
- Communication, Connectivity
- Inclusion and Outreach

The Workshop

The in-person workshop was held on September 21-22, 2016 and was hosted by the Howard Hughes Medical Institute (Chevy Chase, MD). Workshop participants first agreed that the scenarios would explore the focal question and critical uncertainties over a period of 20 years. A 20-year outlook was considered to be an appropriate time frame to implement far-reaching strategies that might be identified in subsequent workshops.

Each of the critical uncertainties was explored in detail, leading to the adoption of two critical uncertainties that would define the scenario space:

Research Environment: Will the research environment of the future have an abundance of resources and investment, or will that environment be increasingly scarce and limited?

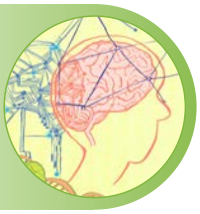
Primary Driver of Plant Science Research: Will the primary driver of plant science research be knowledge advancement for the sake of discovery, or will it be the necessity to solve problems?

The extremes of these two uncertainties can be used to frame X- and Y-axes, creating quadrants, each of which houses one of the four divergent scenarios (see Figure 1 on the inside front cover). Each of the scenarios is given a descriptive name to summarize its key characteristics.

Plant scientists
make the most of what will always be limited resources.

A fictional character, named Dakota, brings the scenarios to life.

The Four Scenarios



Scenario 1: Renaissance Science

A curiosity-driven world that is focused on generating knowledge. Discoveries are diverse, and the pace of change is constantly accelerating. Research (in the laboratory, in the field, and *in silico*) is dramatically transformed.

Scenario 2: Selective Science

A nimble, interdisciplinary world in which resource scarcity drives new models of research to advance knowledge. Machines have taken over much of the rote work, which creates efficiencies but also limits opportunities for human participation.

Scenario 3: Critical Science

A world driven by increasing vulnerabilities to environmental stresses, which in turn foment geopolitical instabilities and conflicts. As the research community reacts to the crisis *du jour*, short-term solutions substitute for deep understanding, and data are collected and utilized with inadequate attention to quality control, curation and standardization.

Scenario 4: Targeted Science

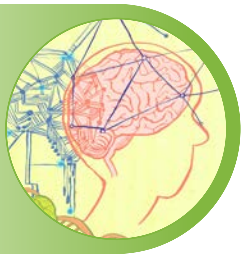
A proactive world in which many science-related challenges are anticipated, and can be more readily addressed, because of deep understanding of organisms and the environment. Although the world is not immune from geopolitical instabilities, such as food insecurity and the impacts of climate change, these threats are effectively managed, and long-term strategies are in place based on the application of new scientific advances.

During the workshop, participants envisioned each scenario in greater detail, aided by the creation of 20-year timelines with media headlines to feature the progression of events in each of the four scenarios. Were the headlines (termed “early indicators”) from any given scenario to appear in reality, they could serve as an early warning that aspects of a given scenario are actually coming to pass.

Using the headlines and other defined characteristics of each future world, participants augmented initial descriptors with arguments as to each scenario’s plausibility and possible areas for investment. A fictional character, named Dakota, brings the scenarios to life as she discovers plant science and engages in its pursuits over a 20-year time span. The opportunities available to Dakota in each of the scenarios, and the choices that she makes, illuminate the nature of each future world in a palpable way.

On the following pages, each scenario is detailed in both descripive and narrative modes.

The Four Worlds



Scenario 1
Renaissance Science

This is a curiosity-driven world that is focused on generating knowledge. Discoveries are diverse, and the pace of change is accelerating. Research in the laboratory, the field, and *in silico* is dramatically transformed compared to 20 years earlier, in large part because data are vetted, standardized and fully accessible to researchers. Indeed, improvements in the availability and reliability of computer-generated analyses make them an ever-present partner to scientists, dramatically increasing the pace and quality of new insights. Different corners of the research world are seamlessly connected, with real-time communication of data and analyses underpinning fluid and global collaborations. Despite the abundance of resources and the value that is placed on fundamental discoveries, professional incentives in the public sector draw researchers and resources away from problem-solving projects that are viewed as mundane. This gap is filled by corporations that draw upon the rich public knowledge bases to build business models around problem solving, but corporations also focus their investments to address market forces. Although competition among corporations drives advances in real-world applications, potential synergies are lost as corporations protect their most advanced technologies. Policy makers and the public appreciate the benefits that foundational science brings to society, elevating its financial and institutional support, as well as the place of science in the national dialogue. Imagination and creativity are valued in the scientific community, with education and training focused on experiential learning, deep computational literacy, flexibility, and transdisciplinary thinking. This situation leads to a strong flow from the public to the private sector, where the publicly-funded focus on discoveries and training provides industry with the knowledge, tools, and skilled researchers required to speed commercialization of novel plant-based solutions. Examples are products for health and nutrition, applications to bioenergy such as artificial photosynthesis, products that help combat or mitigate climate change, and customized agricultural solutions. The public sector generates systems knowledge of the relationships among plant genotype, the air, water and soil and its biotic and abiotic constituents, at scales that span from the molecule to the ecosystem, including accurate predictive models that are leveraged by the private sector to solve global problems.

Plausibility

Today, children are growing up with technology as a primary interface with the broader world. The Internet of Things is changing how humans learn from and understand the world around them. In “Renaissance Science,” our present challenges of vetting, standardizing, curating, updating, storing, and distributing massive data sets have been largely met. Artificial intelligence is a major growth area presently, with interactive computer systems and rapid advances in deep learning algorithms. In “Renaissance Science,” engineers, information scientists, and biologists utilize powerful computational systems to allow for more robust data analysis and predictive modeling. High quality control is ensured, enabling human scientists to focus on the most promising hypotheses and areas for discovery and application. Public suspicion of novel technologies implemented by the private sector is a significant roadblock, presently and in this scenario.

In Renaissance Science, the private sector solves problems while the public sector generates fundamental discoveries: The flow between the sectors is vigorous and productive.

Focus Areas for Consideration

- Training for transdisciplinary local and distance collaboration, fueled by enhanced communication and connectivity among humans and machines;
- Expanding the diversity of researchers operating within broadly conceived projects and objectives;
- Building deep computational literacy, as well as experiential, creative, and adaptive capabilities using new models for higher education;
- Facilitating the rapid transfer of advances in data analytics from the information sciences into the plant sciences; and the use of problems in plant sciences to drive advances in information sciences;
- Encouraging scientifically-based, forward-thinking, innovation-driven policies and regulations, that at the same time build public confidence in private sector applications;
- Developing and building on public science appreciation through agricultural extension activities, crowd-sourcing, citizen science, and formal and informal education.

One Scientist's Story

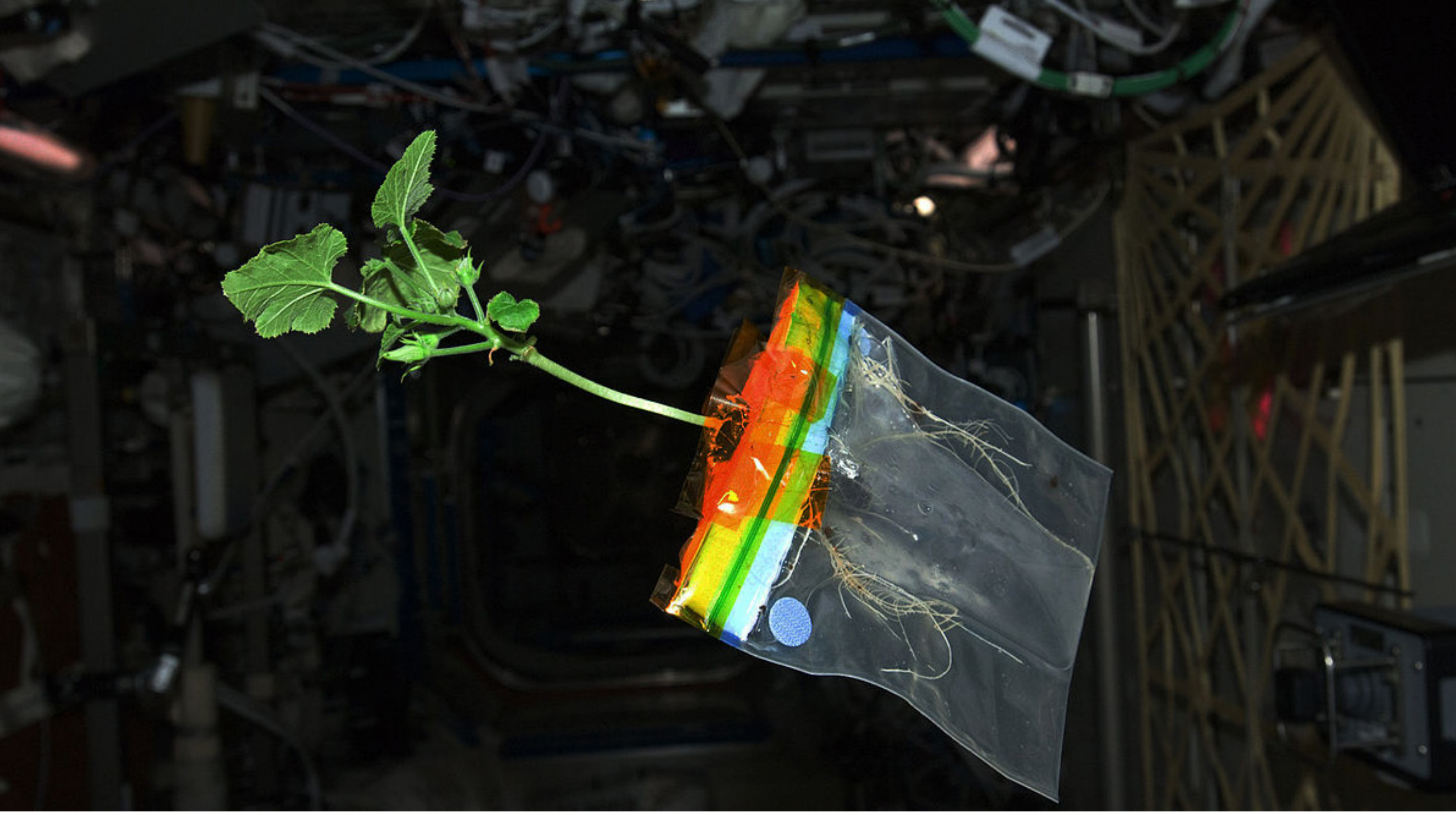
California was certainly a different world from Blazing Hearth, Oklahoma! For the last decade Dakota had been repeatedly amazed. Consider the most popular and cutting-edge restaurant chain, Brainwaves. With a tap on the wrist, your device contacted sensors that would formulate a meal that met your truest desires. Dakota would savor her meal while listening to cowboy poems, letting go as the robot singer's raspy drawl carried her away. Behind the scenes was the *really* cool part. Not a cook or a frying pan to be seen; just a sleepy nerd who kept the food synthesizers running and made sure the ingredient drones docked properly. Dakota's grandfather had told her that as a young man he had peeled potatoes and washed dishes at a diner, but she had always assumed it was a made-up story to impress upon her how lucky she was to live in the Golden Age of Plants and Food.

Back in 2020, when Dakota was a teenager, Blazing Hearth was still a cowboy town. Though she cared little for books, Dakota was whip-smart and well-informed, especially when it came to fireflies. She had favorites among the 2,000 species, namely those that glowed flaming red or were poisonous. Her classmates tended to learn more than they really wanted to, and would ask, "How could you know all that and still fail biology?" The answer was that to Dakota, life buzzing around her was an enchantment, and memorization was a bore.

Somehow Dakota muddled her way through high school, but the rote pathway to university filled her with dread. So after graduation Dakota took a summer job as a counselor at "Camp Bug" where on the first day she was asked why bees liked flowers. "How can I not know this?" she wondered. In two minutes, though, she discovered from OmniPedia that 43,000 miles of bee travel yields one pound of honey, and that bees have hair on their eyeballs. She also learned that bees don't just see flowers, they sense them through electrical fields. Dakota decided then and there to find out how flowers make electricity, and why.

On a whim she applied for one of the specialized DiscoveryCorps programs popping up around the country; this one to explore the generation of bioelectricity. DiscoveryCorps fit in a world in which the patina of a university de-

Enhanced communication and **connectivity** among **humans** and **machines.**



A zucchini plant, floating freely in the International Space Station's Destiny laboratory. (Photo by an Expedition 30 crew member https://go.nasa.gov/2r0UvEg)

gree mattered less and less, and curious minds like Dakota's were freer to search for answers. Dakota's year in DiscoveryCorps honed her skills in adaptive learning and collective inquiry, and was peppered with nuggets like a crash course in electrical currents. By years' end, Dakota's study team had successfully related electrical field modulation to pollinator attraction and genetics. When the work was featured in *Scientific American*, Dakota was listed in the Lead Author Team; the farm lobby picked up on the findings, and a public-private partnership was quickly launched to optimize pollination in California's almond orchards.

Over the next decade, California orchards saw their pollination rates steadily improve. Motivated by her desire to continue to contribute to improved agriculture, Dakota joined the agritech giant AgriValley, leading a team that leveraged gene editing, and a growing library of open source predictive models of plant physiological processes, to further increase water use efficiency and reinvigorate the Central Valley economy. Her team developed a fast turnaround service for a mind-boggling march of genetically-fashionable designer flowers, but customized fruits and vegetables were initially viewed with suspicion by the public. Even these fears eventually receded as product novelty and perceived consumer benefit began to dominate the discussion. Investments at the interface of ecology, environment, artificial intelligence, and plant biology had finally paid off.

It's no wonder that restaurants like Brainwaves thrive in this world, with a rapid-response supply chain, a robust pipeline for discovery and application, and government support helping academics pave the way to whatever the next wave of innovation might hold. In the public sphere, scientific literacy had become a prerequisite to public office, and funding agencies prioritized scientific advancement, defined as "*Discoveries that build careers*."

And what became of Dakota, holder of a C+ GPA from Blazing Hearth High? Does she find solace in the flora of Patagonia's returning glaciers, where the first recorded effects of dramatically reversed carbon emissions take hold? Or perhaps she becomes an avatar for progress, helping to make the term "third world" a now-forgotten anachronism? We leave her at a moment where she is considering NASA's call for the second human mission to Mars, for which a plant biologist is considered to be an indispensable team member.

Scenario 2
Selective Science

This is an interdisciplinary world in which new models of research emerge in response to limited resources to support continued advancement of knowledge. Machines and service labs have taken over much of the rote work previously performed by students and postdocs, creating significant efficiencies but changing and reducing opportunities for human participation and training. The academic research environment develops increasing inequality, with large and successful teams garnering a disproportionate amount of resources, while less visible programs struggle to maintain their momentum. Research collaborations involving multiple groups dominate, facilitated by communications technologies that allow impoverished labs to pool their resources to remain competitive. Despite the consensus that research should advance basic knowledge, resource allocation tends to coalesce around a limited number of focus areas, for example in well-supported model systems or in areas with clear links to the highest-impact nutritional, health, environmental or agricultural traits. The foundation of knowledge strengthens in these selected areas, but languishes in others. The labor-intensive vetting, curation and updating needed to make data reliable and machine-readable falls further and further behind due to funding constraints, fueled in part by a perception that plant science problems are not cutting edge. With the limited funding targeted to basic research, problem-solving is dominated by the private sector, which has the resources necessary to curate data sets, build tools and apply innovative technologies. The pipeline of plant scientists shrinks and fails to diversify, and those that enter are often diverted to other career paths. Despite there being fewer trainees, they are highly innovative, efficient, and seek synergies and collaborations in their vigorous pursuit of novel funding sources, which include philanthropists attracted by societal challenges and the growing interest in biological science among high-tech companies. The highly competitive research environment means that quality data and intellectual property (IP) protection are among the keys to success. Although data from publicly-funded projects continue to be available, they tend to be superficial and unreliable, reducing their utility and value. High quality data sets are mostly found in the private sector, where they are protected as trade secrets. "Knowing the right people" becomes paramount to gain visibility, sustain funding, form connections, and influence the collection and management of data. Other key influencers are those who formulate guidelines for disbursing public and philanthropic funding, and an emergent patron-driven model pairs philanthropists with scientific talent to advance relatively narrow, siloed agendas. The private sector profits from academic flight, yet has ever less foundational knowledge on which to build future product development. Public confidence in science is low as the public sector invests its limited resources in "ivory-tower" research rather than in societal problems.

Plausibility

Public funding is increasingly difficult to secure for many of today's scientists, concentrating opportunities for the most talented, driven, entrepreneurial and opportunistic. The result has been a higher profile for private funding,

The robots toiled tirelessly, **making the world a better place.**

Jane Richardson developed the ribbon diagram method of representing the 3D structure of proteins, and is a Professor at Duke, NAS member, and recipient of a "Genius" award. She never completed her doctorate.

which like an increasing number of federal sources, comes with restrictions on the scope and path of research. Similarly, the environment in "Selective Science" discourages long-term, high-risk research, and has a transiently positive effect on the private sector because academic scientists develop findings closer to application. The public distrusts both "ivory-tower" fundamental research and the implementation of novel technologies for food production by the private sector. Data accumulate at a rapid pace, but are poorly managed by the research community.

Focus Areas for Consideration

Training for diverse career paths;

- Broadening participation in a resource-limited environment;
- Developing viable new models for interdisciplinary collaboration, facilitated by communications technologies that allow meaningful participation by all collaborators;
- Developing efficiency in research with application of automation and centralized service models;
- Developing cheap and efficient computational methods for curating public data that mitigate the typically superficial, ad hoc, and unreliable nature of such methods;
- Creating incentives for public-private partnerships in problem solving;
- Creating openness and sharing in an environment pushing the other way.

One Scientist's Story

As Dakota's Global Microbiome Institute (GMI) prospered, she never stopped traveling, incessantly promoting her institute at conferences worldwide, in TED talks, on talk shows, and through a "Healthy Bug" program that mesmerized local schools - anything to promote the high visibility her institute's funding depended on. But she wished she could spend more time thinking and, when her son was born, more time with her family.

As she gazed at her son and recognized in him her own mother's smile, Dakota recalled a moment in her distant past… "Why is mom having a retirement party?" Dakota had asked her father, in between bites of doughnut. "She's so young!" Her father had averted his eyes. "'Retirement' is just a word," he replied, "an inflection point in life." The truth was, her mother's early retirement from Stream Bank Agricultural College was emblematic of an inflection point in society. For some 20 years, she had taught microbiology to mainly local students and led a research consortium composed of small laboratories that pooled their resources in an attempt to stay competitive. But enrollment at Stream Bank had steadily fallen, undergraduate research funding had been eliminated from the Farm Bill, and Stream Bank was buying out some of its best faculty.

Vowing that her family's legacy of science and teaching would somehow continue, Dakota won first prize in the high school science fair, with her takedown of the minimal science behind probiotics in food. The resultant buzz prompted her to launch a Facebook community group called, *Microbiomes All Around Us*. The group traded articles on probiotics ("Food Fact or Mindless Fiction?"), scientific factoids ("A million species in your bathtub!"), and futuristic doodling ("What Comes after the Martian Microbe Project?"). Dakota's straight-A average from Blazing Hearth High punched her ticket to college, where she dove into a triple major in microbiology, public policy, and data science. Her undergraduate thesis on "The influence of farm policy on the human microbiome" gained her the highly competitive Thinker's Scholarship to continue her education.

As a Thinker's Scholar, Dakota was readily accepted into the leading microbiome laboratory in the country, headed by Dr. Lixue Huang. Dr. Huang also maintained two laboratories abroad, an analytical group in China and

In Selective Science, drones delivered samples which were classified, processed, and assayed by robots. (http://bit.ly/2gIB11B)

a statistical analytics group in India. The Indian group had taken advantage of a large, local pool of well-trained computational biologists to develop private, high-quality datasets out of the generally poorly-annotated public datasets, which it also marketed to the private sector. The analytical group conducted automated sample analysis for agricultural and medical research. The statistical analytics group merged the sample data with their private database, generating hypotheses for the much smaller American laboratory to test. In this environment, Dakota traveled frequently and globally, gaining a profound appreciation for cultural diversity.

With her Ph.D., Dakota was quickly recruited by a major university seeking an energetic entrepreneur who could lead global research initiatives and attract eye-catching philanthropic investments. As a junior faculty member, Dakota quickly established the GMI, which used personal genomics to design probiotics for the promotion of individual health.

Even as Dakota's team grew, the department around her dwindled until eventually only six large, interdisciplinary groups remained. The smaller research groups had fallen victim, as her mother's had, to the downward spiral of public investments. Those that remained had profited from the unequal impact of increasingly dominant research philanthropy, where winners were picked based on their perceived ability to address the philanthropist's favorite issue.

GMI became the go-to resource for other laboratories that could not afford in-house microbiome expertise, but they did so with very few human scientists, greatly reducing the cost of research. Drones delivered samples which were classified, processed, and assayed by robots. The results were delivered to a corporation that crowd-sourced data analysis, often paying laid-off U.S. academics to do piece work for a budget hourly wage. At noon each Friday, a synthetic voice delivered webinars in three languages, explaining the findings and asking for feedback. Humans then reprogrammed the robots and the data loops in advance of the next week's work. This automation revolution augured well for Dakota's home life. Her small team mostly met in a virtual conference room, which she accessed from home. Dakota taught classes and met with other faculty several times a week, but just as often she could be found at a coffee shop or in the park, playing with her son while the robots toiled tirelessly, making the world a better place.

Scenario 3
Critical Science

This is a reactionary world of growing inequality and increasing vulnerabilities to environmental stresses. As the research community repeatedly shifts focus to address the crisis du jour, patchwork solutions tend to substitute for deep understanding of problems. Public datasets are typically narrow in scope with inadequate curation and standardization. Hyper-flexible, rapid-response research practices and technologies begin to emerge, incorporating the latest advances in artificial intelligence and data analytics, but these are primarily concentrated within corporations that have adapted to the business opportunities afforded by repeated environmental crises. Driven by market forces, universities begin to tailor their curricula to produce graduates who possess the characteristics desired by industry. The private sector also becomes directly vested in training, in some cases going so far as to repurpose educational institutions to ensure that the future workforce meets market demand. These "applied science academies" play a long-term role in diversifying the science workforce; the problem-solving mentality of applied research creates economic opportunities and spiritual rewards that are attractive to some who would otherwise be disinterested in such a career path. This resource-limited, solution-driven environment stimulates international scientific cooperation to pool resources. Two types of scientists thrive in this environment: a majority that is adaptable, technically adept and comfortable working in teams; and a minority that excels at problem-solving and possesses the capability, charisma and drive to assemble, lead, and manage teams. The public supports research with tangible benefits, but distrusts the corporate giants that come to dominate environmental crisis management. Fundamental research needed to support problem-solving increasingly moves into the corporate sector, or IP-restricted private-public partnerships. Competition among the giants drives some spectacular innovations, but synergies are lost because IP is tightly held. Among these advances are deep understanding in specific aspects of areas such as host-pathogen interactions, plant water use efficiency, soil physics, and agro-ecosystem response to water stress, including highly advanced predictive modeling and decision analytics. Lagging are greater fundamental understanding of natural ecosystems, plant metabolism and evolution, and relevant high quality, publicly-available datasets and computational tools.

Plausibility

Chronic underfunding and political paralysis regarding climate change could conceivably exacerbate environmental impacts on universal needs, including healthy food and clean and accessible water. Most researchers would agree today that funding is excessively limited, that they spend an undue amount of time seeking it, and that it is often skewed towards need-based, or narrowly-defined areas, sometimes without a well-founded scientific rationale. Examples already exist of private industry moving in to fill gaps in public science and/or driving scientific advances in areas of business opportunity. Eighty-percent of Ph.D. graduates today do not follow academic career paths and there is strong pressure on graduate programs to adopt training models that prepare students for diverse careers. The public perceptions of science is tenuous and ambivalent, swayed by whether science can improve lives in palpable ways, rather than a belief in the long-term value of discovery.

Focus Areas for Consideration

- Training for adaptability, problem-solving in teams, communication across public-private boundaries, understanding of technology transfer and entrepreneurship;

There is strong pressure on graduate programs to adopt training models that prepare students for diverse careers.

- Training plant scientists sufficiently in information science, so that they can bring relevant advances in that field to bear on problems in the plant sciences;
- Attracting a diverse student pool to need-based research;
- Developing new models for multi-group collaboration, facilitated by communications technologies that allow effective problem-solving with limited resources;
- Developing the ability to generate required data rapidly, and to find, assess, and properly utilize poorly vetted, fragmented data;
- Developing policies that support and encourage investment in basic research by the private sector;
- Re-examining the purpose and application of Land Grant funding and agricultural extension services.

One Scientist's Story

Dakota relaxed in her well-appointed office, gazing out at leafy paths of Oklahoma Technical Institute (OTI). She often used time between classes and environmental consulting to reflect back on the 2010's when cascading environmental disasters were tearing apart her home town of Blazing Hearth. With endemic drought, topsoil depletion, and sky-high temperatures making farming a losing game, the dusty remnants of the once-crowded Blazing Hearth farmers' market had baked to a crisp under the cloudless Oklahoma sky, and even birthday cakes became a luxury. At Dakota's alternative high school, the kids weren't just students; they were also the teacher's aides, custodians, and mechanics.

As a teenager, Dakota had been an itinerant learner: flipping through forsaken books at the library, jawboning with struggling local farmers over imitation ice cream, and retweeting anything trending food - the images of lace-glazed, delicate desserts fed Dakota's dream about a greener, healthier Blazing Hearth. One day, Dakota's news feed alerted her to an agribusiness-supported MOOC (a massive open online course) called "The Magic Garden", in which students conducted online research and ran a virtual farm. Though skeptical of corporate giants, Dakota decided she had nothing to lose. In fact, "Piece of Cake Farm" got off to a good start. Trial and error taught Dakota farm management, and she learned which microbial component to use for a given crop genotype, how to minimize water use, and how to predict which genetic traits would prevent disease and minimize insect losses.

Role-playing made Dakota begin to feel more like a scientist than a farmer. The trouble was, no one encouraged her to pursue higher education as a research scientist. Congress had all but starved the basic research engine, and indeed the entire world seemed to be lurching from one crisis to another. But Dakota wanted out, and announced to her parents that she would get a job helping return Blazing Hearth to its greener past.

With a corner on the food and water markets, and nearly unfettered power, agribusinesses were hiring. Dakota joined FirstAg, one of the biggest players, as a soil analysis technician. She discovered *Further Thinking*, FirstAg's after-hours

Training for adaptability, **problem-solving** in teams, communication across public-private boundaries

Short-term solutions substitute for deep understanding: A risk of **inadequate** and **overly targeted funding.**

View from Marine One of California drought, 2014. (Official White House Photo by Pete Souza, http://bit.ly/2qkSmSI)

employee learning program, and buried herself in the intricacies of soil and water. Dakota was surprised that she needed to learn microbiology, evolution, and genomics, along with water physics, a far cry from the button-pushing fun of "The Magic Garden." Dirt was so complicated!

Dakota rose rapidly in FirstAg, valued for her contributions to the company's bottom line. Her lack of formal education was no impediment: a higher degree might have only been a barrier, given the rising unemployment rates and poor job satisfaction for graduate degree holders. Other companies followed suit: Bechtel became "Climate Change, Inc.," and FirstAg eventually took over Oklahoma State University to create the private OTI. The public sector didn't disappear, but scientists were forced into large collaborations with one or more industry partners. These partnerships provided access to predictive analytical tools, significant payments for IP, and ready transitions for students and postdocs who would otherwise face grim career prospects. Research tended away from model systems, but was very data-rich and reliant on real-time communication that saved on travel.

To have more time for her family, Dakota accepted a six-figure instructor's salary at OTI, where she teaches students how to reshape local economies in response to environmental pressures. Dakota's dream of resuscitating Blazing Hearth did not come to pass: its fate was sealed. No matter; the robots that now farm the land care little for the abandoned schools and trailer parks.

Cascading environmental disasters were tearing apart her home town.

Her lack of formal education was no impediment: a higher degree might have only been a barrier.

Scenario 4
Targeted Science

This is a proactive world of solutions-oriented research, in which many science-related challenges are anticipated and can be addressed more readily because of adequate government investments coupled with incentives for private investments, and deeper understanding of organisms and the environment in targeted areas. Although the world is not immune from issues such as food insecurity and the impacts of climate change, these challenges are being effectively managed. Long-term strategies are in place, and they are being updated based on new scientific advances.

Plant science is an integral part of many programs related to agriculture, health, and the environment. Advances in data analytics are rapidly transferred from the information sciences into the plant sciences; reciprocally, outcome-relevant challenges in the plant sciences drive advances in information sciences in both the public and private sectors. The public is increasingly accepting of significant expenditures on outcomes-oriented research. These investments are leading to seismic shifts away from chemical-intensive monoculture while they enhance food sophistication, underpin explosive growth in science-based natural remedies, and catalyze widespread success in conservation of species and utilization of germplasm diversity. This is all made possible by major advances in the understanding of natural products, plant-soil-atmosphere interactions, and organismal evolution.

Discoveries are underpinned by open data sets that have been carefully vetted and curated using universal data standards, and by major advances in artificial intelligence and predictive modeling. Funders and scientists are aligned around the most critical priorities facing the planet, and how to address them in the long- and short-term. Although targeted topic areas are well-funded, basic research outside the target areas is poorly supported, until needed to address an emerging problem. This inequity delays progress on unanticipated problems. The resulting gaps in knowledge also limit research to the most obvious avenues, and disruptive advances that arise from unexpected directions are rare. Data tend to be shared openly, and sophisticated analytic tools provide increasingly earlier warnings of potential threats. The biological breadth of available data, however, is skewed.

Training is focused around the ability to function ably in complex team environments, mechanisms for knowledge transfer to the private sector, and how to identify the main elements of a problem and conceive solutions. Plant scientists act as key integrators in these large projects, and among them are many previously underrepresented members who are drawn to the mission-driven nature of the work.

Plausibility

Present impacts of climate change, population growth, income inequality, and infectious diseases – to name just a few of today's most challenging global stressors – are growing and increasingly visible. Current policies and approaches toward addressing these challenges seem inadequate to mitigate the risks, much less reverse the situation, and the potential for a significant global catastrophe – or a series of them – is very real. A political and commercial sense of urgency could conceivably be generated if the social and environmental damage were more extensive, prompting major investments in global agricultural and ecological systems. Greater investments would enable science to move into a more anticipative space. Such a mindset would require widespread recognition that science is as integral to solutions in agriculture and the environment, as it is in medicine, and this acceptance could lead to a re-visioning of the Land Grant mission, among other fundamental shifts.

Indeed, the entire world seemed to be lurching from one crisis to another.

Focus Areas for Consideration

- Training in how to form and participate in well-led teams composed of specialists in very diverse disciplines;
- Building capacity in specialty areas, achieved in part by reaching into new demographic communities;
- Broadly engaging the agriculture and plant science communities, and the public, in data collection;
- Investing in deep computational literacy, coupled with rapid and standardized vetting, curation, and preliminary analysis of plant-related data;
- Achieving rapid transfer of advances in analytics from the information sciences into the plant sciences; facilitating the ability of problems in plant sciences to drive advances in information sciences;
- Developing policies to encourage public-private partnerships, especially in the transfer of advanced artificial intelligence technologies into the plant and environmental sciences;
- Facilitating dialogue among research practitioners, farmers and other end users, the public, and policymakers.

One Scientist's Story

"When I was a teenager, we often worried that our Squishy's banana splits would only have chemical banana and chocolate flavoring," Dakota told her three-year-old son. "EEEwww!" he cried on cue. "Mom - tell me the story again of how you saved real bananas!"

Bananas had started disappearing back in 2020 when the coffee thrip jumped to banana and decimated crops in Central America, before spreading to the Caribbean, South America, and eventually West Africa. The host jump resulted from intense selection driven by widespread intercropping with coffee plants containing genome edits that conferred thrip resistance. Banana prices had skyrocketed. An unwelcome consequence, given that 80% of bananas are consumed locally, was emergent health problems in populations now deficient in fiber, potassium, and prebiotics.

As a teenager, Dakota had a summer job at Squishy's. One day, eating his favorite but very expensive banana split, her favorite teacher, Mr. Stumpf told Dakota of "Sweet Science," a new after-school program sponsored by Candyopolis, a candy store chain that had recently arrived in town. Dakota, amazed that an after-school program could be built around candy, was one of the 15 lucky initiates, in no small part due to her glowing recommendation from Mrs. Blount, who owned Squishy's and admired Dakota's enthusiasm.

"Sweet Science" was full of fascinating surprises; for example, Dakota learned that bananas are actually berries that grow on an arboreal root, and that they chemically combat depression. By the time Dakota began her senior year she yearned to learn more about food and plants. Accepted into state college, she discovered a program called "Why it Matters," where students commit early to a science-heavy curriculum taught from a problem-solving perspective. Dakota's news feed always seemed to be full of stories about teams of scientists who were anticipating and mitigating the worst impacts from crop failures, floods, and famine. Being part of "Why it Matters" excited her: she imagined herself as a heroic scientist protecting the world.

The 5-year "Why it Matters" curriculum combined Bachelor's and Master's degrees, intertwined with a team-based focus on a specific societal problem. Dakota, of course, chose to focus on the banana. Her team created a "Banana Action Plan," that proposed using statistical models to guide a molecular breeding program for thrip-resistant trees, boosted by repellents based on chemicals found in naturally thrip-resistant plants. They also explored alternative crops that would mitigate health issues.

During Career Week, there was no shortage of opportunities for a dynamic young woman whose senior project

Bananas growing in the Mount Kenya region. (International Center for Tropical Agriculture photo by Neil Palmer, http://bit.ly/2qB42RL)

incorporated statistics, agriculture, ecology, and genomics. In only three years she became a Team Lead on a public-private partnership to deal with the banana thrip. Dakota could draw on a massive data trove from drones and sensors distributed across the agricultural tropics in a program jointly managed by the U.S. Agency for International Development and the Smithsonian Institution. Radical improvements in accuracy and data integration from these sources was due to a refocusing of federal competitive grants around a cross-cutting program called "Agricultural Information for the Future." The ability to follow the thrip in real time, identify key genetic determinants that impacted population fluxes, and understand and manipulate the chemical conversation between the thrip and the plant, quickly led to a novel therapy that targeted a previously unknown bacterium that had colonized the thrip, making it highly damaging. Dakota wove this into a three-pronged approach that added a nutritional assistance program, and a long-term investment in applied plant science research and education called, "For Fun and Food."

Naturally, Dakota had expertly shaped the story to fascinate her three-year old. "And that," said Dakota, "is why we now can have a banana split at Squishy's any time we want!"

Science is as integral to solutions in agriculture and the evironment, as it is in medicine.

Training is focused around the **ability to function** ably in **complex team environment.**

Using These Scenarios

The proximate purpose of the four scenarios was to frame subsequent PSRN workshops on the future of postgraduate training and cyberinfrastructure, as they relate to the plant sciences. Those workshops were held in October 2016, and reports can be found online at plantae.org, in the Plant Science Research Network group. The scenarios played a critical role in the training and cyberinfrastructure workshops because from the start, participants confronted the inherent uncertainty of the future, which sometimes leads to diametrically opposing possibilities. The scenarios also gave participants the tools they needed to address the uncertainties, and thus to develop strategies that would work, at least initially, no matter which aspects of each scenario eventually comprise the future. This approach builds flexibility into strategy development, which can be continually tuned by monitoring early indicators.

There are many possible uses for these scenarios in addition to those outlined just above. Indeed, with a small amount of additional work, these scenarios can be customized for related applications, such as might be required by a funding agency, a scientific or educational society, or for a philanthropic effort. They might also be used by academic departments or schools, as a point of information in how curriculum development or faculty hiring might be approached and/or to assess what sorts of funding streams might materialize and whether or not that entity is adequately prepared to compete for them. Visit us on plantae.org to learn more and to download supporting materials and workshop resources.

The scenarios also highlight some of the dangers that the world faces and the role that plant science research should play in overcoming them. In that sense, the scenarios and stories make good reading as a form of "science fiction," albeit a type that is grounded in a process linked to the very real world of today.

Visit us on Plantae at community.plantae.org
to download supporting materials.

Participants and Support

Participants

Harriet Alexander, *UC, Davis*

Parker Antin, *University of Arizona*

David Asai, *Howard Hughes Medical Institute*

Kaitlyn Bissonnette, *Iowa State University*

Paul Chomet, *NRGene Ltd*

Mary Crowe, *Florida Southern College*

JP Dundore-Arias, *University of Minnesota*

Judy Glaven, *Howard Hughes Medical Institute*

Michael Gonzales, *University of Georgia- Consultant*

Alannie-Grace Grant, *University of Tennessee, Knoxville*

Vanessa Greenlee, *Boyce Thompson Institute*

Natalie Henkhaus, *American Society of Plant Biologists*

Fumiaki Katagiri, *University of Minnesota*

Molly Megraw, *Oregon State University*

Angus Murphy, *University of Maryland*

Clif Poodry, *Howard Hughes Medical Institute*

Paul Okello, *South Dakota State University*

Pam Soltis, *University of Florida*

Chelsea Specht, *University of California, Berkeley*

David Stern, *Boyce Thompson Institute*

Crispin Taylor, *American Society of Plant Biologists*

John Thomasson, *Texas A&M University*

Writing Team

David Stern (PI), Crispin Taylor (co-PI), Vanessa Greenlee (Broadening Participation Coordinator), Natalie Henkhaus (Executive Coordinator), Brett Tyler (Oregon State University)

Plant Science Research Network

Members of the Plant Science Research Network

American Phytopathological Society

American Society for Horticultural Science

American Society of Agronomy

American Society of Plant Biologists

American Society of Plant Taxonomists

Association of Independent Plant Research Institutes

Botanical Society of America

Council on Undergraduate Research

Crop Science Society of America

Ecological Society of America

Genetics Society of America

Global Plant Council

Phytochemical Society of North America

Soil Science Society of America

Acknowledgements

The Plant Science Research Network receives funding from National Science Foundation award #IOS-1514765 to the Boyce Thompson Institute. The workshop was hosted by the Howard Hughes Medical Institute (September 21-22, 2016) and supported by the NSF's Biological Sciences Integrative Organismal Systems and Education & Human Resources (EHR) Division of Graduate Education (DGE).

Illustration was provided by Kristyn Stickley, *Kristyn Stickley Illustrations.* Facilitation was provided by Susan Stickley, *Stratus, Inc.*

September 2016

Participants at the Plant Science Research Network meeting at the Howard Hughes Medical Institute

Front row, left to right:
Vanessa Greenlee, Natalie Henkhaus, Susan Stickley, Angus Murphy, Chelsea Specht, Michael Gonzales, Pam Soltis.

Back row, left to right:
Harriet Alexander, Molly Megraw, Paul Okello, Kaitlyn Bissonnette, Mary Crowe, Judy Glaven, Fumiaki Katagiri, Crispin Taylor, JP Dundore-Arias, Alex Thomasson, Paul Chomet, David Stern.

Plant Science Research Network

Visit the Plant Science Research Network on Plantae at community.plantae.org to learn more and access additional resources.

Plantae