CASA–Bio
Catalyzing Across Sectors to Advance the Bioeconomy

Diversifying Edible Protein Sources for a Sustainable Future

Investments to diversify proteins for human food and animal feed will create food supply chain resilience, drive American innovation in a globally competitive sector, and foster sustainable growth and employment in the modern bioeconomy.

Rohan Shirwaiker, North Carolina State University
Erin Rees Clayton, Good Food Institute
Jasmin Hume, Shiru
David Kaplan, Tufts University
Girish Ganjyal, Washington State University

October 2024

CASA-Bio Pitch: Diversifying Edible Protein Sources for a Sustainable Future

Executive Summary

Need

We have 25 years to figure out how to feed an estimated 10 billion people globally with affordable, nutrient-dense foods while reducing food waste, safeguarding natural resources, and protecting biodiversity. A key strategy for achieving this is food protein diversification, which will require bold investment in scientific research and technological innovation to develop sustainable, affordable, and appealing protein production methods. To seize the opportunity for the U.S. to become a global leader in food protein diversification and food biomanufacturing, we recommend a $1 billion investment over the next five years to bolster the U.S. food system.

Goals

Strategic investment should focus on three critical research and innovation areas:

- **Developing new high-value ingredients** to manufacture protein-rich food from sources including plants, cells (e.g., animal, microbial, algal, fungal), and repurposed food waste.
- **Pioneering nature-friendly manufacturing processes** to produce diverse proteins at high volume and low cost.
- **Establishing standardized research tools and resources** to ensure the safety, nutrition, market acceptance, and rapid scaling of new protein sources.

Cross-cutting Advances

Complementing these research priorities, the investment should support enabling cross-cutting areas:

- **Responsible innovation** through proactive development of best practices for security, safety, equity, accessibility, and sustainability in protein diversification efforts with the inclusion of voices of all key stakeholders.
- **Regulatory science research** for refinement of protein diversification and food biomanufacturing tools, standards, and approaches that support regulatory decision-making.
- **Workforce development** to meet the growing needs of a diversified food protein sector with a diverse, skilled workforce spanning fundamental science to manufacturing.

These research areas and cross-cutting initiatives should be integrated within a **network of innovation hubs across the U.S.** to accelerate the development, production, and adoption of new and diverse food proteins by leveraging regional strengths and fostering cross-sector collaboration among the agricultural community, academia, industry, nonprofits, government, and consumers.

Investing $1 billion in food protein diversification is not just about addressing a critical challenge – it's about seizing a timely and transformative opportunity to get ahead of the global competition. Bold action can future-proof the U.S. food system, advance the American bioeconomy, enhance national security, and create a more sustainable, resilient, and equitable food future for all.

Motivation

Over the next 25 years, the world must figure out how to feed an estimated 10 billion people with protein-rich, nutrient-dense foods while reducing food waste, safeguarding natural resources, ensuring robust supply chains, and protecting biodiversity. Scientific research and technological innovation that diversify food protein will build resilience and address these challenges. Dedicated research and development (R&D) for manufacturing new protein-rich foods can spur innovation across the agri-food ecosystem, enabling faster, scalable solutions that engage and benefit multiple industry sectors and drive the future of the U.S. bioeconomy.

Global investment estimates suggest that $10.1 billion annually will be needed to fully realize the economic and environmental benefits of food protein diversification.[1] Current funding levels fall significantly short of this target, with less than 5% of the needed investment achieved in 2023. Without significant investments, the U.S. risks losing its competitive edge to countries including Canada, China, Denmark, Germany, India, Israel, the Netherlands, Singapore, South Korea, and the UK, which are rapidly diversifying their protein sectors.[2] A substantial U.S. commitment over the next five years would address the unique challenges of protein diversification, such as scaling production, reducing costs, and enhancing consumer acceptance. This investment would accelerate domestic innovation, infrastructure, and economic development while creating new markets for agricultural goods and reinforcing the country's position as a global leader in food production. Such investment is well-aligned with the national bioeconomy strategy [3,4] and global sustainable development goals.[5] The 2022 U.S. Bioeconomy Executive Order[3] underscores the need for new approaches to diversify food sources, calling for strategic plans emphasizing biotechnology and biomanufacturing advancements, and a subsequent report[4] outlines research priorities necessary to drive food and agricultural innovation.

A recent CASA-Bio[6] workshop brought together diverse stakeholders from academia, industry, nonprofits, and government to discuss critical challenges and identify high-priority R&D areas that need this U.S. public investment to accelerate food protein diversification. **The key recommendation from this workshop, as proposed in this document, is to implement a collaborative, whole-of-government strategy with a $1 billion investment over the next five years to develop and scale manufacturing of novel protein-rich foods that will complement existing sources of food proteins to add resiliency to the U.S. food system.**

This investment should support R&D in three primary areas: (1) creating value for new and existing food ingredients; (2) developing affordable and nature-friendly large-scale protein production methods; and (3) designing tools and resources to speed up product development, safety testing, and market acceptance. These R&D efforts will accelerate the manufacturing and commercialization of new palatable, affordable, nutritious, and safe protein-rich foods. A key to success is the establishment of comprehensive databases, data-sharing frameworks, and accessible repositories of foundational research. These resources would enable a more coordinated and efficient approach to data-driven innovation, bridging gaps between discovery and commercialization by matching innovations with consumer demand.

The proposed investment also addresses cross-cutting needs such as workforce development, advancements in regulatory science to support decision-making, robust data and industry standards for food quality and safety, and frameworks for responsible innovation. These R&D and cross-cutting themes converge in a distributed network of regional research and innovation hubs that leverage local strengths, foster collaboration, translate research into successful commercial endeavors, and maximize

resource utilization. This synergistic approach will drive regional economic growth while strengthening national efforts to build a diverse, resilient food production system aligned with bioeconomy, climate, and public health goals.

The rest of this document highlights the key strategic R&D areas that U.S. government investments should catalyze to accelerate the diversification of food proteins integral to a sustainable, safe, and secure agri-food ecosystem. While these recommendations (summarized in Figure 1) are tailored to food, some may apply to animal feed or other aspects of the American bioeconomy, including accelerated plant breeding, creating value from waste carbon, and building resilient supply chains, as well as to in-space manufacturing.

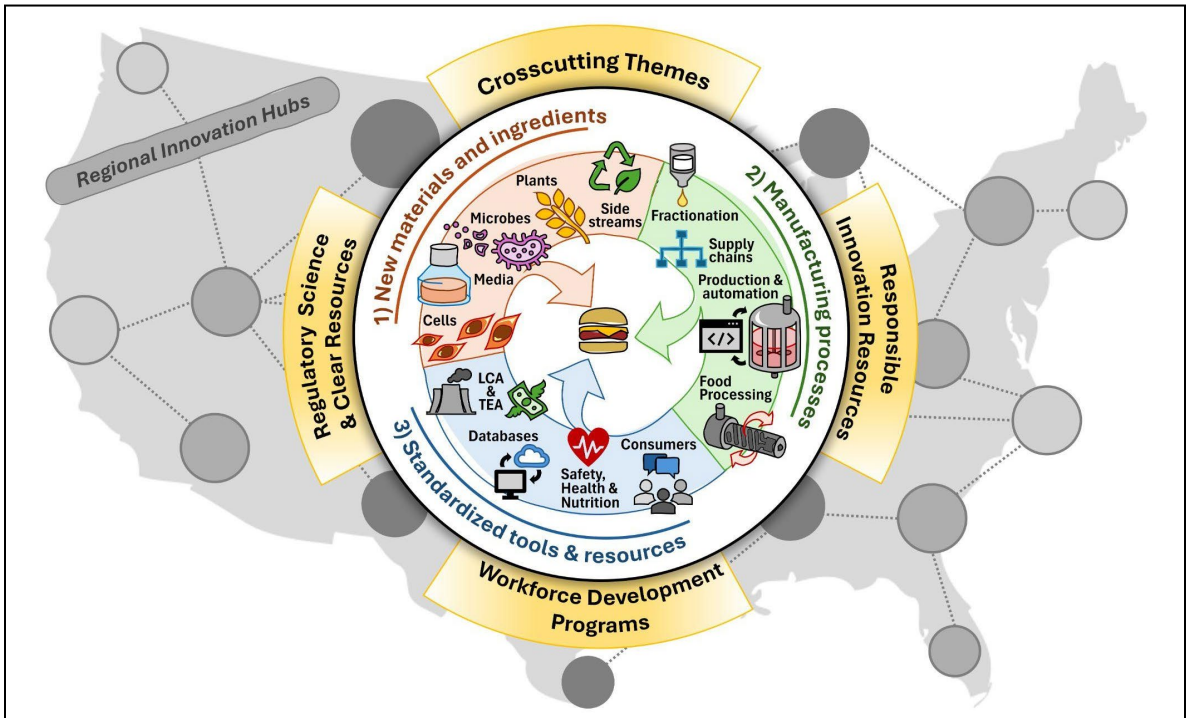

Figure 1. Overview of recommended food protein diversification investment, including critical R&D areas, cross-cutting themes, and a network of innovation hubs across the U.S.

R&D Deliverables: Recommended Investment, $600 M over 5 years

Deliverable 1: Creating value in current and new materials and ingredients to produce diverse food proteins

Access to a variety of raw materials and ingredients is crucial for a diverse and resilient food supply. Animal and microbial cells are promising sources for producing protein-rich foods, but currently there are limited types of food-grade cells available, they are expensive to grow, and we do not have the capacity to produce them at scale. We can solve these challenges by not only building upon ideas from the biofuels and pharma industries but also developing new innovations in engineering, cell culturing, and large-scale food processing equipment. Plant-based ingredients are also promising materials for creating protein-rich foods, but food manufacturers need access to consistent supply chains and

inexpensive plant proteins that will behave in predictable and desirable ways. Developing commodity and specialty crop ingredient supply chains can spur new markets that turn existing crop materials into high-value products for farmers to sell. Exploring and engineering these new protein sources, along with understanding how to combine diverse plant- and cell-based ingredients for optimal use in foods, can add diversity and resilience to our food system. Existing and emerging food and agricultural side streams and byproducts could become high-value, low-cost, sustainable inputs for novel protein production, making our entire food production system more efficient and profitable.

<u>Key Milestones:</u> To find and create value in new materials and ingredients to produce novel protein-rich foods.

Animal and Microbial Cells	• Improve cell production efficiency and lower costs by identifying, developing, and cataloging cells that enhance the flavor, texture, nutrition, and other key functional properties of protein-rich biomass and formulated food products. • Optimize cell production processes by establishing correlations between culture system inputs and outputs (e.g., flavor, texture, nutrition, safety). • Develop computational models of cell types (e.g., metabolic and systems biology models) to feed into bioprocess modeling, media development, and process optimization.
Plants	• Identify and harness new plant sources, including via byproducts upcycling, to provide low-cost, scalable ingredients that enhance texture, flavor, nutrition, and other functional qualities in alternative protein products. • Establish relationships between plant sources, ingredient attributes, and flavor profiles to guide the engineering of biosynthetic pathways for improved food product quality. • Create comprehensive, open-access catalog(s) of plant-based raw materials and ingredients, including fibers, starches, oils, and proteins, along with their sensory, nutritional, safety, and functional properties. • Investigate the relationships between plant- and cell-based ingredients to optimize the formulation of hybrid products with desired sensory, nutritional, and economic parameters.
Cell Culture Media	• Identify new sources of low-cost, sustainable, value-added ingredients (e.g., plant, algal, microbial, insect) to support cell culture for food protein production. • Explore crop-derived inputs from various agricultural sources in different regions of the country to improve supply chain diversity and resilience.
Valorized Streams	• Innovate and implement technologies to convert food and agricultural side streams into inputs to diversify protein production. • Systematically evaluate and catalog potential major side streams of novel protein production and create ways to convert them into inputs for other food and non-food (e.g., packaging, chemicals) products. • Foster partnerships in the agri-food and closely allied sectors to commercialize technologies designed to convert side streams and byproducts into high-value products.

Deliverable 2: Pioneering large-scale methods to produce alternative proteins affordably and sustainably:

The U.S. produces 30 billion pounds of food protein annually.[7] Diversifying protein production will build food supply chain resilience, but protein biomanufacturing can only be economical at large-scale and low-cost. Advancing cell culture technologies (including microbial fermentation), improving methods to extract plant-based ingredients, refining food processing technologies, automating biomanufacturing processes, and integrating production and supply chain systems will help overcome critical challenges for production efficiency, consistency, and scalability. Innovations in these areas will enable the large-scale biomanufacturing of affordable and desirable novel protein-rich foods.

<u>Key Milestones</u>: Underlie this holistic approach to drive scalable protein production while supporting sustainability and economic resilience.

Cell Culture Technologies	• Develop and validate bioreactor technologies for different types of cell cultures (e.g., animal, insect, microbial, algal) at scales ranging from 2500-250,000 L that are validated against lab and pilot scale systems. • Develop and optimize cost-effective co-culture strategies and non-standard production systems (e.g., solid phase) to enhance protein and biomass outcomes by reducing the impact of metabolic wastes and maximizing the efficient growth of organisms. • Explore alternative materials for bioreactors to overcome stainless steel supply constraints and ensure food-grade safety and performance.
Plant-Based Ingredient Fractionation	• Develop novel fractionation technologies that are more efficient, cost-effective, and maintain native protein functionalities. • Enhance current wet processing methods to improve efficiency and reduce environmental impact. • Innovate methods to modify plant proteins for consistent quality and functionality.
Food Processing Technologies	• Develop scale-up strategies for the mass production of textured proteins and co-products with plant proteins and cells. • Advance understanding of how processing changes affect interactions between ingredients and together influence the resulting physicochemical, sensory, safety, and nutritional properties of the end product. • Develop artificial intelligence/machine learning (AI/ML) tools based on large, high-quality data sets to predict relationships between material inputs, processing methods, and resulting product attributes (e.g., flavor, texture) to optimize the product development pipeline.
Automation and Digitization	• Develop frameworks for automating and digitizing bioprocesses with advanced sensors and real-time process analytical technologies. • Integrate AI/ML for automation, predictive control, and optimization of bioprocesses to enhance yield and reduce variability. • Establish virtual models (e.g., digital twins) tailored to bioprocesses at various scales, enabling real-time monitoring, process optimization, and predictive maintenance.

Integrated Production and Supply Chain	• Design modular, scalable production platforms that are adaptable to varying production requirements. • Develop systems integration frameworks to synchronize biomanufacturing processes with supply chain elements, emphasizing data interoperability and holistic optimization. • Innovate methods for end-to-end production simulation and supply chain circularity to improve sustainability and traceability.

Deliverable 3: Creating tools and resources to accelerate food innovation, production, safety, and adoption

If accessible at the onset, a robust suite of R&D tools and resources will support food innovation through development, scale-up, and adoption. Food scientists could use consumer behavior tools to design products that align with market demands. Ingredient manufacturers could use predictive modeling tools to custom-tailor ingredient processing methods, streamlining innovation and reducing time-to-market and development costs. Food safety specialists, regulators, and public health officials could use safety and nutritional models trained on large, high-quality datasets to ensure food safety, regulatory adherence, and nutritional requirements, building trust in novel food products. Economists could use standardized life cycle and techno-economic analyses (LCA and TEA) tools to inform food producers about environmental and economic impacts, reducing uncertainty in sustainability and investment decision-making. These tools and resources require open-access, standardized databases, and repositories, which will accelerate R&D, support data-driven decision-making, and promote collaboration across food system stakeholders. Together, these interconnected efforts can rapidly advance food protein diversification, ensuring foods are safe, sustainable, affordable, and widely accepted by consumers.

Key Milestones:

Consumer-informed Science:	• Develop socially informed, data-driven models to understand and rank consumer preferences across raw material sources, nutrition, taste, price, and sustainability, using data from diverse demographic and geographic segments. • Generate predictive models sensitive to the many aspects of product development, including cost, sustainability, mouthfeel, biomass generation time, and related attributes, and that report on trade-offs to minimize specific hurdles to consumer acceptance. • Launch non-competitive test kitchens for novel products to gather real-time consumer feedback, helping refine and accelerate product development. Involve chefs and culinary experts to show consumers how to integrate new ingredients and foods into their everyday lives.
Safety, Nutritional, and Health Modeling:	• Assess safety hazards and risks associated with novel ingredients, end products, and production methods for diverse bio-based proteins, including data-driven assessments of manufacturing systems and contamination risks. • Establish nutritional standards for novel protein ingredients and end products with considerations for different end uses. • Develop real-time sensors and diagnostic systems for monitoring food quality, safety, and nutritional content--for integration into food tracing and security to enhance transparency and quality control throughout the supply chain.

LCA and TEA:	• Create a suite of integrated, user-friendly LCA and TEA tools validated through pilot studies to assess the sustainability and economic viability of various food protein production technologies. • Establish a roadmap with best practices for integrating LCA/TEA tools in product development, ensuring adaptability to evolving technologies. • Develop a comprehensive decision-making framework for evaluating technological, economic, and sustainability readiness, tested and validated across multiple food protein production innovations.
Open Databases and Repositories:	• Develop a roadmap and standardized frameworks for various open-access databases and repositories, ensuring continuous updates and contributions from academia, industry, non-profits, and relevant government agencies. • Establish open access databases and repositories to catalog information (e.g., nutritional, safety, sensory attributes) and specimens of various raw materials and ingredients, bioprocesses, and tools generated through all the above R&D efforts to accelerate innovation and reduce duplication. • Compile and validate LCA and TEA data on novel protein manufacturing to guide sustainable, cost-effective process design and scaling.

Crosscutting Themes: Recommended Investment, $200M over 5 years

To drive the development and diversification of novel food proteins, it is essential to also foster responsible innovation, advance collaborative regulatory science, and develop a skilled workforce. Responsible innovation resources will guide stakeholders in making ethically sound and socially beneficial advancements while minimizing negative impacts. Collaborative advancements in regulatory science will facilitate regulatory decision-making, increase consumer trust, and support adoption of novel foods. Finally, a diverse portfolio of workforce development programs will address the talent gap across the food development pipeline, from R&D to commercial manufacturing. Together, these efforts underpin the successful implementation of the recommended R&D investments, ensuring that the diversified food protein industry can scale sustainably.

Key Milestones:

Responsible Innovation Resources	• Create ethical guidelines and best practices for responsible innovation in protein production involving stakeholders from across sectors. • Develop a publicly available toolkit with resources such as impact assessment templates and guidelines for ethical decision-making. • Form an advisory committee with diverse stakeholder representation to monitor responsible innovation practices in the field, providing guidance, evaluating emerging technologies, ensuring alignment with societal values, and facilitating meaningful dialogues between researchers, innovators, regulators, and the public.

Collaborative Regulatory Science and Clear Resources	• Identify effective risk communication strategies to inform consumers about the safety, benefits, and potential risks of novel food production methods and resulting products. • Develop industry best practices and acceptable methods (including animal-free and in vitro tests) for creating metrics around novel bio-based protein product quality, safety, and sustainability. These can inform the development of clear standards to accelerate product development through large-scale production as well as facilitate regulatory review. • Launch new collaboration and communication initiatives between researchers, innovators, manufacturers, and regulatory agencies to make current regulatory processes more transparent. Some of these can be modeled on existing successful initiatives [8]
Workforce Development Programs	• Develop open-source training modules accessible to students and professionals at all levels, covering key topics across novel protein biomanufacturing. This includes trade schools and community colleges, especially in regions with strong manufacturing training programs. • Conduct regional boot camps to provide hands-on training in biomanufacturing operations, analytics, safety assessments for diverse food proteins, and farm-specific and 4-H outreach programs to identify opportunities for revenue from untapped farm resources. • Establish fellowship programs for students, educators, and professionals to support inter-industry internships and exploratory opportunities in academia and industry, fostering real-world experience and cross-sector collaboration.

Distributed Network of Regional Hubs for the Convergence, Validation, and Scaling of New Food Proteins: Recommended Investment, $200M over 5 years

A network of regional research and innovation hubs across the U.S. can drive protein diversification and achieve the aforementioned R&D and cross-cutting advances. These hubs will not only support research into new processes, ingredients, and foods, but also be centers of excellence for materials testing, process validation, LCA/TEA, and facility planning, all of which are critical for creating and scaling new innovations. Successful commercialization of new food products and manufacturing processes will depend on the creation of investable technologies and products with solid techno-economics, flexible technology transfer arrangements, and fair equity ownership. Each hub can be tailored to leverage the unique strengths of its region, fostering collaboration among academia, industry, non-profits, government, and local communities. These hubs would play a pivotal role in workforce development, collaborative regulatory science advancements, and public engagement, creating a comprehensive ecosystem that supports responsible innovation. This strategic investment will drive breakthroughs and cutting-edge research across diverse protein production technologies, boost local economies to provide tangible societal improvements, and exemplify U.S. leadership in the global bioeconomy.

Key Milestones:

- **Establish clear criteria for hub success**, including infrastructure needs, partnership models for innovation, and key performance indicators. Develop a detailed plan and timeline for rolling out the full network of hubs.

- **Conduct a comprehensive U.S. regional analysis** to identify key strengths, resources, and opportunities for each hub. This will include mapping existing capabilities and assessing regional assets such as agricultural resources, talent pools, and existing biotech infrastructure.
- **Form a national steering committee** to oversee hub development, ensure inter-connectivity, and guide strategic priorities. This committee will include diverse stakeholder representation.
- **Create blueprints for pilot-scale and demo facilities** that can be adapted to various regions. Share these blueprints widely to facilitate the rapid development of infrastructure that meets the needs of local stakeholders such as food developers and manufacturers, consumers, chefs, farmers, researchers, and educators.
- **Launch at least one hub in a strategically chosen region** with limited representation in the current bioeconomy. This hub, which will include lab and pilot facilities, educational programs, and business services, with involvement from the government, academia, philanthropy, and the private sector, will serve as a model to stimulate local bioeconomies and lead to the development of new food innovation regions across the country.

Conclusions

The recommended $1 billion investment over five years in food protein diversification presents a transformative opportunity for the U.S. to address existing societal challenges and secure long-term bioeconomy benefits. By targeting three key R&D areas designed to propel innovation, scaling, and standardization, this initiative will modernize food protein production to make it more efficient, cost-effective, consumer-friendly, and environmentally sustainable. Addressing the cross-cutting themes will ensure these advancements align with societal values, consumer expectations, nutritional requirements, industry needs, and regulatory guidelines. A network of regional hubs will help spark local innovation as part of a broader national strategy, enhance collaboration among stakeholders across the country, and identify ways to help companies succeed with translating innovations into commercial products that can address consumer demand and bolster the national bioeconomy. This holistic approach promises to deliver significant impacts: accelerating technological advancements in protein diversification and biomanufacturing, driving economic growth, enhancing food security, and building a robust and resilient food system. The proposed investment positions the U.S. at the forefront of global efforts to responsibly and effectively meet future food demands and is expected to catalyze similar actions from philanthropic, private sector, and international partners.

Authorship and Acknowledgements

This document was written by:
Rohan Shirwaiker, North Carolina State University; Erin Rees Clayton, Good Food Institute; Jasmin Hume, Shiru; David Kaplan, Tufts University; and Girish Ganjyal, Washington State University.

This report was produced as a part of a multi-organization series of activities, called Catalyzing Across Sectors to Advance the Bioeconomy (CASA-Bio; www.casa-bio.net). CASA-Bio was inspired by the Bioeconomy Executive Order[3] issued by the Biden White House in September 2022, which called in part for collaboration across government, industry, non-profits, and academia to identify key areas for foundational research and development needed to advance U.S. biotechnology and biomanufacturing in five areas: climate change solutions, food and agriculture innovation, supply chain resilience, human health, and cross-cutting innovations. The ideas contained in this report were informed by discussions at a CASA-Bio workshop, “Food Protein Diversification” that was held August 22-23, 2024. The authors

are grateful for the generous and thoughtful input from the many members of the research and development community who participated in the workshop. The authors also thank the team from Knowinnovation for facilitation, colleagues on the workshop planning committee for invaluable feedback during the preparation of this document, and Andrew Stout of Tufts University for help with Figure 1.

References

Sources accessed on October 8, 2024

1. Climate Works Foundation. Global Innovation Needs Assessments Report on Protein Diversity
2. Good Food Institute. The State of Global Policy on Alternative Proteins
3. The White House. Executive Order on Advancing Biotechnology and Biomanufacturing Innovation for a Sustainable, Safe, and Secure American Bioeconomy
4. The White House. Bold Goals for U.S. Biotechnology and Biomanufacturing
5. United Nations, Department of Economic and Social Affairs. 2030 Agenda for Sustainable Development: The 17 Sustainable Development Goals (SDGs)
6. Catalyzing Across Sectors to Advance the Bioeconomy (CASA-Bio)
7. Calculated from the Nutrient Availability Table that is part of the USDA ERS Food Availability Data System
8. Specialty Crop Regulatory Association. Nuts and Bolts of Biotech Regulations Workshop