Wellcome Sanger Institute and Wellcome

The Genomic Futures Series

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Overview of the Genomic Futures Series

Foreword

In 1953, the discovery of the double helix structure of DNA by Watson and Crick marked a critical milestone in our understanding of how life works, and set the foundation for the molecular biology and DNA sequencing revolutions. Half a century later, another milestone was announced at a joint press conference between 10 Downing Street and the White House: the first draft of the human genome, released openly by an international consortium of researchers. In the quarter century since the first draft was released until today, the pace has continued, even accelerated - while sequencing a whole genome in the nineties might take years, it can now be done in a day.

We are in the era of the genome: human genomes tell us about our deep and recent history, our population diversity, our susceptibility to disease and our response to treatments, while the application of sequencing technologies to other organisms has changed our understanding of evolution, allowed us to track the many pathogens that affect us, and guided the design of conservation strategies for healthy ecosystems. We now have tools to synthesise any sequence and even whole genomes from scratch, and to go into our own cells to edit those genetic changes that cause disease. We are moving from genomics as a predominantly descriptive science to a predictive one.

In these times of seemingly perpetual advances, we might benefit from standing still, and looking not backwards but forward. What will be the scientific revolution(s) of 2050, following those that happened fifty years (the human genome) and a hundred years (the double helix) before? As we are already half way there, what do we need to do to achieve these aims, to ensure that the tremendous promise of genomics in society and the planet is fully realised? Just as importantly, how do we ensure the public stays on the side of our science, and who do we need to include on our journey?

These were the questions that inspired the Genomics Futures series, a collaborative horizon scanning initiative between the Wellcome Sanger Institute and Wellcome to explore and debate the possibilities of genomics. The Wellcome Sanger Institute and Wellcome have been on an extraordinary journey over the past 30 years, playing a key role in the field of genomics, alongside many other collaborators. The series comprised six workshops that invited **133 participants** from **86 different organisations** and **24 countries** and **6 continents** to offer their perspectives and identify opportunities for genomics over the next 25 years as well as identifying the possible barriers and bottlenecks. Reaching beyond the normal grant or review cycle which only looks 5-10 years at most into the future, we wanted participants to think explicitly about the long term. This also presented an opportunity to explore the future Genomics landscape from a wide range of perspectives identifying potential barriers and opportunities and proposing any immediate actions for progression. The workshops addressed six distinct areas of genomics and the wider research ecosystem. The discussions and ideas addressed across each are addressed within this report alongside cross-cutting themes that were central to the series.

A handful of participants, in each workshop, were invited to speak and share thought-provoking and challenging content to set the scene and inspire their fellow workshop participants based on their unique perspective. Speakers were briefed to capture topics such as progression in the field, learnings, what we know today, challenges, opportunities and emerging trends, ensuring awareness of the diversity of expertise within the group and sharing their perspectives in an accessible, forward-thinking and helpful manner for further group scenario development. With different chairs, speakers and participants in each workshop the discussions took different directions and elicited an array of futures - desirable and undesirable, utopian and dystopian and equitable and inequitable.

We hope the discussions and ideas shared from this workshop series, including this report, will catalyse conversations across the research community and help inform how we all respond to and tackle these challenges or capture these opportunities.

Understanding and engineering cells and genomes for the future

Chaired by Muzlifah Haniffa and Ben Lehner

The goal of this workshop was to develop a long-term vision for understanding and engineering living systems, focusing on the emergent properties that govern biological complexity and exploring how genomes and cells might be harnessed to address challenges beyond traditional biological contexts.

Central to discussions was the vision of harnessing advancements in artificial intelligence (AI) and synthetic biology to enable predictive, personalised, and ethically grounded healthcare. These technologies can extend benefits from individual patients to population-level impact, transforming both disease prevention and intervention.

While tools such as the AlphaFold protein structure database demonstrate the value of standardised data for predictive biology, broader challenges persist due to limited integrative datasets and the complexity of synthesising and testing diverse protein combinations. These challenges illustrate why imagining futures, rather than simply predicting outcomes, is important for genomics as a foundational capability across disciplines.

Framing the Challenge: Genomics Beyond the Next Grant Cycle

Genomics is increasingly positioned as a foundational capability across scientific disciplines. Short-term, project-based approaches are insufficient for addressing long-term questions about biology and health. Workshop discussions highlighted the need for long-horizon thinking that connects immediate research outputs to transformative impacts on society, medicine, and our understanding of life itself.

Advances in AI and computational modelling allow the prediction of molecular and cellular behaviour at unprecedented scales, but these predictive tools raise questions about understanding. Can we claim to understand biological systems if we can predict outcomes without explaining mechanisms? Participants emphasised that foundational, hypothesis-generating research is essential to answer the fundamental questions of what, why, and how.

What Does It Mean to Understand Life in the Age of AI

Workshop participants discussed three complementary dimensions of biological research: prediction, explanation, and engineering. AI can generate highly accurate predictive models, but these may lack mechanistic insight. Combining predictive power with experimental perturbation, including synthetic biology, allows causal relationships to be explored and emergent behaviours to be studied.

The duality of ‘day science’ and ‘night science’ was highlighted. ‘Day science’ refers to hypothesis-driven, precise, disciplinary approaches, while ‘night science’ is exploratory, interdisciplinary, and metaphorical. Both are required to generate transformative scientific insights. AI may accelerate night science by generating hypotheses at scale, but human judgement, creativity, and interpretation remain essential for guiding experiments and maintaining robust research culture.

Building Biology on Demand: Promises and Limits of Engineering Life

Genome and cell engineering are emerging as general-purpose tools for manipulating living systems. Participants explored two complementary approaches:

Natural modification versus de novo synthesis: Some applications focus on editing existing genomes, while others aim to construct entirely new sequences using synthetic nucleotides. Both approaches face challenges of reproducibility, control, and robustness and require careful consideration of societal permission, safety, and governance.

10-Year Vision: Engineering Controllable Biological Systems

Deconstructing and Reconstructing the Units of Life: Synthetic Blood

This vision describes a future in which synthetic immune system models based on human haematopoietic stem cells (HSCs) can generate any blood cell type on demand. The goal is to create controllable platforms to study immune responses, blood cell development, and disease susceptibility.

Mechanistic insights would be pursued through a combination of synthetic biology, computational modelling, and targeted genetic perturbations. By systematically altering regulatory components, researchers aim to map differentiation pathways and identify factors that govern functional specialisation.

Key challenges include bias in existing datasets, particularly a lack of ancestral and environmental diversity, which limits predictive model generalisability. In addition, incomplete knowledge of cell differentiation and essential transcription factors constrains model reliability.

Experimental platforms, including in vitro microfluidics and whole-organism models such as zebrafish, will be essential for validating differentiation pathways and observing developmental dynamics in vivo. This approach highlights the intersection of mechanistic investigation, technological innovation, and rigorous experimental validation.

10-Year Vision: Building Biology on Demand at Scale

Engineering by Natural Modification versus de novo from Synthetic Nucleotides

This vision describes a future in which scalable, cost-effective genome engineering and interoperable data ecosystems allow biology to be designed, tested, and deployed widely, contingent on public legitimacy and sustained investment.

Major advances would enable synthesis and editing of long DNA sequences at any scale and reduce genome synthesis costs by two orders of magnitude. Synthetic biology would be integrated into society through demonstrable public benefits, including health and ecological applications.

The vision also explores non-DNA-based innovations and alternative biological systems to expand the conceptual and technical foundations of biology. Democratising access to computational tools, data, and AI models is central to this approach. Standardised formats and cross-platform interoperability would be supported by institutions and existing funding infrastructure.

Challenges include public scepticism of synthetic biology and fragmentation across data repositories. Addressing these barriers is critical to scaling capability while maintaining public trust and enabling equitable participation.

From Precision Medicine to Precision Global Health

Technological innovation underpins the emerging concept of precision global health, extending the promise of highly individualised care to population-level impact. Key drivers include:

- **Demographic change and disease transitions**: Rapid population growth in Africa and ageing populations in Europe increase genetic diversity and shift disease burdens toward non-communicable conditions.
- **Network-based and population-level approaches**: AI and computational modelling can identify intervention points across complex disease networks.
- **Bridging innovation and equity**: Breakthroughs in genomics, synthetic biology, and computational modelling must benefit populations globally rather than reinforcing existing inequalities.

Precision global health relies on interdisciplinary collaboration and data integration, enabling actionable insights across populations while maintaining attention to ethical, societal, and environmental considerations.

Data, Models, and Bottlenecks in Progress

Participants identified data generation and integration as major constraints on discovery.

- **Diversity in datasets**: Most genomic data comes from populations of European ancestry, limiting model generalisability.
- **Multimodal data requirements**: Predictive biology requires integration of DNA, RNA, protein, metabolomic, environmental, and contextual data.
- **Interoperability and governance**: Standardisation, secure open access, and

sustainable infrastructure are critical for scaling biological engineering.

10-Year Vision 3: Learning Generalisable Rules of Living Systems

Modelling Multiscale Interactions and Emergent Properties

This vision focuses on deriving generalisable rules governing emergent properties in simple multicellular systems to support predictive models. Research would progress in a structured manner, moving from cell co-cultures to 2D bioprinted models, 3D organoids, organs, and multi-organism interactions.

Cellular communication and cross-species interactions, inspired by natural collective systems such as bird flocking and bee cooperation, would inform the study of emergent behaviours.

Success depends on fostering global interdisciplinary research communities integrating biology, ecology, and social sciences alongside continued development of organoid culture and bioprinting technologies. Collaboration across disciplines is essential for addressing the complexity of multiscale biological systems.

Who Does Science and Who Benefits

Discussions highlighted power imbalances and inequities in the global research ecosystem.

- **Extractive versus equitable collaboration**: Many datasets and biological resources are generated from populations that receive little benefit. Ethical and scientific considerations require equitable partnerships.
- **Barriers to participation**: Access to genomic tools, data, and infrastructure remains concentrated. Global participation can be expanded through training, affordable technology, and inclusive funding.
- **New organisational models**: Long-term science requires flexible, interdisciplinary, and collaborative structures beyond traditional grant cycles. Networks bridging biology, computation, and social sciences can integrate diverse perspectives to guide the trajectory of the field.

Equitable engagement is not just a moral imperative; it also enhances innovation, improves dataset diversity, and strengthens the relevance of discoveries to global populations.

Public Trust, Ethics, and Societal Permission

Scientific advancement cannot be separated from societal values and ethics:

- **Cultural and regional differences**: Risk perception varies across populations, requiring tailored engagement strategies.
- **Co-exploration, not one-way communication**: Decisions about synthetic biology and AI should involve public input on priorities, acceptable applications, and governance.
- **Managing misinformation**: Transparent engagement is critical to prevent misrepresentation or misuse of emerging technologies.
- **Societal permission as an enabler**: Technical feasibility alone is insufficient; public trust is essential for legitimacy, adoption, and responsible deployment of innovations.

Ethical and societal considerations must evolve alongside technical advances, ensuring benefits are safe, equitable, and socially accepted.

Looking to 2050: Questions Beyond the Next Decade

Beyond the 10-year horizon, several long-term considerations emerged:

- **Emergent properties across organisms and ecosystems**: Understanding multicellular systems and their interactions remains a long-term goal.
- **Human–machine discovery partnerships**: AI can generate novel hypotheses, but human oversight is crucial for interpretation, ethics, and collaboration.
- **Science as an awe-inspiring endeavour**: Epiphanies, curiosity-driven exploration, and the elegance of biological systems remain central to innovation and discovery.
- **Unpredictable discoveries**: Scientific progress is rarely linear; balancing hypothesis-driven research with exploratory approaches ensures that serendipitous insights are captured.

Open Questions and Directions of Travel

Key unresolved questions highlight tensions between ambition, ethics, and feasibility:

- Is prediction enough without understanding? Can AI-driven models substitute for mechanistic insight? Foundational inquiry remains essential.
- How much control over biology is desirable? Engineering genomes raises questions of robustness, reproducibility, and unintended consequences.
- Can genomics advance without deepening inequality? Equitable partnerships and democratised access are crucial to ensure benefits reach diverse populations.
- How should society shape the trajectory of biological science? Public engagement, governance, and societal permission are central to the legitimacy and sustainability of new technologies.

Together, these questions frame a long-term research agenda that integrates technical, societal, and ethical dimensions, highlighting that the future of genomics depends as much on governance and culture as on experimental capability.

Challenges and Considerations for Future Health Research

Demographic changes emerged as a significant driver of future health challenges. Rapid population growth in Africa and ageing populations in Europe increase genetic diversity and drive a shift from communicable to non-communicable diseases. Addressing these trends will require targeted interventions informed by network theory, alongside technological enablers such as AI, quantum computing, and equitable international collaborations.

Understanding biology in this context raises deeper scientific questions. Can predictive models alone provide genuine understanding, or must mechanisms be explained? Workshop discussions emphasised the need for foundational, exploratory science, adopting a “slow science” approach to answer fundamental questions. The duality of day science (hypothesis-driven and precise) and night science (exploratory and interdisciplinary) remains critical. While AI may accelerate hypothesis generation, the human element is indispensable for interpretation, judgement, and fostering research culture.

Our relationship with microbial life

Chaired by Claire Chewapreecha and Nicholas Thomson

The workshop *Our Relationship with Microbial Life* was hosted in Bangkok, Thailand, chosen to ensure representation from southeast Asia, recognising Thailand as both a hub for microbial research and a region experiencing one of the highest microbial disease burdens; A situation exacerbated by climate change.

Genomics has transformed our understanding of pathogens, revealing their diversity and how they evolve. It has also shed light on the human microbiome and its influence on development, health, and disease. Despite these advances, critical gaps remain in our understanding of disease susceptibility, daily microbial interactions, and effective public health interventions.

The workshop focused on exploring how we might move beyond descriptive science towards predictive microbiology and how these predictive capabilities could be harnessed by 2050 to address key challenges, including reframing neglected tropical diseases.

Participants identified several challenges central to enhancing predictive capability:

- **Improving genotype-to-phenotype mapping**, particularly to better predict bacterial metabolism and ecological behaviour from genomic data.
- **Strengthening data integration, sharing, and storage** through globally federated systems while maintaining local ownership.
- **Applying AI-driven phenotype detection** and open-access databases to guide precision medicine.
- **Refining sampling strategies** to address biases and ensure broader representation of genetic diversity.
- **Developing field-ready sampling and preservation methods** to maintain sample integrity in low- and middle-income countries (LMICs) and remote regions.

Central Themes

Discussions encompassed progress and future directions across immunology, microbiome research, and microbial surveillance.

Equity and Inclusion in Microbial Genomics

A recurring theme was the complex interplay between the human immune system and the microbiome, informed by extreme immune responses such as immunodeficiencies. These insights highlight both the promise of precision immunology and the barriers to its application. Despite technological advances in deep phenotyping, genotyping, sequencing, and cross-disciplinary research, gaps remain in pathogen diagnostics and in addressing health burdens in LMICs.

Persistent inequalities in the distribution of scientific advances were highlighted. Only a small fraction of the global population currently benefits from genomic technologies, leaving the majority underrepresented in research, funding, and application of science. Workshop participants emphasised the urgent need to decentralise scientific resources, expand access, and integrate local expertise.

Diversity in Microbial Genomics

Surveillance strategies are often disease-focused, overlooking colonisation and broader microbial ecology. Expanding frameworks to capture both colonisation and disease with improved geographic and temporal resolution was identified as a major opportunity.

Participants also emphasised the urgent need to restore microbial diversity in humans and the environment. Rapid urbanisation, lifestyle changes, antibiotic overuse, reduced contact with nature, processed diets, and environmental degradation have accelerated microbial loss, threatening human health, ecosystem resilience, and biodiversity. Immediate conservation and restoration efforts are required to prevent irreversible losses.

Future Visions: 10- and 25-Year Outlooks

Workshop discussions explored four interconnected themes, identifying aims for the next 10 years and a blueprint for 2050.

1. Global Health: Removing the "Global"

Two core challenges were highlighted:

1. **Inequities in data access** – Data systems are fragmented and unequal across regions. Greater collaboration, decentralisation, and contextualisation are essential, alongside investment in education, standardisation, and equitable funding.
2. **Problematic framing of "global health"** – The term implies a foreign-led perspective, often Western-centric, which can perpetuate power imbalances, exclude local and indigenous knowledge, and reinforce colonial dynamics. Participants proposed reframing the field simply as "health" to promote inclusivity.

Vision:

By 2050, the framing of "global health" is replaced with *health*, ensuring research, resources, and interventions are locally led and equitable.

Key insights from discussions:

- **Decentralisation of resources:** Current systems concentrate talent, equipment, and funding in high-income regions. To achieve equitable health outcomes, resources must be distributed through regional hubs and empowered local networks, particularly in Africa and Asia, where the fastest-growing populations will live.
- **Local leadership:** Research agendas must be set by local scientists, integrating indigenous knowledge and community priorities.
- **Data equity:** Access to genomic, microbiome, and environmental data must be open and fair, with infrastructure for storage and analysis in LMICs.
- **Education as an enabler:** Early training in genomics, microbiome science, and computational biology will prepare future generations to lead locally relevant research.

Practical steps for 2050:

- Establish regional centres of excellence with shared infrastructure for sequencing, bioinformatics, and microbiome analysis.
- **Implement global but federated data-sharing frameworks**, with clear governance and ownership at the local level.
- Engage communities in co-creating research agendas, ensuring trust and uptake.
- **Reform funding models** to incentivise locally led projects and long-term capacity building.

2. Microbiome: Optimising for Health

Vision:

By 2050, human and environmental microbiomes are understood, conserved, and optimised to promote health, prevent disease, and restore ecosystem function.

- **Global microbiome initiative:** Collect representative, longitudinal microbiome datasets from diverse populations, body sites, and environments.
- **Conservation and restoration:** Implement microbial conservation strategies in humans, agriculture, and the environment. Promote diets rich in fibre and fermented foods, reduce unnecessary antimicrobial use, and restore microbial reservoirs such as soils and wetlands.
- **Regional hubs and equitable access:** Not every country needs full infrastructure; hubs can provide expertise, training, and analysis for surrounding regions.
- **Integration with health outcomes:** Link microbiome data with immune profiles, disease incidence, and environmental metrics to guide interventions.

Implementation pathways:

- **Develop standardised protocols** for microbiome sampling, preservation, and historical benchmarking.
- Encourage collaborations between research, industry, and local communities for translational interventions.
- **Influence policy to reduce regulatory barriers** to sample collection and intervention studies.

- **Promote longitudinal, mechanistic studies** to enable causal inference and predictive modelling of microbiome effects.

Cross-Cutting Forces for Realising 2050 Visions

- **Technology and innovation:** Wearables, AI, smart sampling, high-throughput genomics, and digital twin platforms.
- **Collaboration and equity:** Empower local networks, decentralise funding and infrastructure, and integrate indigenous knowledge.
- **Data governance:** Federated systems with privacy, consent, and audit trails.
- **Education and capacity building:** Early education, professional training, and skills development to prepare future generations.
- **Policy and regulation:** Flexible frameworks enabling microbial conservation, microbiome interventions, and predictive modelling across regions.

3. Microbe–Host Interactions: Disease Risk

Vision:

By 2050, disease risk is predicted and mitigated through integrated host–microbe–environment models, enabling personalised and population-level interventions.

- **Integrated longitudinal datasets:** Collect human genomics, epigenomics, immunology, pathogen genomics, microbiome data, and environmental data (air, water, soil, vector presence) to model disease risk accurately.
- **Personalised interventions:** Use predictive insights to optimise vaccines, therapeutics, and microbiome interventions for individuals and populations.
- **Cultural and environmental context:** Risk models must consider local exposures, nutrition, and socio-economic variables.
- **Mechanistic understanding:** Beyond correlation, participants emphasised causal insights linking host genetics, microbial dynamics, and disease outcomes.

Steps toward 2050:

- **Deploy wearables and smart devices** for real-time longitudinal data collection, integrated with environmental and public health datasets.
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- **Establish proof-of-concept studies** in diverse populations to demonstrate feasibility and scalability.
- **Develop AI-driven models** capable of predicting pathogen evolution and host susceptibility while remaining interpretable and reliable.
- **Embed ethical, privacy, and consent frameworks** into all data collection and modelling efforts.

4. Mathematical Modelling: Building a Digital Twin

Vision:

By 2050, integrated, representative and longitudinal datasets facilitate a comprehensive "digital twin" ecosystem modelling infectious disease dynamics, immunity, and pathogen evolution to enable real-time intervention and policy guidance.

- **Digital twin components:** Data spanning population immunity, pathogen genomic variation, microbiome interactions, climate, vector distributions, human mobility, and public health intervention.
- **Multi-scale integration:** Models operate coherently across individuals, populations, cities, and global interactions.
- **Policy and response simulation:** Digital twins enable counterfactual testing of interventions, outbreak mitigation, and vaccination strategies.
- **Trust, ownership, and governance:** Oversight by the WHO or a similar global body , with robust anonymisation and data governance frameworks to ensure privacy and maintain public trust.

Implementation pathways:

- **Establish federated datasets and interoperable platforms** connecting existing surveillance, clinical, and environmental data.
- Deploy wearables and community-level sampling for immune and microbiome monitoring.
- **Integrate AI, mechanistic models, and grey-box approaches** (AI informed by domain knowledge) for robust prediction.
- Develop audit trails, regulatory frameworks, and public engagement campaigns to build trust in the system.

Key Takeaways

The workshop emphasised several overarching themes and opportunities for microbial genomics:

Opportunities:

- Removing the “global” from global health.
- Leveraging AI, digital modelling, and improved genotype–phenotype mapping.
- Developing field-ready sampling and preservation techniques.
- Establishing federated, globally integrated but locally owned data systems.
- Aligning funders, regulators, and research priorities.

Barriers:

- Limited training and infrastructure in LMICs.
- Microbiome data remains incomplete and unrepresentative.
- Fragmented data systems with inconsistent standards.
- Ongoing degradation of microbial diversity.

Emerging Concepts from Workshop Discussions

Descriptive to Predictive Science. Genomics has evolved from sequencing single genomes to predicting evolutionary trajectories and disease risk at global scales. Participants emphasised the need to integrate descriptive, mechanistic, and predictive approaches, combining deep domain expertise with AI, modelling, and ethical frameworks.

Equity and Decentralisation. Scientific resources, training, and infrastructure are currently concentrated in high-income regions. Participants called for decentralisation, equitable access to data and technologies, and inclusion of local and indigenous knowledge.

Microbial Ecology and Conservation. Beyond disease, microbes are integral to ecosystem stability and human health. Conservation and restoration of microbial diversity in humans, animals, and the environment are critical to long-term health and resilience.

Digital Twins and Predictive Modelling. Building digital models of population immunity, host–microbe interactions, and pathogen evolution will require integrated datasets, wearable devices, environmental monitoring, and robust governance frameworks.

Public Engagement and Trust. Community involvement and education are vital to ensure adoption of predictive tools, ethical use of data, and alignment of interventions with local needs.

Looking to 2050

Participants envisioned a world where:

- Health research is equitable, locally led, and inclusive.
- Predictive models inform personalised and population-level interventions.
- Microbiomes are actively conserved, restored, and harnessed to optimise health.
- Digital twin models guide real-time disease monitoring, outbreak prediction, and vaccination strategies.
- Global health is reframed simply as *health*, moving beyond colonial legacies and foreign-led priorities.
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The workshop concluded with a consensus that training, early education, equitable resource distribution, and international collaboration are essential to achieve these long-term goals. Participants emphasised the urgency of acting now to equip the next generations with the tools, knowledge, and networks necessary to realise the predictive, equitable, and conservation-focused vision of microbial science.

Understanding and sustaining life on earth

Chaired by Mara Lawniczak and Mark Blaxter

The goal of this workshop was to develop a long-term vision for biodiversity genomics, ecosystem monitoring, and ecosystem restoration, exploring how genomic technologies, AI, and data integration can support planetary health. Participants reflected on how these tools could transform our understanding and management of ecosystems, food systems, and global biodiversity, while ensuring ethical, equitable, and societally responsible outcomes.

Central to discussions was the recognition that biodiversity underpins human survival. As Mark Blaxter noted, the thread connecting humans and ecosystems is unraveling, and urgent action is needed to safeguard it. By imagining the possibilities for 2050, participants aimed to identify actionable steps today that could prevent ecological decline and support a liveable planet.

Framing the Challenge: Biodiversity Beyond 2050

Biodiversity genomics is increasingly positioned as a foundational capability for **planetary-scale monitoring, ecosystem management, and sustainable food systems**. The workshop emphasised that short-term projects alone are insufficient to address the magnitude of ecological, climate, and societal challenges.

Key challenges include:

- **Rapid environmental change:** temperature increases, invasive species, and anthropogenic pressures threaten ecosystems.
- **Incomplete knowledge:** only a fraction of Earth's species have been sequenced, and much ecological data remains fragmented, inaccessible, or unsuitable for large-scale analysis.
- **Governance and equity:** sharing of genomic data, benefit-sharing with indigenous and local communities, and global coordination remain unresolved.

Participants highlighted the need for **long-term, integrated strategies** that combine monitoring, functional understanding, and intervention. This includes planetary-scale sequencing, environmental DNA (eDNA) sampling, predictive models, and real-time ecosystem observation.

Central Themes

Discussions explored challenges at the intersection of genomics, artificial intelligence (AI), climate, and ethics, particularly:

- **Limited biological data**: AI in biology is limited by the lack of comprehensive, machine-readable datasets. While compute power has increased, large-scale growth of biological AI has slowed due to data scarcity and legal or political restrictions around access. The need for long-term, high-resolution environmental DNA time series encompassing the full diversity of organisms was identified as critical for understanding natural dynamics and informing ecosystem preservation efforts.
- **Ethical, social, and legal implications:** Indigenous knowledge, benefit-sharing, and rights of non-human species were highlighted as central concerns. Participants emphasised designing ethical frameworks proactively, rather than reacting after technologies are deployed.
- **Global collaboration and equity:** The importance of inclusive international partnerships was noted, ensuring that countries with the greatest biodiversity also have the capacity and access to benefit from genomic data.

Climate and Sustainability

The workshop emphasised the integration of **climate, health, and genomics** to enable coordinated global responses to environmental crises. Topics included:

- **Transdisciplinary knowledge ecosystems:** Combining physiology, epidemiology, exposomics, social sciences, and genomics to understand climate impacts on human health and agriculture.
- **Food systems and bioeconomy:** Sustainable, low-input, genetically diverse agricultural systems are critical to feed populations equitably while reducing environmental impacts.
- **Ethics and equity:** Indigenous knowledge, benefit sharing, and rights of ecosystems and non-human species are central to responsible implementation.

The discussion highlighted the need for **proactive ethical and regulatory frameworks**, referencing:

- **25 years since the Asilomar Conference (1975):** A benchmark for responsible scientific self-regulation.
- **Copenhagen Protocol:** Proposed as a foundation for ethical genomics in ecosystems, with participants advocating for expansion to encompass planetary-scale considerations and equity.

Future Visions

Participants distilled visions for a future in 2050 into three interconnected key areas.

Biodiversity and Monitoring

Vision:

Integrated, affordable, automated, real-time monitoring of global ecosystems.

Technologies and approaches:

Personal wearables for citizen science, automated molecular detection, spatiotemporal biodiversity change tracking, and real-time alerts for invasive or novel organisms.

Key assumptions:

- Completion of the Earth BioGenome Project by 2035.
- Implementation of the Kunming-Montreal Global Biodiversity Framework.
- Affordable, accessible sequencing technologies.
- Resolved data analysis and compression challenges.
- Local genomics expertise and global internet coverage.

Global coordination:

International agreements and national frameworks are required to safeguard data and ensure interoperability while preventing misuse.

Bioprospecting for Transformed Food Systems

Vision:

Environmentally sustainable, genetically diverse, and climate-resilient agricultural systems that provide equitable access to nutritious food while reducing environmental impact.

Goals for 2050:

- Reduce extractive human practices, aiming for **50% of land and sea protected**.
- Minimise inequalities and societal conflict related to food security.
- Enable rapid development and deployment of fortified crops and climate-adapted varieties.

Requirements:

- Global capacity for crop monitoring and development, with focus on equity and benefit sharing.
- Accessible genomic crop diversity databases and AI-informed analytics.
- Political will, consumer engagement, and international treaties to ensure responsible use of new biotechnologies.

Functional Diversity and Ecosystem Resilience

Vision:

Enhance ecosystem resilience and productivity by combining natural processes with carefully guided interventions to maintain biodiversity while supporting human and planetary needs.

Approaches:

- **Natural ecosystems:** Nature-based solutions for restoration, conservation, and keystone species management.
- **Engineered interventions:** Use of microbiomes, plants, and possibly synthetic organisms for remediation, reforestation, and pollution mitigation.
- **Urban environments:** Increased green spaces to promote biodiversity and

human well-being.

Challenges and requirements:

- Regulatory frameworks to enable responsible deployment.
- Public trust and acceptance of new technologies.
- Integration of **omics-informed decisions** into real-time, AI-readable formats.
- Comprehensive data collection and advanced analytics for decision support.

Data, Models, and Bottlenecks

Participants highlighted that **data generation, integration, and accessibility** remain major constraints on discovery and action. Notably, there was disagreement around data generation: while the landscape is rapidly evolving, some participants expressed concern that current infrastructure and analytical systems may not be able to handle the anticipated volumes of genomic and environmental data:

- **Dataset diversity:** Many ecosystems and microbial communities remain unsequenced; representation across regions is uneven.
- **Functional annotation gaps:** Assigning DNA sequences to species, molecular functions, or ecosystem processes is incomplete.
- **Infrastructure:** Data storage, retrieval, and energy-efficient archiving are urgent challenges.
- **Interoperability:** Harmonising Earth BioGenome, microbiome, and metagenomic datasets is critical.
- **Equity:** Capacity-building in biodiverse countries is essential to prevent inequities.

Equity, Ethics, and Governance

The workshop underscored the centrality of ethical, societal, and planetary considerations:

- **Copenhagen Protocol:** guiding principles for ethical engagement with humans, non-human species, ecosystems, and future generations.

- **Indigenous knowledge:** Respecting local communities, benefit-sharing, and co-governance in sequencing and intervention initiatives.
- **Global coordination:** Data governance, biosecurity, and responsible commercialisation.
- **Ethics-first research:** Ethical considerations integrated at the earliest stages of project planning.

Participants emphasised that **genomics is a powerful tool**, but its applications must be aligned with societal, environmental, and planetary priorities.

Long-Term Questions and Open Challenges

- How much can predictive models substitute for mechanistic ecosystem understanding?
- What are acceptable limits for intervention or engineering in natural ecosystems?
- How can biodiversity genomics avoid reinforcing global inequities?
- How should society regulate the commercial and environmental applications of genomic knowledge?
- How do we balance immediate action with long-term observation and learning?

Opportunities and Barriers

Opportunities

- AI-enhanced analytics for biodiversity and ecosystem function.
- Use of engineered organisms and synthetic biology for ecosystem restoration.
- Integrated, automated real-time biodiversity monitoring.
- International, interdisciplinary collaboration to align data, ethics, and action.

Barriers

- Public skepticism or rejection of engineered organisms and geoengineering.
- Risk of inequity if high-income countries or corporations dominate genomic data systems.

- Need for **proactive** ethical and regulatory frameworks, not reactive measures.

Key Takeaways

The workshop highlighted the importance of:

- Expanding research into **remote and underrepresented ecosystems**, including oceans and polar regions
- Fostering **interdisciplinary collaboration** across ecology, data science, ethics, and social sciences
- Ensuring **equitable access to data and technologies**, especially for countries with high biodiversity
- Building **ethical and governance frameworks** that anticipate risks and guide responsible innovation

Innovative technologies for measuring and engineering life

Chaired by Mathew Garnett and Leopold Parts

This workshop investigated which technologies will be required to measure life, predict disease, and engineer medicines, with a particular focus on the role of AI and machine learning as tools in biological research. The guiding question was: *"What are the tools, platforms, and engineering approaches that will shape the future of genomics?"*

Participants contributed perspectives highlighting the difficulties of linking cellular and organismal phenotypes to omics data, and noted that AI-driven models are currently limited by a lack of high-quality, interoperable datasets. Breakthrough technologies and changes in ways of working were identified as having transformative potential, including:

- **Advanced in vivo measurement technologies:** Methods to track cellular function in real time, inside the human body, providing molecular-level insights comparable to *ex vivo* tissue analysis and supporting the creation of human tissues for perturbation screening and pharmaceutical research.
- **AI-driven biological modeling and experimentation:** Systems capable of performing highly predictive simulations at scale, integrating automated experimentation with machine learning models for rapid hypothesis testing.
- **Rethinking scientific collaboration and funding structures:** Novel institutional arrangements to support high-risk, long-term technological innovation.

Central themes

Participants examined both technical and conceptual challenges of advancing biological engineering at multiple scales, from nanoscale mechanisms to ecosystems, drawing inspiration from the complexity and adaptability of natural systems. Key themes included:

DNA Synthesis and “writing life”

A central challenge identified is the ability to “write” DNA at the scale of living organisms. Achieving this requires significant improvements in the speed, accuracy and scalability of DNA synthesis pipelines. Beyond technical hurdles, understanding *what* to write is equally important. Approaches highlighted included:

- **Combinatorial genetics and functional selection:** Generating and testing variants to map genotype–phenotype relationships.
- **Learning-based approaches:** AI and data-driven systems to guide DNA design.
- **Accelerated evolution experiments:** Orthogonal replication systems with mutation rates millions of times higher than host genomes, enabling exploration of evolutionary fitness landscapes far beyond what natural evolution can achieve.

Challenges also arise from the ‘error threshold’ inherent in chemical DNA synthesis, which limits sequence length and accuracy. Technological innovations such as megabase genome synthesis, improved nucleic acid chemistry, and assembly within living cells are critical to bypass these limits.

Biological Innovation

From both technological and data perspectives, the field faces major challenges:

- **Automation:** Flexible systems are needed to scale experimental work and reduce method dependence in phenotypic assays.
- **Datasets:** Large, diverse, and well-structured datasets are critical for effective AI. Factors such as internal structure, clear performance criteria, and the degenerate solution space of biology (e.g., protein sequences) determine the success of predictive models.
- **Integration:** Foundational initiatives like the Human Cell Atlas (HCA) provide detailed maps of cell types and states, which can guide future engineering of cellular function, similar to how next-generation sequencing transformed genomics.

Future visions

Group discussions surfaced insightful thinking for the future in 25 years. Visions were formed across two major themes.

Writing and engineering DNA at scale

Participants envisioned a future with **free, decentralised DNA and protein synthesis**, supporting genome-scale design and the ability to generate human tissues for disease modeling, drug development, and possibly transplantation. Key components include:

DNA-level capabilities:

- Synthesis on demand at gigabase scale, with reduced cost and improved accuracy.
- Handling long DNA sequences, improved pooled oligo assembly, and error mitigation to overcome the limitations of current chemical synthesis methods.
- Multiplex mutagenesis to generate multiple genome changes simultaneously, enabling exploration of complex traits such as polygenic disease or carbon fixation efficiency.

Cellular-level control:

- Predicting and regulating cell states, enzymatic activity, and overall cell population composition.
- Integration of live biosensors to track molecular and phenotypic changes in real time.
- Linking cellular-level data with organ-level outputs to bridge scales from molecular activity to tissue function.

Organ and tissue engineering:

- Moving beyond simple organoid models to incorporate structural complexity, vasculature, immune components, and interspecies chimera techniques.
- Producing human tissues or organs for drug testing, disease modeling, and transplantation.
- Using stem-cell–derived synthetic tissues as **human proxies** to study genotype–phenotype relationships and drug responses.

Use cases highlighted:

- Serial crops engineered for nitrogen fixation, reducing greenhouse gas emissions.
- Microbes designed to produce chemicals sustainably, potentially in low-resource or decentralised environments.
- Synthetic immune systems, requiring combined computational and experimental design to explore complex genetic and functional networks.

Enablers and pathways:

- Innovation ecosystems that support ambitious, high-risk projects with flexible funding, career structures, and collaborative infrastructure.
- Standardised, interoperable data pipelines and automated experimental platforms.
- Integration of predictive modeling, combinatorial genetics, and accelerated evolution experiments to rapidly explore fitness landscapes beyond what natural evolution allows.

AI and automation-enhanced experimentation

This vision described enhanced experimentation enabling global, accessible and accelerated biology. Research will be undertaken at an abstract, higher level, with queries in natural language, following a similar path to how code has evolved. People will be able to make conceptual leaps and remote access to experiments will become an option for anybody. One way to think about this is by considering how this may benefit a genomics user of the future, for example a student from a lower- or middle-income country being able to answer a biological question by; commissioning experiments in automated facilities using natural language or querying foundational models for cellular systems with high predictive abilities. With the latter example there is also a scenario where AI takes that input, but works to assist or augment the knowledge base of that individual or guide experiments and produce foundational data, creating a two-way conversation between AI and scientist. Implicit in this thinking is a requirement for democratisation of genomics and substantial, high-quality data sets to build up accurate, predictive computational models.

Key elements include:

AI-driven experimentation:

- AI operates fully in the experimental loop, guiding the design of experiments, interpreting results, and generating foundational datasets.
- Foundational models of individual cell types created from high-quality, multimodal datasets.
- Predictive modeling of genotype–phenotype relationships to enable “genome-to-drug” workflows in a single day.

Automation and scalability:

- Automated lab infrastructure capable of performing thousands of parallel experiments with minimal human intervention.
- Iterative experimentation with rapid feedback loops, inspired by high-throughput and chip-design principles.
- Standardised, AI-compatible readouts to ensure seamless integration with machine learning systems.

Scaling biological understanding:

- Within 10 years: in vitro models for all known cell types, capturing cell diversity at high resolution.
- Within 15 years: integration of multiple cell types into organ-level models, potentially producing **digital organs**.
- Within 25 years: complete **digital human twins** capturing molecular, cellular, tissue, and organ-level dynamics, enabling predictive modeling of health and disease.

Democratisation and accessibility:

- Students, researchers, and institutions worldwide could access experiments and models remotely, enabling participation from low-resource settings.
- AI and automation lower the barrier to entry, making complex experiments feasible without extensive physical infrastructure.
- Foundational datasets and predictive models would be openly accessible, creating an equitable platform for innovation.

Use cases highlighted:

- Predicting the function of uncharacterised genes and proteins using AI-driven models.
- Iteratively designing human tissues in a dish to test drug responses, simulate disease progression, and inform personalised medicine.
- Remote, AI-guided experimentation allowing global collaboration and participation in large-scale genomics projects.

Enablers and pathways:

- Designing experimental readouts and instrumentation inherently interpretable by AI.
- Standardising data collection, annotation, and integration to maximise predictive power.
- Coordinating automation strategies with AI-driven modeling for rapid, iterative exploration of complex biological systems.

Key Takeaways

Central themes of the workshop included the challenge of scaling biological data and models, questions of equity and democratisation, and the increasingly dominant role of artificial intelligence and machine learning in biological research. By contrast, topics such as DNA sequencing advancements, including the goal of achieving a one dollar genome, and protein science received comparatively limited attention.

A key takeaway was the value of adopting a **metrics-driven approach** to track and accelerate progress in both data generation and technology development. Participants emphasised the importance of defining measurable indicators of scientific advancement, such as the proportion of gene functions that have been characterised, or the fraction of conserved human DNA bases for which biological function can be reliably determined.

Illustrative targets discussed included assigning function to **50 percent, 75 percent, and ultimately 99 percent** of conserved mammalian DNA bases; engineering new cells containing **1 Mb, 10 Mb, and 100 Mb** of designed DNA for under **£100**; or reducing the human time required to run a high throughput experiment from **14 days to 3 days to 2 hours**, with remaining processes handled through automation.

Participants noted that clearly articulating these goals, alongside the technological pathways and challenges required to reach them, could help focus investment, align community effort, and accelerate progress across the field.

Opportunities identified:

- Automated labs with AI-compatible instrumentation.
- Free, decentralised DNA synthesis and delivery.
- Live biosensors across diverse organisms.
- Democratised access to experimental and computational platforms.

Barriers identified:

- Lack of large, diverse, high-quality datasets.
- Limited global infrastructure for automation-ready laboratories.
- Energy-intensive data storage and interoperability challenges.
- Absence of universal standards for open datasets and benefit sharing.

Additional insights:

- Many existing technologies are near physical limits; progress will depend on unexpected breakthroughs.
- Ethical, societal, and governance considerations must be addressed in parallel with technological innovation.
- Metrics-based approaches can focus research on concrete milestones, enabling measurable progress and better coordination across institutions.

Novel approaches to achieve and deliver impact

Chaired by Matthew Hurles

The fifth workshop in the Genomics Futures series took a step back to explore broader, systemic shifts in how research may be conducted, organised and translated into impact by 2050.

Participants reflected on lessons from the past 25 years, including the transformative effects of genomic technologies, AI, open science and large-scale collaborations, while recognising that institutional models, funding systems and global inequities have evolved much more slowly. Across discussion, there was emphasis on the need to rethink how research is generated, governed, funded and applied if future advances are to deliver meaningful, equitable and sustainable societal impact. Participants explored both aspirational (utopian) and cautionary (dystopian) futures, highlighting key decision points that could influence whether scientific progress becomes more inclusive, effective and trustworthy or more concentrated, fragmented and inequitable.

The workshop explored possible future across three interconnected themes:

- AI and changes data generation and data integration
- Institutional models - Research organisations and research performers
- Globally equitable life sciences research

AI and changes to data generation and integration

Discussions examined the evolving role of artificial intelligence in driving large-scale scientific discovery and translational impact. One major theme was the staged evolution of AI systems, moving from self-learning models, to domain-specific applications delivering real-world impact, and ultimately toward intelligence capable of supporting discovery across diverse fields.

Platforms such as AlphaFold were cited as early examples of how AI can accelerate biological insight, while also highlighting the infrastructure and integration challenges associated with widespread adoption.

Future scenarios: Utopian and Dystopian Pathways

In a utopian or optimistic future, ethical and explainable AI would support happier, healthier populations, promote scientific transparency and enable adaptive governance evolves with technology, responds to novel challenges, and is not limited by silos and legacy systems. AI could promote diversity in collaboration, deepen systems-level understanding and support discovery from fundamental biology to complex systems.

In a dystopian future with a more pessimistic trajectory, intentional and/or unintentional misuse of AI, unequal access to AI infrastructure and monopolisation of data could exacerbate global disparities and entrench inequitable power dynamics around who makes decisions and what data is collected. This could make scientific discovery rigid, disconnected from society and deepen siloes that inhibit collaboration and progress.

Both futures depend on continued advances in technologies that generate and analyse ever-larger, higher-quality datasets. However, outcomes diverge at key decision points. Participants identified three critical crossroads: control over data, control over research agendas, and control over AI systems themselves. Ensuring diversity, accountability, and inclusive decision-making at these junctions was seen as essential to shaping a positive trajectory.

Both trajectories to these futures could rely on better, faster and cheaper technologies capable of producing and analysing larger, high quality datasets which improve our understanding of data points in various contexts.

Three key crossroads were identified: control over data, control over research agendas and control over AI systems themselves. In the utopian path participants suggested we'd see individuals

Ensuring diversity, accountability, and inclusive decision-making were seen as critical to shaping a positive future.

Research organisations and research performers

The session examined how research organisations and funding models may need to evolve to support large-scale, long-term scientific ambition.

Focused Research Organisations (FROs) were highlighted as a promising model for tackling tightly coordinated, non-profit scientific challenges that sit outside traditional academic or commercial structures. Key challenges include identifying shared scientific bottlenecks through structured roadmapping and locating strategic leverage points that enable coordinated progress at scale.

Participants also discussed shifts in the funding landscape, including efforts to support high-risk, high-reward research that bridges gaps between conventional grants and commercial investment. Entrepreneurial scientists were seen as critical actors in advancing multidisciplinary projects with bold, long-term objectives.

New venture creation models were presented as pathways to translate scientific hypotheses into tangible outcomes, moving from early exploration through prototyping to company formation. Priority areas include genome synthesis, zero-shot drug design, logic-based therapeutics, and the development of shared AI and experimental infrastructure. Looking ahead to 2050, participants envisioned research organisations as shared-intelligence hubs, integrating human creativity with automated, machine-driven experimentation.

Institutional models were recognised as pivotal in determining whether these futures are realised in utopian or dystopian forms. A utopian future would see lower barriers to entry and reduced costs enabling greater diversity among researchers, with diversity increasingly reflected in funding and leadership structures. Conversely, a dystopian trajectory could involve misconduct in funding, declining public trust, and the dominance of national interests over international collaboration. This would risk producing “sloppy science”, eroding job security, weakening incentives, and breaking the talent pipeline.

Key drivers and decision points include funding models, governance structures, dissemination practices, talent development, and incentive systems. Major considerations include improved inclusivity in funding structures, determining trends in government tendencies leaning towards national control/international cooperation, disrupting current publication models, as well as the sustenance and erosion of research careers. Participants emphasised the importance of broadening definitions of who can be a researcher, lowering entry barriers, diversifying skill sets, and recognising that impactful contributions may not require a PhD. Notably, strategic differences may emerge across regions, with Low- and Middle-Income Countries increasing national coordination to build capacity, while excessive nationalism in High-Income Countries could undermine global collaboration.

Globally equitable life sciences research

Discussions on global equity focused on the structural forces that shape research agendas, including who controls funding, time, infrastructure, and goal setting, and who bears the risks when projects fail.

Participants contrasted international research models, noting that some systems, such as those in China, enable rapid development and execution, while parts of the Global North operate through slower, more restrictive processes that can impede large-scale international collaboration.

A major challenge identified was improving technology translation in the Global South through the development of robust, locally embedded innovation systems. Without deliberate strategies to ensure effective translation, technological advances risk being underutilised or inequitably distributed.

Conducting science in context was emphasised as essential for building equitable and globally relevant research ecosystems. This includes recognising geographic inequalities, incorporating diverse perspectives and systematically evaluating research methods to improve design and decision-making. Integrating insights from social sciences and humanities was seen as critical for analysing where power is held and how science is practised.

In a utopian future with an equitable life science research ecosystem, governance structures operate across national, regional and international levels to manage data access, ownership and infrastructure. Data are representative, easily accessible and demonstrably beneficial to the public. Current frameworks would be enhanced by integrating tools from social science and humanities to conduct critical analysis on where power is held, further developed ethical and equity frameworks which provide alternate perspectives and methodologies to the way science is currently approached. This would also include producing encompassing models, beyond human-centricism, and strengthen local participation especially in the Global South; enhancing collaborations and encouraging diversification of perspectives on how scientific priorities are set.

A dystopian scenario would present crisis scenarios such as climate catastrophe or resource conflict which could impede cooperation and collaboration. Science may become monopolised,with research agendas skewed towards narrow interests and technologies only available in high-resource settings. There would also be no evolutions in current frameworks and overreliance on AI may contribute to a loss of foundational skills which halt developments in science. Any developments in technologies would be reserved for the wealthy - causing technological elitism. Key drivers and crossroads include the implications of a climate crisis, geopolitics influencing research agendas, AI regulation, governance, power distribution particularly when synthesising agendas and whether interdisciplinarity to improve the holistic analysis of policies and systems. Importantly, changes in technological landscapes can alter the definition of a “good vision”.

Key Takeaways

Discussions recognised both the opportunities and risks associated with different approaches to achieving impact, emphasising the need for careful security of methodologies and meticulously planned before execution, particularly for initiatives operating on a global scale.

Opportunities

- Self-learning AI, integrated into experimental labs, capable of visually processing the environment
- Deeper integration across disciplines, deepening understanding of systems-level biology and supporting democratisation of research
- Focused Research Organisations (FROs) to tackle large-scale, tightly coordinated, non-profit scientific challenges
- Expanded definitions of who can contribute to research, with lower entry barriers and more diverse skillsets
- Representative, accessible data- systems supported by locally embedded innovation ecosystems

Barriers

- Misuse or monopolisation of AI
- Lack of inclusivity in funding structures and governance
- Technology elitism limiting access and participation
- Geopolitical pressures shaping research agendas through and control of money, power, and time

Understanding, predicting and altering disease

Chaired by Carl Anderson

This workshop explored future approaches to understanding, predicting and altering disease across clinical medicine, pharmaceutical research and global health systems. Discussions centred on how advances in genomics, artificial intelligence, automation, and data integration could transform disease prevention and treatment over the next 25 years. In developing potential utopian and dystopian futures, participants emphasised the need to move beyond fragmented models of disease towards end-to-end understanding across biological scales, while ensuring that technological progress remains equitable, patient-centred, and globally relevant.

Perspectives on understanding disease

A clinical perspective

From a clinical viewpoint, the importance of improved pattern recognition in patient symptoms was highlighted as a pathway to more efficient diagnostics.

There is a need to bridge current knowledge gaps in histology as well as a need to transition from 2D tissue orientation analysis to 3D and cell profiling, highlighting its relevance in determining gene expression trends. While advances in understanding individual gene functions have been substantial, major challenges remain in elucidating mechanisms of action, a potential key factor in reducing drug development costs.

Current clinical genetics often focuses narrowly on gene susceptibility, but integrating broader genomic data such as transcriptomics, epigenomics and environmental context could refine phenotype identification and therapeutic targeting. Maintaining a patient-centred approach and ensuring research is both globally coordinated and locally relevant were identified as key priorities.

Pharmaceutical and technological perspectives

Technological innovation is expected to play a major role over the next decade. Advances in AI could provide equal or superior capabilities in reasoning, hypothesis generation, and tool development, while improvements in cellular models and molecular understanding could enable transformative technologies comparable to CRISPR.

Enhanced automation and robotics are likely to support experimentation at unprecedented scale and complexity and further deepen understanding of causal biology. This may improve the success rate of drug candidates entering clinical trials, enable more efficient target validation and accelerate the development of personalised and preventative therapies. Participants emphasised that these advances rely on sustained investment in fundamental biology and continuous technological improvement to ensure translation into clinical impact.

Predicting and altering disease trajectories

Discussions highlighted the need to distinguish between prediction, early detection, and prevention. Early detection was seen not only as a clinical tool but as a mechanism for uncovering early biological processes that could inform new interventions.

Participants envisioned a shift from reactive treatment models toward preventive and personalised approaches that alter disease trajectories before symptoms emerge. Integrated data across molecular, clinical, and environmental domains could enable clinicians to identify high-risk individuals earlier and tailor interventions accordingly.

At the same time, ethical challenges were raised around predictive information, including the psychological burden of genetic risk knowledge and the responsibilities of clinicians in communicating uncertainty. Questions about how much mechanistic understanding is necessary before acting on predictive signals also emerged as a central tension.

Global health, equity and implementation

Discussions around public and global health highlighted demographic shifts, particularly aging populations, which are shaping a treatment-focused culture rather than one centered on prevention. Preventive approaches were identified as crucial for better disease prioritisation and early identification of high-risk individuals. Funding models were noted as a barrier, with many emerging biobanks relying on expensive technologies and thus public–private partnerships as the main funding source, often leading to underrepresentation of the populations that should be served.

Challenges in rare disease diagnosis and treatment in regions such as Africa illustrated disparities between therapeutic innovation and local access, compounded by infrastructure limitations, including unreliable internet access. Strengthening local laboratory capacity and improving science communication, and fostering public and political demand were proposed as strategies to address these gaps.

Data sovereignty, equitable data governance and equity were recurring themes, with calls to shift genomics research from elitist to inclusive and equitable. Proposals included initiatives such as a Pan-African genome cloud built on ethically sourced, representative datasets through increasing local access to genomic technologies, AI, and analytical tools. This was a common sentiment among other Global South regions such as Latin America, where data generation capacity often outpaces local analytical capability, reinforcing dependencies on Global North institutions. Participants emphasised the importance of embedding innovation systems locally to ensure data generation capacity translates into analytical independence and meaningful impact.

Future visions: utopian and dystopian pathways

Definition of disease

A utopian vision would define health using data as opposed to drug-mandated definitions, including for mental health diseases. In this world patients would have access to holistic treatments where doctors or AI can prescribe optimal medicinal treatments for their disease, and allow for re-diagnoses to enhance treatment efficacy. Integrated datasets would help develop systems capable of tackling infections and emerging diseases.

Although a dystopian vision speculates that the development of AI on the limited existing data will not guarantee diagnosis, treatment or re-diagnosis. Bad actors could exacerbate the information through outlets such as eugenics, social hierarchies or bioterrorism, targeting certain groups or market specific products. Genomics may also be misused to develop animals and food for extraplanetary systems following the decline of Earth's environment.

Genomics in healthcare

Participants imagined a utopian vision which would promise everyone 80 "good years" of life by continuously monitoring health using a wearable device that collects real-time multi-omic data. Real-time data analysis would guide lifestyle choices, provide therapeutic interventions, accelerate drug manufacturing, adjust and gene regulation for optimal health. Ideally this technology would be compatible with all belief systems. Conversely, in a dystopia visions included monopolisation of health data by commercial or governmental actors, loss of personal autonomy, and models trained on unrepresentative populations. Overreliance on automated systems could reduce human clinical engagement and exacerbate global inequities with models trained on data from the Global North only.

Shortening times to new treatment

This utopia also envisioned a monitoring device for biological health which would also collect data from birth to enable predictive medicine. In the vision populations would be trial-ready and patients would be treated preventatively. The data would be used to create a digital twin to perform clinical trials to understand responses to interventions. An enhanced understanding of molecular mechanisms would enable rapid hypotheses development for quick, effective treatments.

In contrast, participants envisioned a dystopia where drug development productivity declines,treatments become accessible to only wealthy populations and monopolies dominate the pharmaceutical landscape. Society would be further polarised, looking for populations to blame, while public trust in healthcare and research institutions could drastically decline leading to weakened regulations and reduced global collaboration.

Universal tech and data access

A utopian vision with "universal tech and data access” would integrate data to provide a longitudinal view to help individuals understand the impacts on their lives in the long-term. They would be able to access their data and results from continuously analysed data, facilitated by shared ownership policies. A brain-data interface would enable the data to directly interact with an individual’s thinking process, as opposed to outside their body.

A dystopian vision for the future included access and misuse of data by bad actors, further exacerbation of current concerns around misinformation, overreliance on data and technology leading to “health determinism”, erosion of human agency and environmental impacts from large-scale data infrastructure. They also raised concerns on whether the system would still promote a capitalist agenda instead of empowering the community, even if led by the Global South.

Implications for Research Systems and Healthcare: Key Takeaways

This workshop highlighted the importance of effective collaboration and responsibility among different regions of the world. Participants collectively acknowledge discrepancies in knowledge, expertise and access to resources on a global scale, promoting the narrative improving inclusivity, diversity and empowering low-resourced regions for an enhanced future of genomics over the next 25 years. Some key opportunities and barriers identified are highlighted below.

Opportunities

- Continuous multi-omic monitoring and personalised prevention using wearable devices
- Integrated datasets supporting AI-driven discovery
- Digital twins and predictive modelling for clinical trials
- Strengthened global data infrastructures and representative research e.g. a Pan-African genome cloud of ethically-sourced and representative data
- Expanded roles for patients and communities in research prioritisation
- Improved communication strategies targeted to politicians and citizens

Barriers

- Persistent gaps in causal biological understanding
- Risk of monopolisation and misuse of data and technology
- Inequitable access to therapies, infrastructure, and connectivity
- Declining public trust and fragmented governance frameworks

Common themes

Through the course of the six workshops, participants identified a set of recurring technological, societal and scientific themes shaping the future of genomics and related life science research. This section synthesises these cross-workshop discussions and highlights opportunities for impact, barriers and considerations, and forward-looking actions. Participants were encouraged to consider not only technological potential but also responsible development, governance and public benefit. Ethical, Legal and Societal Implications (ELSI) were explored retrospectively using the Anticipate, Reflect, Engage, Act (AREA) framework developed by UKRI (UK Research and Innovation & UKRI, 2023).

Integration of AI and Emerging Technologies

Digital technology and AI have already revolutionised the way we live and will inevitably play a central role in the evolution of genomics over the next 25 years. Across all the workshops, participants highlighted the transformative potential of emerging technologies to drive advances in patient diagnosis and enable precision modelling of disease, biological systems and environmental ecosystems.

Opportunities for Impact

- Integration of AI into labs could create an automated lab infrastructure that enables fast, iterative experimentation where readouts/instruments are compatible for AI interpretation.
- The potential of digital twins to revolutionise genomic engineering emerged in multiple contexts, from individual patients and organ systems, to mapping infectious disease dynamics at the population level and modelling of non-human biological systems as a means of testing scenarios, predicting outcomes and guiding interventions without real world risk.

Barriers and Considerations

- Limited global infrastructure for automation-ready labs remains a significant constraint.
- Of particular importance in the advancement of AI, is developing “explainable” AI models that (a) make clear what datasets were used for training, and (b) are able to share the reasoning behind their outputs in a human-readable format.

- Participants expressed concern about AI models trained on data that is either intentionally or unintentionally biased, which could lead to inequitable treatments or exacerbate existing inequities. High-quality and diverse, datasets were repeatedly emphasised as prerequisites underpinning the potential applications.

Forward Look

- Promote open and publicly accessible AI training data, model architectures, and parameters to strengthen global research capacity, foster transparency, and accelerate collaborative improvement of AI technologies.

- Validate and scale AI models so they can match the precision of wet-lab experiments and be trusted in clinical and ecological applications.

- Expand automation-ready labs and energy-efficient storage solutions, particularly in low- and middle-income countries (LMICs), to democratise access.

- Accelerate digital twins and predictive models for healthcare, agriculture, and environmental systems to move from descriptive to preventive science.

Data and Infrastructure

The scalability of data in both diversity and quantity was discussed across a number of workshops. Given that the use of genomic and health data resources could become increasingly routine in clinical care, the resilience and adaptability of technological systems, together with the capability and stewardship of those responsible for data governance, were identified as key determinants of the future of genomics.

Opportunities for Impact

- Wearables and biosensors could enhance real-time monitoring and collection of data from individuals for multi-omic screening, which could be used for personalised medicine, public health policy interventions and drug development. They could also enable biodiversity monitoring through eDNA screening.
- Open-access databases and shared analytical tools could further democratise the benefits derived from large-scale data generation. By improving accessibility, interoperability, and collaboration, these resources can help ensure that the scientific, clinical, and societal gains from genomics are more equitably distributed.

Barriers and Considerations

- Real-time monitoring offers great potential for scaling data and advancing understanding, but concerns were raised around data storage with the potential for personal information to be exploited for commercial, discriminatory or surveillance purposes.
- Risk to biosecurity arising from the misuse of genomic data was also explored, including the engineering of pathogens and development of bioweapons or the use of data-informed genetic engineering that has the potential to interfere with natural biological processes, with cultural, religious and ecological implications.
- To tackle some of the risks associated with advances in technology and data accessibility, such as monopolisation or misuse, integration of multiomic environmental or personal data from biosensors or wearables will require technical and human infrastructure capable of storing and making these resources usable across diverse geopolitical contexts. Physical and digital infrastructure must be modular, interoperable, and globally distributed, allowing researchers and healthcare providers in all settings to contribute and benefit.
- The requirement for standardised data formats was highlighted to ensure interoperability and accessibility
- With the potential offered from data generation becoming cheaper and more accessible came a matched consideration for sustainability of data infrastructures. These challenges might be partially addressed through reduced duplication and improved long-term physical storage methods. Some participants explored how a cloud-based open-access data infrastructure could enable data usage between collaborators worldwide, but noted issues around equitable benefit if researchers from well-resourced settings are better placed to analyse such open data for reasons such as internet accessibility.

Forward Look

- Foster open dialogue between stakeholders, especially the public, to discuss risks of data misuse, and devise strategies to minimise risk.
- Develop standardised, interoperable, and open data systems to enable large, integrative datasets across genomics, microbiomes, and ecosystems.
- Invest in federated data infrastructures that are globally integrated but locally owned, ensuring community governance and benefit-sharing.

- Support real-time monitoring (biosensors, wearables, citizen science tools) to link genomic, environmental, and health data streams.
- Support the development of a skilled workforce across research, regulation and clinical care, with the expertise to work across disciplines and facilitate a high turnover of clinical trials. In the case of health care, it expedites the speed at which life changing treatments go from screening to market for the benefit of patients and thus dedicated patient support will be crucial e.g. genetic counsellors.

Equity, Inclusion and Representation

Throughout the workshops, participants discussed the range of stakeholders who were needed to participate in an effective, inclusive and equitable genomics ecosystem - including community organisations, civil advocacy groups, researchers, innovators, governments, ethicists, social scientists, legal experts, indigenous peoples, and public groups. Some workshop participants also emphasised a less "human-centric" approach to stakeholder engagement, with non-human species and wider ecosystems - and even planet Earth - considered as equal stakeholders (sometimes referred to as 'A One Planet Approach'). How and when genomics researchers should engage different stakeholder groups was also considered. For example, involving ethicists, legal experts and civil society throughout the project from the beginning could positively influence decisions on what research is conducted, how it is carried out, and what outcomes are produced.

Opportunities for Impact

- Proactive engagement with public groups could contribute towards decisions and outputs that ultimately support equitable benefit from genomics. Further engagement tailored towards public groups from less represented areas such as communities in the Global South and non-scientific communities could improve accessibility.
- Expansion of global initiatives, with regional hubs and equitable sampling could improve accessibility and diversity of research participation.
- Better, faster and cheaper technologies capable of producing and analysing larger, high quality datasets has the potential to reduce barriers to diverse sampling, ultimately improving our global biological understanding.
- The approach of addressing "power imbalances" may not be possible to achieve

at the same pace as advancements in genomic technologies. Instead, the concept of “power dynamism” may offer a more sustainable solution for less-resourced regions, which focuses on maximising inherent strengths. For example, regions with rich biodiversity may benefit from focussing efforts on developing sampling and sequencing techniques or natural resource extraction. In essence, genomics-related clinical and research endeavours do not need to evolve in an homogenous manner across the globe, but could rather respond to the particular context and ecosystem of different regions.

Barriers and Considerations

- Despite recent advances in genomics worldwide through global collaboration, there was strong agreement that participation in and benefit from genomics is still strongly biased towards countries in the Global North.
- Many workshop participants acknowledged that research on human health is overly centered on data from individuals with European ancestry, based in the Global North, with other ancestries and geographies lacking representation.
- Participants also highlighted risks to advances in AI and automation including ‘technology elitism’ which has the potential to amplify a global scientific divide.

Forward Look

- Increase the involvement of Global South collaborators in genomics research, especially large-scale global research endeavours.
- Decolonise scientific language and practice by removing western-centric framings (e.g., “global” health) and valuing indigenous and local knowledge.
- Build regional labs, training programs, and biobanks in LMICs to ensure equitable participation in genomics and healthcare innovation.
- Create representative datasets that reflect geographic, demographic, and ecological diversity, including African and Indigenous populations.
- Develop communication and engagement materials that are widely accessible (e.g. translation into multiple languages with minimal scientific jargon).

Governance and Ethics

Participants discussed how governance frameworks can be further developed and implemented to advance the benefits and mitigate the risks from advancements in genomics. It was also highlighted how consistent consideration of responsible and ethical decision making when conducting research and developing technologies should be embedded within these frameworks.

Opportunities for Impact

- The governance of data access was addressed across several of the workshops. Some participants proposed the creation of a large, global, neutral oversight body dedicated to genomic data, with representation from member states in a similar model to United Nations (UN) bodies or the International Bureau of Weights and Measures that coordinates the International System of Units (SI). The oversight body may focus on delivering an international framework to advise and coordinate governments on data governance - or even directly oversee data access requests itself.
- To supplement top-down governance frameworks, participants stressed the importance of bottom-up training for genomics researchers in ethical and responsible decision-making. This includes training in consent, equitable benefit, and collaboration. Other stakeholders including policy-makers and healthcare professionals could also receive training in responsible research, innovation and adoption.

Barriers and Considerations

- Geopolitics and control of money, and time in research agenda-setting shapes who benefits from science. Current frameworks often exclude or slow Global South innovation.

Forward Look

- Establish proactive governance frameworks for AI, synthetic biology, environmental genomics, and ecosystem interventions to avoid misuse and inequity.
- Develop international structures (e.g. a “WHO for planetary health”) to guide equitable, interdisciplinary approaches to biodiversity, ecosystems, and climate resilience.

- Continue to embed benefit-sharing mechanisms in bioprospecting and pharmaceutical development.

Scientific Culture and Research Models

Beyond technological advances, participants reflected on how scientific culture and institutional structures shape research outcomes. Discussions around scientific culture and research models revealed a tension between speed and depth in discovery, with participants emphasising the need to balance rapid scaling (“fast science”) with deeper reflection (“slow science”) to ensure robust understanding before large-scale application. Complementary modes of inquiry were highlighted, from hypothesis-driven “day science” to more exploratory, interdisciplinary “night science,” with calls to value both human creativity and AI-assisted discovery. Across workshops, participants envisioned new institutional models that move beyond siloed, hierarchical structures.

Opportunities for Impact

- Alternative institutional models (Focused Research Organisations, citizen science) were proposed to foster agility, inclusivity, and high-risk/high-reward research.
- Expanding definitions of who counts as a researcher could increase inclusivity and diversify skillsets.

Barriers and Considerations

- There is a tension between embracing AI as a “partner” in creativity and research vs risks of overreliance or erosion of foundational scientific skills.

Forward Look

- Balance “fast science” with “slow science”, ensuring deep understanding before scaling applications.
- Foster interdisciplinary and global collaborations, spanning biology, ecology, social sciences, and humanities.
- Experiment with new institutional models such as Focused Research Organizations (FROs) to tackle high-risk, high-reward challenges.
- Broaden definitions of “researcher” by lowering entry barriers, diversifying skills, and moving beyond PhD-centric pathways.

Public Engagement and Trust

Public engagement and trust emerged as central to the future of genomics, AI, and biotechnology, with participants warning that societal scepticism could undermine innovation. Concerns around predictive medicine, synthetic biology, environmental interventions, and data use highlighted the need for transparent, creative, and accessible communication to demonstrate clear benefits and address ethical concerns. Participants stressed that trust cannot be built solely through information provision but must involve genuine dialogue, co-creation, and citizen-driven demand for equitable healthcare and environmental stewardship.

Opportunities for Impact

- Public engagement and trust-building were recognised as critical, particularly around synthetic biology, AI, and engineered organisms.
- Improved communication strategies could provide some mitigation by generating citizen-driven demand for equitable and ethical healthcare and incorporation of new technologies.

Barriers and Considerations

- There is currently public mistrust in the pharmaceutical industry and research, as well as wider societal scepticism towards engineered organisms, predictive medicine, and AI-driven science.

Forward Look

- Establish meaningful two-way public engagement that supports scientific decision making.
- Prioritise transparent and creative science communication to build trust in AI, synthetic biology, and predictive medicine.
- Highlight clear societal benefits of genomics and biotechnology to counter scepticism and ethical concerns.
- Encourage citizen-driven demand for equitable and ethical healthcare by engaging communities in shaping innovation.