Adaptive Brain and Behavior Across the Lifespan

Background: Our aim is to understand adaptation and improve human lives in various contexts. Inequalities and environments in which people live affect their health and behavior — and their success of remaining healthy for a lifetime. Virginia Tech has embraced the idea of understanding how the brain is linked to human experiences, constraints, and behavioral choices that not only affect neural well-being, but overall health. The effort is aided by new, sophisticated technologies (e.g., ones that map the brain in real time or allow clearer diagnosis of disease). Individuals must continue to function in the world in terms of addictions or life consequences from poor decision-making, developmental disabilities such as cerebral palsy, brain cancer, and other health challenges. Pursuit of innovative science to cure diseases is an important thrust of this Destination Area, in concert with evidence-based treatments and interdisciplinary training of individuals who work with people who are affected for the long-term by diseases and atypical disorders and conditions. Virginia Tech is mobilizing all emerging tools to improve people's lives.

Today, neuroscientists understand our brain in action, at the level of molecules, cells, circuits, systems, and behavior — but more remains to be understood. Likewise, brain diseases and traumatic brain injuries, which can result from diverse causes that range from drug addiction to physical impact, have been difficult for society to grasp. Our current knowledge and research in both the human and animal domain will provide substantial opportunities for "brain exploration" with an intention to solve human health issues and address societal issues and behaviors across the lifespan. A vital humanities and social science approach connected to neuroscience and medical approaches promises to move solutions to brain and behavior problems forward. We will also focus on social aspects of human development as people live longer, through the creation and application of new technologies.

Current Virginia Tech Differentiators:

- Neuroimaging/functional brain imaging of multiple interacting individuals
- Biomarkers of disabilities and atypical behaviors
- Schools of Neuroscience and Biomedical Engineering, which stretch across the colleges
- Research in veterinary medicine that translates to human systems
- Health across the lifespan, from the laboratory to communities
- Cellular/molecular biology research
- Cross-cutting expertise in environmental science and engineering
- Implementation science, policy, and community members self-advocacy

Experience and Assets: Notable pockets of disciplinary and interdisciplinary expertise will work to advance human health across the lifespan. The work is catalyzed, in part, by the Virginia Tech Carilion School of Medicine and Research Institute, the Biocomplexity Institute, the Fralin Life Science Institute, the Center for Gerontology, the School of Neuroscience, the Laboratory of Neurotoxicity Studies at the Virginia-Maryland College of Veterinary Medicine, the Center for Drug Discovery, and the Center for Autism Research, and collaboration with Wake Forest School of Medicine.

The Department of Human Development in the College of Liberal Arts and Human Sciences runs four centers that provide "living laboratories" for access to populations who develop through time (inclusive

of disabilities) – the Child Development Center for Learning and Research, the Adult Day Services, and two Marriage and Family Therapy Centers. Each of these centers is an avenue to investigate treatments and enable students and researchers understand the expression of disorders as well as typical development and aging. Similarly, the Department of Psychology in the College of Science runs outreach, teaching, and research centers. Students across the university can gain understanding of the unfolding of typical and atypical development and neurodiversity via the diverse disciplinary training associated with this Destination Area.

Computational neuroscientists at the Virginia Tech Carilion Research Institute are working to understand mechanisms in brain tissue, dovetailing with a large-scale research endeavor, the Roanoke Brain Study, which is aimed at understanding the neurobiology of decision-making through the lifespan and its relationship to brain development, function, and disease. Meanwhile, the Addiction Recovery Research Center examines decision-making processes that support dysfunctional behaviors and seeks novel therapeutic means to repair those dysfunctional processes.

Likewise, the Virginia Tech Center for Drug Discovery is an interdisciplinary group committed to grow and advance the stature of the existing drugs. The changing landscape of drug discovery provides opportunities for universities to make significant contributions to human health. Relatedly, Virginia Tech bioengineers work to find solutions to abnormal brain function, and neurological and psychological diseases.

Examples of Targeted Hot Spots:

- Develop and study novel technologies to understand the human brain and treat its disorders; create and support integrated human brain research networks
- Discover dynamic patterns of neural activity that are transformed into cognition, emotion, perception, and action in health and disease
- Neuroethics to solve issues about neural enhancement, data privacy, and appropriate generation and use of brain data in law, education, and business
- Social Neuroscience: Education on the interface of neuroscience, from neuroeconomics to neuroscience in the courtroom
- Personalized portable brain monitoring systems for field deployment
- Development of brain-machine interfaces and smart prosthetics; connect systems, as in neuroscience with engineering
- Device and tissue design/polymer science/drug delivery and drug discovery and therapeutics
- Pursue the human-animal nexus by studying non-human brains and behaviors and developing animal models and taking advantage of the presence of veterinary medical school. Additionally, expertise in sociology, animal science, and entomology will help us pursue relevant intersections, e.g., understanding social insects as a model for neural network dynamics.
- Bridge the fields of basic science, liberal arts, social science, engineering, and medicine through an integrated approach to brain science and the study of behavior.

Data and Decision Sciences

Background: Data science has percolated into everyone's daily lives. From the social web and e-commerce (e.g., Amazon, Facebook, eHarmony) to smart thermostats (e.g., Nest) to crowdsourcing for better traffic data (e.g., Waze) to massive administrative sources (e.g., electronic health records), the data environment today is ubiquitous. Any fields not functioning in a data-driven manner are ripe for disruption.[1] In the era of Big Data, Virginia Tech believes every professional must become conversant in data science to be successful, and that the principled collection and analysis of data are vital guides for sense-making, discovery, and decision-making. We envision data science woven into the learning and research experience of students in every discipline. Virginia Tech graduates must be prepared to be leaders in a world where evidence-based decisions and systems are pervasive.

Current Virginia Tech Differentiators:

- Data science is being integrated into all disciplines: from the humanities and liberal arts to engineering, science, and business
- A "plus-data" concept takes advantage of existing collaborations to support degrees and programs that support the data revolution
- Virginia Tech has one-of-a-kind facilities, testbeds, and instrumentation featuring data science in action. These facilities support the "university as the sensor" viewpoint as a unifying theme
- The university is a research leader in all layers of the "data stack": new high performance data-intensive computing platforms, data mining/analytics algorithms, and visualization capabilities
- The university and its partners answer ambitious societal questions using data science and computational modeling in areas such as national security, epidemics, transportation, food security, international commerce, and social science.

Experience and Assets: Dozens of ongoing projects and examples of living laboratory programs illustrate the university's presence in the Data and Decision Sciences Destination Area.

Researchers in the not-so-distant past examined living systems one small slice at a time. We can now find complex connections ranging from activity at a cellular level to its effects on public policy. The Biocomplexity Institute of Virginia Tech is at the forefront of this scientific evolution, applying a contextual approach to answer some of the most pressing challenges to human health, habitat, and well-being. The Discovery Analytics Center brings together computer scientists, engineers, and statisticians to develop knowledge discovery systems in important areas of national interest. Its IARPA-sponsored EMBERS project scours vast quantities of public information in tweets, Facebook pages, news articles, blog posts, food prices, weather data, and economic indicators to forecast potentially disruptive societal events across the globe. The Center for Business Intelligence and Analytics undertakes quantitative and qualitative analysis of vast collections of business data to support planning and decision-making. Its work in mining online forums has led to earlier detection of automobile defects.

While data-pervasive environments are traditionally associated with STEM fields, Virginia Tech surmounts traditional boundaries by developing and enabling new technology for use of analytics in the

[1] Workplace Technology (A Special Report) Wall Street Journal, March 2016

social sciences and humanities. For instance, a "Digging into Data" project, supported by the National Endowment for the Humanities, capitalizes on expertise in computer science, history, and English to understand how newspapers shaped public opinion and represented authoritative knowledge during the deadly 1918 "Spanish" flu pandemic. In the humanities, gamification has brought to virtual life human tragedies concerning how we confront our greatest dilemmas.

Virginia Tech's versatility at training students in data-driven disciplines is apparent at all levels. Innovative new undergraduate majors (e.g., Computational Modeling and Data Analytics, Environmental Informatics), graduate degrees (e.g., Master of Science in Business Analytics, launching in 2016) and graduate certificates (e.g., Data Analytics, Urban Computing; launching in 2016) distinguish the university. Students are taught to work with community partners on how to gather information and use it ethically and professionally. In addition, our faculty, students, and partners also have access to data-collection tools and environments unlike any others on the planet. For example, Goodwin Hall, the world's most-instrumented building for vibration measurement, uses 241 accelerometers to give an unprecedented look at the secret lives of buildings: how weather and aging affect the structure and how its "metabolic" energy waxes and wanes, how the building can be a "first responder" to an emergency. Similarly, the hallmark laboratory of the Institute for Creativity, Arts, and Technology and the Center for the Arts is a highly adaptable space to create immersive audio and visual performances and conduct experiments. Here, researchers can simulate natural environments that people do not normally experience, e.g., a walk through a virtual tornado to understand weather and climate.

Examples of Targeted Hot Spots:

- **Data Miner in Your Pocket:** By 2047, Virginia Tech will develop technologies that will enable us to combine the power of data, analytics, and crowds so that every aspect of daily life is captured, harnessed, and mined to improve personal experience and forecast personal outcomes.
- **Data Journalism:** Data journalism will be the primary way by which results are communicated to the broader public. Data provides the medium by which democratization of science happens.
- **Internet of Analytics**: Virginia Tech's emphasis on "university as a sensor" will enable an emphasis in natural and built environments (e.g., future buildings, coupled water-food-energy systems, ecosystems support for human habitability, unmanned aerial vehicles/drones).
- **Precision Medicine:** Our emphasis on combining data science and mathematical modeling and expertise in human aspects enables us to significantly contribute to national "big data" challenges such as precision medicine (The White House's Precision Medicine Initiative has been touted the ultimate Big Data project.)
- **Community Learning Systems:** Virginia Tech is working with Washington, D.C., metropolitan area communities to liberate and repurpose their data flows to provide the data driven evidence necessary for communities to build an equitable and sustainable social transformation.
- **Knowing how people and organizations use information:** A reluctance or inability to act on information may influence how people make decisions, not lack of data. This research focuses on uncovering institutional problems in using information for problems such as head injuries in sports, the harms of tobacco, and health decisions.

Integrated Security

Background: Individuals and communities prosper in the presence of security, but required elements of security evolve and expand rapidly. Social, political, and financial networks connect individuals to communities, and communities to the world; infrastructure and commerce networks connect us to essential resources, and information networks store unprecedented amounts of data. These networks and assets allow us to explore opportunities and ensure the availability of water, shelter, food and energy. However, reliance on interconnected networks makes individuals and communities vulnerable to complex threads that have the same dynamical and multi-scale properties as the networks themselves.

This Destination Area seeks to identify, understand, and mitigate vulnerabilities to increase individual, community, national, and global security. This mission cuts across four other Destination Areas, intersecting at key points of national interest where Virginia Tech has developed considerable strength over its history of service. It is incumbent on Virginia Tech to work in partnership with government and industry to mitigate security vulnerabilities and to address the critical workforce and technology needs of state and federal and defense sectors.

Current Virginia Tech Differentiators/Objectives:

- Build upon robust education and research programs in critical infrastructure sectors — including energy, transportation, water, telecommunications, military platforms, environmental, agricultural, and financial networks — to address challenges in security. Enable homeland defense, develop national security policies, and promote global and international security.
- Leverage unique interdisciplinary expertise that spans science, technology, policy, and governance to produce well-rounded graduates that understand security challenges, while also enabling interdisciplinary research that creates innovative solutions to security problems and the trans-disciplinary knowledge required increase security in a complex world.
- Enhance the university's investment in the other Destination Areas by coupling security experts with domain experts to promote "security by design" in emerging technologies and systems.
- Engage faculty and students across colleges, institutes, the Corps of Cadets, and Reserve Officer Training Corps programs in security research and instruction.
- Reflect the university's land-grant mission and service ethic by contributing to national and international security while promoting environmental conservation and economic development.

Experience and Assets: Virginia Tech has a tremendous advantage: an existing collaborative, interdisciplinary infrastructure already dedicated to education and research in security and resiliency. This Destination Area supports the university's "binary star" strategy by leveraging existing strengths in national security, public policy, and cybersecurity that extend from Blacksburg to the National Capital Region. With strong, historical partnerships with industry, government agencies, and civil society organizations, the university can build on an existing network of employers, research sponsors, and collaborators. The university embarks in this area with well-developed programs in key fields including energy cybersecurity, automotive cybersecurity, embedded system security, wireless security, information security, social and civil security, environmental security, cybersecurity education, business analytics, biosecurity, food defense, security policy, and environmental security.

This interdisciplinary research ecosystem comprises college-, center-, institute-, and laboratory-level collaborations, including numerous NSF Industry/University Cooperative Research Centers. The Hume Center for National Security and Technology leads research in cybersecurity and resilience of national and homeland security and has developed interdisciplinary education. The Institute for Critical Technology and Applied Science has incubated and enabled much of the technology ecosystem with investments in relevant centers focused on wireless, big data, space and satellites, autonomous systems, and military platforms. The Virginia Tech Transportation Institute offers expertise in automotive safety and cybersecurity and the Biocomplexity Institute offers expertise in resilience of complex networks.

Within the social sciences and liberal arts, the Metropolitan Institute promotes research into community resilience, while the Department of Political Science, Center for Public Administration and Policy, and programs in Government and International Affairs conduct research into security governance. Collaborations between the colleges of Veterinary Medicine and Science have developed robust capability in biological and agricultural security. Aggregating these strengths across the university provides the capability for high-impact research, technology development, and creative policy programs, while enhancing external partnerships. Existing interdisciplinary education programs include a minor in cybersecurity; minors and majors in national security; and graduate certificates in homeland security, information assurance, and security studies. Additionally, there are security-oriented tracks in a number master's degree programs, including Information Technology, Political Science, and Public Health, along with numerous engineering majors, such as Computer Science and Computer Engineering, as well as Interdisciplinary Graduate Education Programs in global change, sustainable nanotechnology, water, and disaster resilience. Resources will be leveraged to develop the embedded majors and minors envisioned by the Beyond Boundaries initiative.

The university also operates infrastructure to uniquely participate in security research. With Biosafety Level 3 facilities, research on biological agents can be undertaken. In addition, the university operates secure research facilities to execute classified programs sponsored by defense and intelligence agencies, and employs nearly 100 researchers and support personnel with active security clearances.

Examples of Targeted Hot Spots:

- **Critical Infrastructure Protection:** Virginia Tech has the opportunity to be a leader in critical infrastructure protection, particularly in food, water, energy (conventional, renewable, nuclear), finance, and transportation systems, with integrated expertise from embedded control systems through effective regulation of private infrastructure to address public needs.
- **Cybersecurity Technology, Governance, and Citizenship:** As smartphones, the Internet of Things, cyber-physical systems, cloud computing, and software-defined networking reshape the cyber landscape, education and research initiatives will focus on human factors in cybersecurity, protecting personal data/metadata, and regulatory and policy frameworks for digital privacy.
- **Defense Technology, Strategy, Policy:** As strategic defense and intelligence initiatives expand beyond the past 15 years of counterterrorism to include emerging national threats, mission scope now ncludes areas where Virginia Tech has unique expertise, including nonproliferation, biodefense, nuclear security, aerospace platform resilience, and cyber defense.
- **Biological and Social System Security:** Biological data science and personalized medicine offer health benefits but raise security and privacy issues. Generation/aggregation of important data must be coupled with trusted, secure data computation and storage.

Intelligent Infrastructure and Human-Centered Communities

Background: The world is witnessing a dramatic transformation due to the confluence of disruptive trends, which include: (*i*) rapid urbanization and explosive growth in population that is shifting locus of economic, social, and technological activity toward emerging countries and communities — these communities are undergoing industrial, social, and economic revolution, (*ii*) accelerating technological change leading to transformative advances in information technology, health care, manufacturing, and transportation — leading to instant communication and boundless data; here, data is a new natural resource, mobile is the new office space, personalized and precision products and medicine are the new ways to satisfy the consumer, (*iii*) the world is smaller and more connected in so far as information, mobility, and trade is concerned — complex co-evolving socio-technical networks are enabling more efficient flow of capital, goods, people, and information. Infrastructure networks that support our communities co-evolve with the communities that use and modify them.

This Destination Area aims to design, develop, and understand social, technical, economic, cultural, political, and information paradigms to support sustained and adaptive human societies. This area seeks to find a balance between advancing the technology with economic and policy structures that are equitable, fair, and lead to overall well-being of the society. By nature, the Destination Area is multi-disciplinary — new paradigms in experiential learning and training that will produce graduates who are the world leaders. Technology, infrastructure design and development, policy, data science, and economics will be woven with traditional disciplinary curriculum to create "VT-shaped" students who will contribute to society and employers immediately. Themes include smart, healthy, and sustainable cities and communities; transportation systems; human safety, health, and wellness; integrated energy systems; network science and engineering; public policy; and cyber-physical systems.

Current Virginia Tech Differentiators:

- Pioneering intelligent autonomous systems that operate in land, sea, and air domains. Focus has been on safety systems, self-driving cars, and mobility
- International leadership in integrated energy systems, including power electronics, power systems analysis and energy management and policy; focus on integrated energy systems leading to energy efficiency, zero-net energy usage, renewable energy sources, and decreased fossil-based energy solutions
- Cyber-physical systems that leverage the Internet of Things revolution and advances in pervasive computing leading to adaptive and resilient systems; improving infrastructure systems by using wireless sensors and actuators to enable robust, resilient monitoring, and management
- Modeling, simulation, analytics, and decision-support environments that leverage modern high performance computing and big data to advance the state of the art in public policy, economics, network science, and smart cities.
- Strong emphasis on rural communities, infrastructure, ecology, and end-to-end agriculture, using autonomous systems, cyber-physical systems, and novel informatics.

Experience and Assets: Virginia Tech comprises a large number of disciplinary-specific and interdisciplinary assets to develop intelligent infrastructure and human-centered communities. The Virginia Tech Transportation Institute has superior knowhow in vehicle-to-vehicle or vehicle-to-infrastructure systems. The Virginia Connected Corridors and the Virginia Automated Corridors

initiatives represent partnerships between the transportation institute, the Virginia Department of Transportation, and the Virginia Department of Motor Vehicles, among others. These initiatives allow connected- and automated-vehicle developers to develop technologies along two test-track environments — the Virginia Smart Road in Blacksburg, Virginia, and the Virginia International Raceway in Alton, Virginia — as well as on operational roadways in Northern Virginia. In addition, the Virginia Center for Autonomous Systems, which is an interdisciplinary initiative of the Institute for Critical Technology and Applied Science and the College of Engineering, conducts research that spans every application domain — sea, land, air, and space. The Center for Power Electronics provides state-of-the-art solutions to problems in electrical power delivery and distribution. The center has more than 90 industrial affiliates and has graduated over 150 doctoral students. The Biocomplexity Institute of Virginia Tech is at the forefront of developing scalable cyber-infrastructures and decision support systems that aid in the design, analysis, and engineering of complex inter-dependent physical, social, and informational infrastructures. Wireless@Virginia Tech partners with the Center for Advanced Engineering and Research and the Mid-Atlantic Broadband Cooperative to identify medical applications and address the challenges of the increasingly cluttered wireless spectrum. The Discovery Analytics Center leads advanced analytical and visualization tools for urban science, health sciences, and critical infrastructure protection. The Global Forum on Urban and Regional Resilience leads effort to unite policymakers, urban planners, and architects to study important questions related to resiliency and sustainability issues as they pertain to regional and national development. The Metropolitan Institute focuses on issues related to urban growth. In addition, the university's Center for Design Research has led the development of futuristic new structures known as lumenHAUS and futureHAUS. Other assets include the Urban Living Laboratory in the National Capital Region, the Center for Energy Harvesting Materials and Systems, the Center for High Performance Environments, the Smart Infrastructure Laboratory, and the Hume Center for National Security and Technology.

Examples of Targeted Hot Spots:

- **Cyber-physical systems**: Opportunity to lead the development of sustainable materials with sensors and instruments providing on-demand data about performance and efficiency for systems that are smart and self-healing.
- **Pervasive decision support systems**: Based on advances in HPC, data sciences, modeling and simulation to develop novel decision support and policy informatics environments.
- **Autonomous Systems**: Lead the development of self-driving, interconnected transportation systems with a focus on human safety and wellness. Issues of policy and ethics are interspersed in the development of such systems.
- **Integrated energy systems**: Distributed Smart Energy, focused on developing on-demand energy through a combination of highly efficient and environmentally friendly conventional and renewable energy sources.
- Enhance the university's investment in the other Destination Areas by coupling experts in security, public policy, data and decision sciences, and integrated health to work on emerging problems in sustainable and ecologically sensitive urban growth, smart and connected infrastructures, and policy making in the digital world.

Resilient Earth Systems

Background: The human population is projected to increase from 7 billion to more than 9 billion over the next 35 years. An overarching challenge of our time is to meet accelerating needs for food, energy, water, and basic health, while maintaining stability between earth environments and society. This challenge is compounded by complexities between social and ecological systems, as exemplified by animal-human transmission of the Zika virus. In 1947, the first known case of Zika fever was reported in a Rhesus monkey in Uganda. After the first human outbreak in Micronesia (2007), Zika has spread through at least 59 countries and territories. This growing health crisis threatens billions of dollars in tourism for South America and has sparked an intense social debate regarding birth control in the region. Such time-critical challenges are most effectively addressed through collaborative research and partnerships with industry and government sectors focused on providing solutions. New educational models must also be developed to produce a workforce that understands already-strained ecological systems and earth resources, and complex social and environmental interconnections.

The Resilient Earth Systems Destination Area emerges from Virginia Tech's leading reputation for innovative research and education in food, water, and other natural resources. Social stability is critically dependent upon the human condition and perspectives from the social sciences and humanities are important in this Destination Area. Its mission is to educate students with expertise in ecological, earth, and social systems while fostering the ability to collaborate broadly, approach problems from interdisciplinary perspectives, and anticipate the consequences of system interconnectedness. Pulling together internationally recognized expertise at Virginia Tech and building upon programs for interdisciplinary research and student training, this cornerstone Destination Area is naturally coupled with other Destination Areas in data analytics, security, health, and civil infrastructure.

Current Virginia Tech Differentiators:

- Expertise in the development and management of water resources
- Emphasis on host-pathogen-environment interactions and microbiomes
- Advanced capabilities in remote sensing, modeling, and forecasting of global processes
- Innovations in agriculture in response to pollution, bio-invasions, and climate change
- Leading scholarship in ecosystem processes and biodiversity conservation
- Expertise in coastal processes and hazards in a changing climate
- Forward-looking Interdisciplinary Graduate Education Programs (IGEPs)

Experience and Assets: In addition to the examples of areas of strength noted above, multiple interdisciplinary research and education programs focus on the society-environment nexus. These programs combine expertise from the biophysical sciences, data analytics, engineering, and social sciences to prepare the next generation of scholars.

Four highlights: **1)** The Virginia Tech Global Change Center is a university-wide, faculty-led initiative that addresses major challenges to environment and society including disease, climate change, pollution, habitat and biodiversity loss, and invasive species. In its first year, the Global Change Center has already published 176 journal articles, with 72 more submitted or in review. Eighty-three new grants were

funded for a total exceeding $27 million, and 25 Ph.D. students and 120 undergraduate researchers were mentored. **2)** The Water INTERface program is united by a central focus of "Water for Health," spanning from "pipes to people." Accomplishments in the 2014-15 fiscal year include 56 journal articles, four book chapters, 13 Ph.D. students and seven new grants totaling more than $2.6 million. **3)** The Remote Sensing group and Space@VT collect big data using advanced instrumentation for monitoring the physics and biogeochemistry of water, forest, atmospheric, and the near-earth space environments. **4)** The Fralin Life Science Institute supports several additional critical areas that will support this DA, to include the Vector-Borne Disease program that focuses on diseases transmitted by mosquitoes.

Notably, Virginia Tech's existing Interdisciplinary Graduate Training Programs serve as a "trans-cutting" model that enables all of the above areas. A foundation provided by several problem-focused IGEPS in the areas of global ecological change, water, plant sciences, nanotechnology, health sciences, and remote sensing will support this Destination Area.

Examples of Targeted Hot Spots:

- **Water Security:** From food and energy security to human and environmental health, access to freshwater is vital to social well-being and economic growth, affecting the livelihoods of billions. Emerging needs include water quality and availability, water demands for food production, integrity and safety of drinking water, water systems that prevent the spread of disease and antibiotic resistance, and understanding effects of water pollution on biodiversity. This will require highly integrated water resource development and management that considers diverse issues ranging from ecological impacts to human rights.
- **Agriculture in a Changing Climate:** Human and ecological health are intimately reliant on sustainable agricultural practices. Agriculture requires 70 percent of all freshwater use, accounts for 65 percent of antibiotic applications, produces 30 percent of greenhouse gas emissions, is a significant contributor to environmental pollution, and is increasingly vulnerable to climate change. An urgent need exists to improve the resilience of crops and livestock to drought, disease, invasive pests, and other stressors and exploit technology for precision agriculture to improve production while reducing environmental, human, and animal health impacts.
- **Ecology of the Microbiome:** The microbiome revolution is revealing the instrumental role of microbes in critical ecological processes, ranging from biogeochemical cycling of nutrients to complex relationships within host organisms. Data analytics and emerging technologies allow us to finally answer long-standing questions regarding microbial interactions in natural and built environments. Examples include indoor plumbing pathogens, bio-transformations of environmental pollutants, plant-microbe-soil interactions, the microbiome's role in human and animal health, and engineered microbial solutions to wastewater treatment.