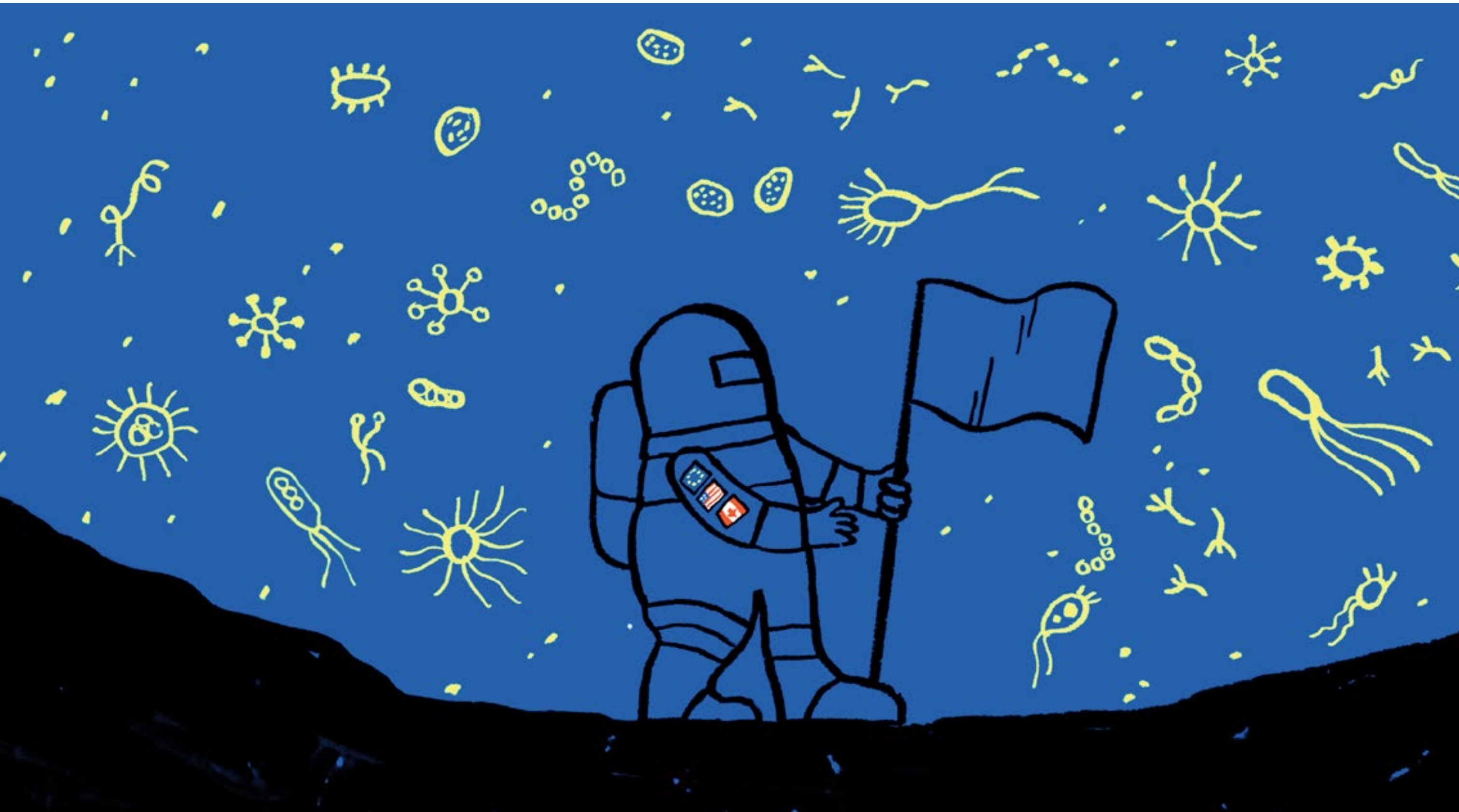
AORA

ATLANTIC OCEAN RESEARCH ALLIANCE

Marine Microbiome Roadmap



This Vision Statement, or Roadmap, of marine microbiome research is conducted within work package 6 of the Atlantic Ocean Research Alliance (AORA) between Canada, the European Union and the United States of America.

The scope of the document was presented at an AORA meeting in December 2018. Three workshops were held, in Brussels in June 2019, in Reykjavik in October 2019 and in Halifax in January 2020. A diverse group of stakeholders participated in this work and the outcome, as presented here, is a result of extensive consultation with those who directly participated in the workshops as well as others that were invited to comment on the work as it progressed. The editorial team would like to thank all those who contributed with comments and input.

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EXECUTIVE SUMMARY

“The Science We Need For The Ocean We Want” [1]

We are on the threshold of a new and exciting era of discovery in the oceans that will shape the development of human endeavours for decades to come. New insights on the significance of the microscopic scale of ocean life has shown this level affects almost every aspect of our lives (health, food, industry, ecosystems). For society’s future, we need to investigate the science of marine microbiomes, integrate the novel technologies discovered and initiate policies that foster truly sustainable marine development.

The United Nations will dedicate the next decade to Ocean Science for Sustainable Development. The Decade’s vision and mission are consistent with the objective of the Atlantic Ocean Research Alliance (AORA) between Canada, the European Union and the United States of America, that is to *“advance the shared vision of an Atlantic Ocean that is healthy, resilient, safe, productive, understood and treasured, to promote the well-being, prosperity and security of the Atlantic for present and future generations”*.

Relevant to the missions of both AORA and the Decade, here, we outline how the marine microbiome is at the heart of the ocean as a living system, driving its nutrient and biogeochemical cycles, forming the basis of its food webs, performing essential and yet unknown functions in climate regulation, including buffering the effects of global change. Furthermore, the oceans are a largely untapped resource for biodiscovery and the bioeconomy, with a high potential for the development of new products and processes.

To ensure early coordination and interoperability guided by a shared vision, we need to bring together science, industry and policy makers to advance the “Next Great Exploration of the Oceans”. The following Roadmap is the result of an international cooperative effort between Canada, the European Union and the United States of America produced within the AORA framework and consistent with the Galway Statement on Atlantic Ocean Cooperation.

Within the marine microbiome Roadmap, three thematic pillars have been identified by AORA scientists and policy makers, all supported with underlying cross-cutting elements: **Environment and Climate, Food Value Chain and Biodiscovery.**

[1] *Vision statement of UN Decade of Ocean Science https://oceandecade.org/*


there are more microbes in the sea than stars in the sky...

INTRODUCTION

“The diversity of microbial life remains unquantified and largely unknown and represents a hidden treasure for human society” [2]

Marine life is a major contributor to the health of Earth’s ecosystems, through supporting food production and its role in environmental and climate issues. The overwhelming part of marine life is made up of microorganisms that are important regulators in geochemical cycles and the marine food web, without which life on Earth would not be possible. Within the vast oceans, microorganisms have colonised virtually every environment where life can exist. Their diversity in each of these environments reveals how life is responding to and shaping the ocean system.

Microbiome is a term used for the communities of microbes, and their combined genetic material, that have settled in a particular environment. The advancement of genetic (DNA and RNA) sequencing technology, with its ever-decreasing costs, has greatly accelerated the study of microorganisms within complex ecosystems.

Only a small fraction of marine microbial diversity has been characterized to date. However, advances in genetic (DNA and RNA) sequencing technology coupled with decreasing costs have revolutionized our ability to monitor and study microorganisms within complex ecosystems.[3] Although research and operations focused on the marine microbiome are relatively new endeavours, efforts have already provided important insights into the structure and function of the marine ecosystem and supported the creation of new bioindicators[4] to help protect human and environmental health. A variety of research successes - including the Human Microbiome Project (HMP), the Tara Oceans Expeditions, the Earth Microbiome Project (EMP), and eDNA analysis associated with the Marine Biological Observing Network (MBON) - have deepened our understanding of the microbiome’s importance in sustaining the health of organisms and ecosystems. The wealth of data from microbiome research has resulted in a dramatically revised tree of life and stimulated entirely new fields of research. Such work has also led to far-reaching innovations in terms of technologies, methods, infrastructure, and research design.

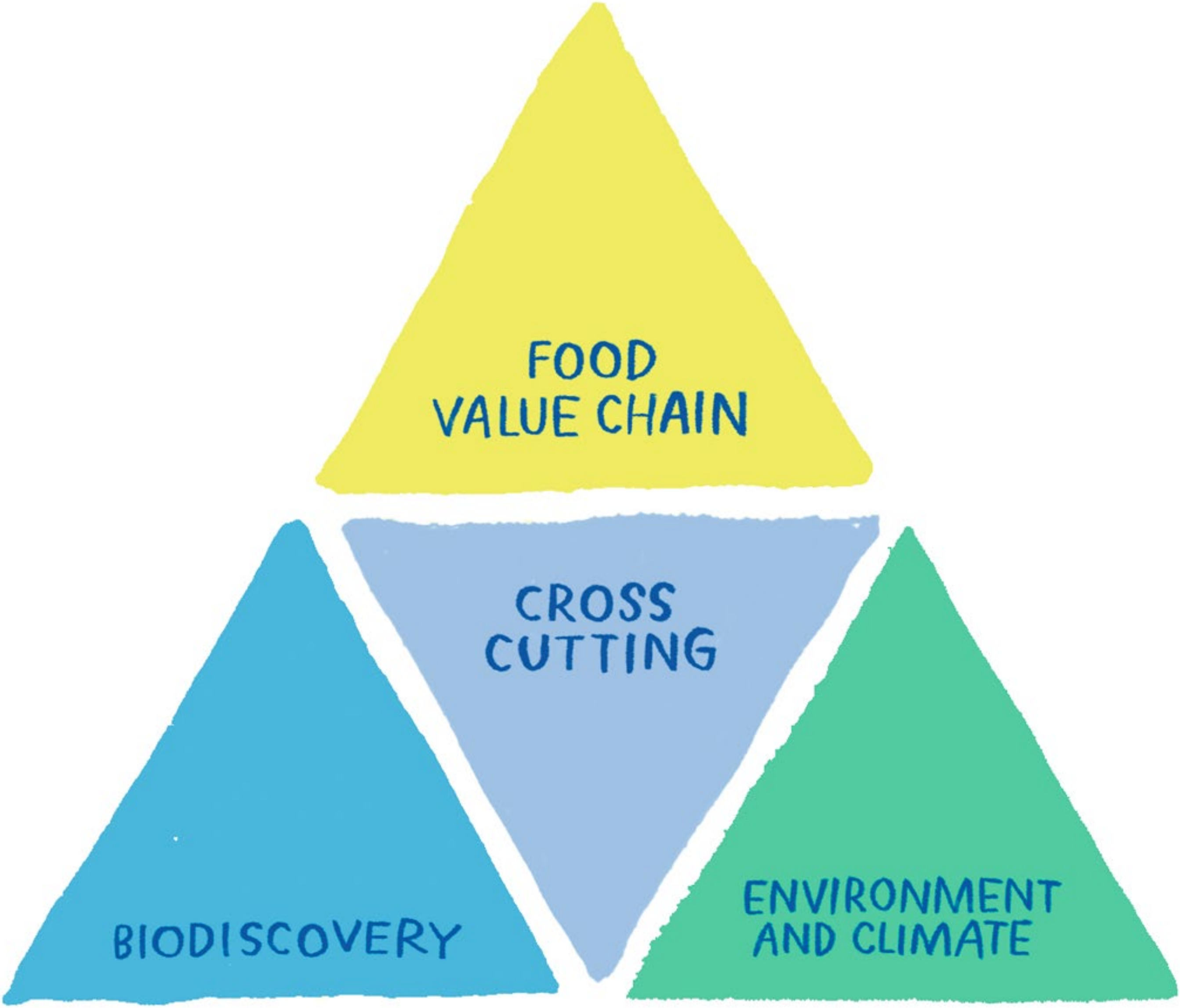
These successes provide a firm basis to develop a Marine Microbiome Programme with the framework of the Atlantic Ocean Research Alliance (AORA) between the European Union, Canada and the United States. Through the Atlantic Ocean Research Alliance, stakeholders along and across the Atlantic are laying the groundwork to contribute to the *“Last Great Exploration on Earth”* to discover, understand, protect and harness our Oceans.

[2] *The Marine Microbiome. An Untapped Source of Biodiversity and Biotechnological Potential. Editors: Stal, Lucas J., Cretoiu, Mariana Silvia (Eds.)*
[3] *Such as the use of the 16S gene for deep exploration of microbial diversity, e.g. Sunagawa et al. 2015*
[4] *Buttigieg et al. 2018*

Focus on the marine microbiome is consistent with AORA objectives to *"advance the shared vision of an Atlantic Ocean that is healthy, resilient, safe, productive, understood and treasured, to promote the well-being, prosperity and security of the Atlantic for present and future generations"*. These efforts also are in keeping with the Galway Statement on Atlantic Ocean Cooperation (May 24, 2013), which intends *"... to show how results of ocean science and observation address pressing issues facing our citizens, the environment and the world and to foster public understanding of the value of the Atlantic Ocean"*. Furthermore, marine microbiome cooperative research and applications *"may result in mutual benefits including better ecosystem assessments and forecasts and deeper understanding of vulnerabilities and risk, including those relating to the global climate system and climate change impacts. It can also help to generate new tools to increase resilience, conserve rich biodiversity, manage risk and determine social, environmental and economic priorities"*.

To ensure that competence in microbiome research and application efficiently matures across sectors, it is important that governments, academia, and industry cooperate and align their strengths, objectives, and incentives to meet shared goals. To these ends, AORA scientists and policymakers have developed a Roadmap to help align and advance an Atlantic-wide approach to microbiome research and monitoring to (a) facilitate cooperation along and across the Atlantic, (b) increase the visibility of marine microbiome research, and (c) promote a healthy ocean and sustainable bioeconomy. The Roadmap identifies three thematic pillars supported by key cross-cutting elements to support a mission to better understand, protect, predict, and sustainably harness the marine microbiome. Goals include mapping the marine microbiome to help understand and predict environment and climate. In doing so we will investigate different ways to sustainably utilize marine bioresources to meet demands for sustainable biomass harvesting, food security and biodiscovery.

The Galway Statement on Atlantic Ocean Cooperation (May 24, 2013):
"This cooperation may result in mutual benefits including better ecosystem assessments and forecasts and deeper understanding of vulnerabilities and risk, including those relating to the global climate system and climate change impacts. It can also help to generate new tools to increase resilience, conserve rich biodiversity, manage risk and determine social, environmental and economic priorities".


FOOD
VALUE CHAIN
CROSS
CUTTING
BIODISCOVERY
ENVIRONMENT
AND CLIMATE

EVERY SECOND BREATH YOU TAKE

YOU CAN THANK THE OCEAN

ENVIRONMENT AND CLIMATE

Vision Statement

The marine microbiome will be at the heart of understanding ocean ecosystems and the sustainability of the services they provide to society

Background

Just as the human microbiome is central to our health, the ocean microbiome is key to a healthy and resilient biosphere.

Microbes permeate the ocean and their activities deeply influence its chemistry, physics, and underpin all marine life. The marine microbiome is sensitive to environmental stress and shapes ecosystems across the entire planet. Vitally, this also affects our planet's climate system, as marine microbes are responsible for pumping atmospheric carbon into the oceans and preventing the release of methane from the ocean's depths into the atmosphere. They are also key to sustaining the ecosystem services that humans rely on and thus highly relevant to multiple aspects of the Sustainable Development Agenda. For example, their diverse metabolic abilities can deactivate and recycle waste products and pollutants while provisioning food webs and fisheries with essential nutrients. Simultaneously, some kinds of marine microbes pose significant threats to living systems through their ability to cause disease, produce toxins, resist antibiotics, and form harmful algal blooms and oxygen-depleted dead zones. These roles also make microbiomes sensitive and broad indicators of the state, functions, changes, and health of marine ecosystems.

Despite the importance of the marine microbiome to both science and society, our ability to observe it at scale is underdeveloped and under-coordinated compared to current physio-chemical ocean observation efforts. However, recent advances and the falling costs of technologies such as high-throughput sequencing, e.g. of eDNA, remote sensing and autonomous sampling, and emerging coordination networks are a game changer.

We are now capable of mainstreaming microbiome observations in ocean science and operations at large, complementing existing capacities with new biological and ecological perspectives. Integrating microbiomes within ecosystem models will help to improve our ability to better predict and respond to climate variation and ecological hazards. It allows us further to investigate the microbiome of global Marine Protected Areas in order to fully understand these systems from the microbes up. Indeed, in 2018, the Global Ocean Observing System (GOOS) established a Microbial Biomass and Diversity Essential Ocean Variable (EOV), acknowledging the key role of microbes in the Global Ocean. Within AORA, we seek to catalyze the mainstreaming of marine microbiome research and application, integrating these with existing programmes in environmental monitoring and science.

Goals

- Map the Atlantic microbiome and its connectivity and variation in time and space
- Identify novel microbial indicators of ocean health and change
- Improve capacities for the prediction of the future state of ocean health
- Characterize and quantify the microbiome-related ecosystem services to societies, and provide insight into their drivers and their future trajectories
- Provide responses to challenges identified by the Intergovernmental Panel for Climate Change (IPCC) and the Intergovernmental Panel on Biodiversity and Ecosystem Services (IPBES)

Specific Objectives

- Develop and disseminate best practices to assess microbiomes across the Atlantic's diverse ecosystems
- Broaden spatiotemporal coverage of Atlantic microbiome observations and experiments (mm to km and minutes to years) to characterize its core features and behavior
- Define baselines for different microbiome states (e.g. pristine, impacted by pollution) and indicators to detect deviations and risks of exceeding ecological tipping points
- Monitor and measure spatiotemporal variations in microbiome composition, function and health status
- Improve the understanding of how microbiomes within and between ocean regions connect with and influence one another
- Enhance capacities in data science (especially artificial intelligence (AI) technologies and distributed processing of complex data) to accelerate the production of data, information, and knowledge products suited to a wide range of stakeholders
- Improve the transfer of basic science into the development of predictive models used for the response of the microbiomes to environmental change, e.g. biogeochemical cycling, ecosystem structure, trophic status, and environmental hazards

ACTION ITEMS

Short Term

- Align existing Atlantic microbiome initiatives through the support of collaborative networks, standards, and best practices to promote greater interoperability and basin-scale cooperation

- Select sites or areas - along and across the Atlantic - to conduct repeated and long-term sampling, augmenting our capacity to monitor marine microbiomes
- Across the Atlantic, strongly improve the bridge between environment observations, controlled experiments (lab based, mesocosms, cultivation of mixed microbiomes), data science, and predictive modelling to create deep and validated understanding

Medium Term

- Map the Atlantic microbiome, emphasizing the variability in its diversity, functions, and the services it provides to human society
- Building on increased data availability, build and integrate predictive models across the ocean value chain and contribute to predictions of global ecosystem state (e.g. climate variation, biodiversity loss and gain)
- Develop robust financial concepts to maintain coordinated, long-term microbiome observation and research in the Atlantic
- Improve - across sectors - the crediting of rapid microbiome data release
- Develop, test and deploy sensors and samplers for broadscale, near real time synoptic observations of microbiomes and their physical and chemical environments

Long Term

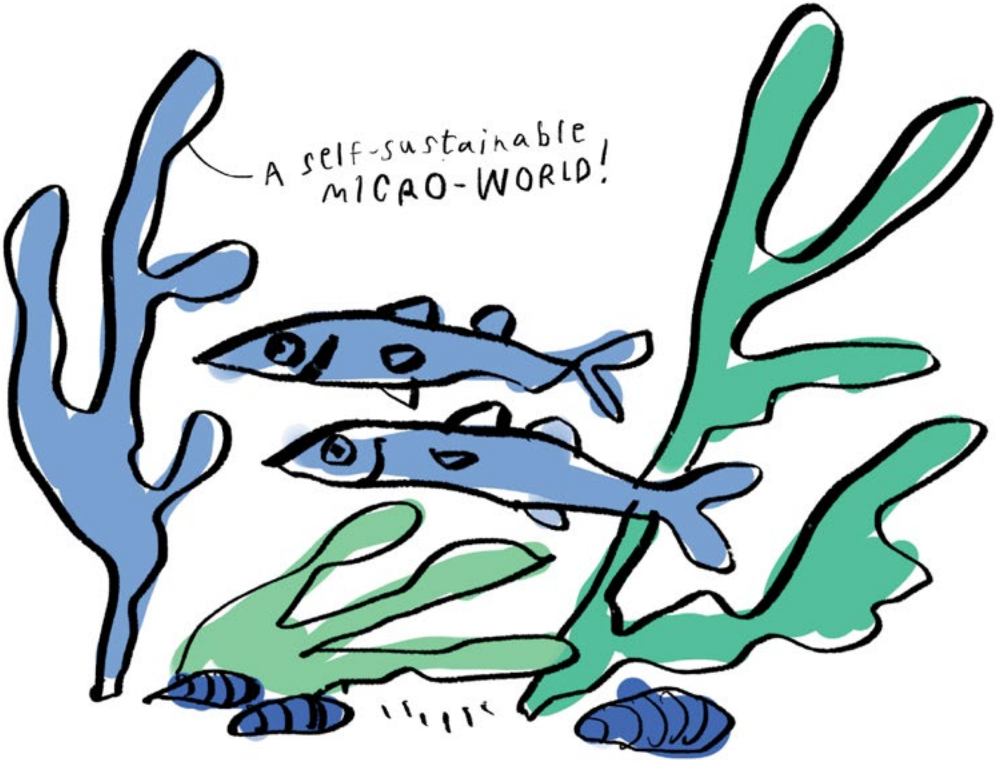
- Collaboratively and continuously update and maintain quality-controlled maps of the Atlantic microbiome, fully integrated with other ocean data layers
- Provide a global understanding of the role of microbiomes in the ecosystem's state, change, and health
- Promote rapid and automated reuse of microbiome data (assisted by AI solutions) and delivery of tailored information products across ocean stakeholders

Priority List

Conduct experiments and field observations in systems of concern such as those:

- Capable of or demonstrating high carbon capture and/or release
- Undergoing rapid change
- Impacted by human activity and in need of bioremediation such as Marine Protected Areas and the degradation of plastics and oil
- Impacted by biohazards such as Harmful Algal Blooms, parasites, viruses, jellyfish
- With minimal human impact as baselines for ecological restoration
- Of special biological and ecological interest such as biodiversity hotspots

THE OCEAN FOREST FARM



FOOD VALUE CHAIN

Vision Statement

The marine microbiome will be key to securing and facilitating sustainable production of food from our oceans

Background

Human populations are rapidly growing, and with them the demands for marine food resources. Microbes are key to securing the marine food supply in an ecologically sustainable way. They provide essential nutrients to entire food webs, recycle waste products, and form protective layers on and in larger organisms. Although marine fisheries (including fish and shellfish) and the use of seaweeds are many eons old, the direct application of individual or communities of microbes to facilitate healthy marine food production is still in its infancy. This emerging status, together with our current knowledge on the essential interactions of microbiomes with their hosts and our awareness of the fragility of many of Earth's ecosystems, offers a great opportunity to develop a strategy that includes sustainability and fair-trade where each participant (farmers, industry, public) can benefit without destroying the natural habitats.

Marine food from fisheries and aquaculture refers to any food source directly or indirectly derived from the marine ecosystem. This includes higher organisms (grown on fish farms, shellfish farms, crustacea farms) and algae (seaweeds and micro-algae). Marine food production is not limited to the open waters of seas and oceans. Rising seawater levels put more coastal regions under the direct influence of salt water, including upwelling saline groundwater. Novel developments in saline agriculture where salt tolerant crops are amended with salt tolerant microbiomes could save these regions from desertification. Studies on marine food-associated microbiomes are far behind current state-of-the-art research in terrestrial, fresh water-based agriculture and human plus cattle related microbiome studies. Catching-up requires investments and effort from policy, industrial researchers and scientists.

Goals

- Advance the scientific understanding of microbiomes associated with or applied to marine food production to be on par with that of agricultural and human systems
- Develop novel technologies to apply microbiomes for healthy eco-friendly marine food production
- Integrate microbiome monitoring in the management of sustainable marine food production
- Increase the ability of food producers (both small and large scale) to leverage microbiome technologies to promote stock health and productivity

Specific Objectives

- Provide a wide inventory of various marine derived food sources and existing technologies in marine aquaculture. A complete inventory is needed to identify essential growth parameters between food source, microbiome and ecosystem and of local markets and preferences in marine food consumption
- Provide an inventory of existing programs involving marine microbiomes for sustainable food production from the USA, Canada and the EU and their targeted model systems to enhance communication and accelerate progress
- Harness marine microbiomes to move past traditional, non-sustainable agriculture and develop marine food-related applications that balance long-term services with ecosystem preservation
- Develop novel microbiome related technologies hand in hand with novel cultivation techniques. Collaboration along and across the Atlantic is key to propel this process and stimulate exchange of knowledge and novel techniques and to include diverse food sources and variations in local ecosystem
- Develop novel tools in high throughput DNA sequencing, bioinformatics and ecosystem modelling to handle the large datasets that will be generated

ACTION ITEMS

Short Term

- Raise international, political and public awareness of potential applications of marine microbiomes in sustainable marine food production
- Encourage universities to initiate targeted marine food microbiome related fields of study and establish novel university chairs
- Initiate large scale studies to analyse composition and functional diversity of marine food related microbiomes and their role in food and food supplement production
- Develop and apply new multivariate statistics and meta-analysis for large datasets to understand the relationships between microbiome, host and environment
- Learn from other microbiome research areas (terrestrial, human, etc.) and transfer relevant results and methodologies to the marine microbiome food production

Mid Term

- Development of novel technologies to secure sustainable ecological friendly aquaculture based on circular ecology principles such as Integrated Multi Trophic Aquaculture (IMTA)
- Develop quick microbiome analysis tools for monitoring and control of microbiomes in aquaculture production facilities
- Study Impact of novel marine microbiome facilitated food source on human & cattle health (gut microbiome intervention studies)

- Provide input to update the FAO Code of conduct for responsible fisheries, specifically addressing aquaculture and the role of the marine and freshwater microbiomes
- Provide access to technical training (e.g. handling microbiomes in relation to aquaculture and big data analysis) and opportunities that inspire entrepreneurship

Long Term

- Marketing of marine microbiome derived food as an honest truly eco-friendly, sustainable alternative to traditional food resources
- Developing a global knowledge hub on marine microbiomes to facilitate access and exchange of data, information and knowledge
- Free exchange of knowledge and technology to encourage uptake by farmers from small and medium enterprise aquaculture
- Stimulate sustainable saline agriculture in coastal regions affected by climate change

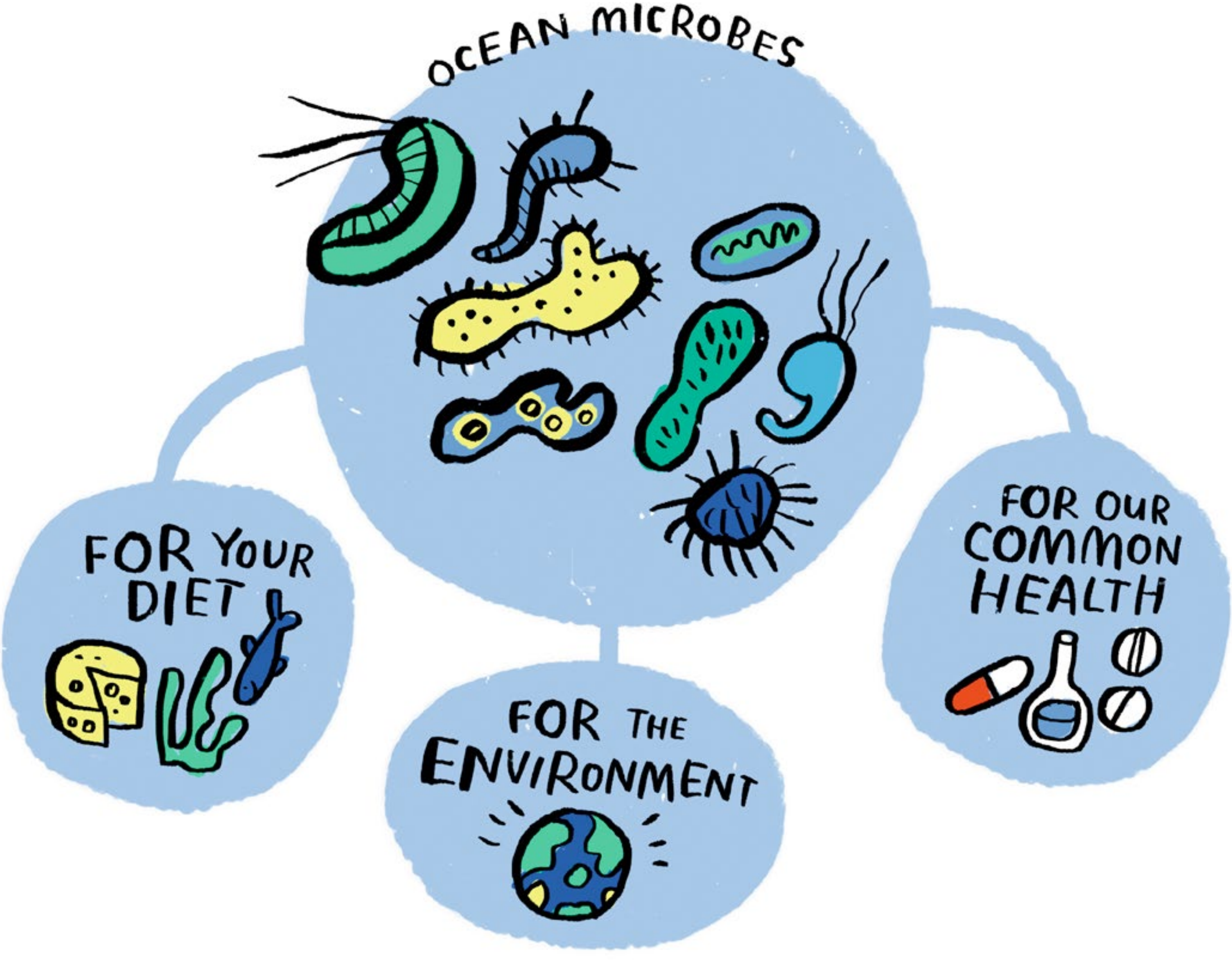
Marine food value plan:

- investigate - The science of marine food related microbiomes
- integrate - Novel technologies based on marine microbiomes in food
- initiate - A truly sustainable and fair marine food market

Priority List:

Investigate and improve application of marine microbiomes for marine food production

- Secure sustainability of food production in changing climate
- Invest in Integrated multi trophic aquaculture using microbiomes for healthy hosts and recycling of waste products
- Develop healthy, safe microbiome starter cultures for closed systems, e.g. aquaculture
- Secure healthy sea farms through healthy livestock microbiome (fish, shellfish, crustacean)
- Partly replace animal based food for humans and fish farms by microbiome enhanced seaweeds and microalgal based food products and food supplements
- Salt tolerant marine microbiomes for saline agriculture in coastal areas
- Promote microbiome enhanced seaweed and microalgal based food for human nutrition


OCEAN MICROBES
FOR YOUR DIET
FOR THE ENVIRONMENT
FOR OUR COMMON HEALTH

BIODISCOVERY

Vision Statement

The Marine Microbiome will Propel Biodiscovery, Providing New Sources of Value to Society

Background

Microorganisms contain a plethora of metabolic pathways that allow them to exist and thrive in a variety of challenging environments. These pathways can yield beneficial products such as medicinals, nutraceuticals, and compounds for industrial applications. Furthermore, characterization of new genes, proteins, and metabolic pathways can advance our basic scientific understanding of marine biodiversity, as well as identify targets for ecosystem monitoring, bioindication, and bioremediation.

Biodiscovery can be viewed from a variety of perspectives. Though often understood in an industrial or commercial sense, biodiscovery can yield numerous benefits to the not-for-profit sectors, such as academia and government. In academia, continually evolving research programs may be used to document and understand biodiversity, gain mechanistic understanding of ecological relationships, and increase the overall knowledge base of a discipline. Environmental managers may prioritize research that yields cause-effect understanding and indicators that can be used to manage the impact of anthropogenic activities on ecosystem services. From an industrial perspective, profitability is a necessary science outcome, so research priorities may include investigations into biomolecules, synthetic pathways, and other marketable technologies with protection of intellectual property and minimal restrictions. Although the aims and priorities of these groups may differ, collaboration will multiply the value of marine microbiome research into innovative products and services.

The potential for biodiscovery in the marine environment remains largely untapped due to the sheer size of the ocean realm and the inaccessibility of areas such as the deep sea. Furthermore, the search for bioproducts has largely been limited to single microbial types, rather than the microbiome as a whole. Such a narrow focus limits prospects for discovery, as 1) few marine microbes can be cultivated in isolation and 2) bioactive compounds may be produced only when multiple microorganisms interact as a community. Consequently, microbiome-scale biodiscovery is a promising and challenging task that will be best accomplished through multidisciplinary collaboration.

Goals

- Support the science of marine microbiome biodiscovery
- Demonstrate the value of microbiome research and development to resource and industrial managers for solving their current and near-term management needs
- Inspire marine microbiome entrepreneurship, develop the next generation of innovators, and stimulate job growth
- Facilitate Open Innovation and Technology Transfer through early connections between science and industry

Specific Objectives

- Go beyond traditional bioprospecting that focuses on single microorganisms, towards discovering biological compounds that are obtained only through complex interactions involving whole microbiome communities
- Create the basic framework to incorporate microbiomes into environmental monitoring approaches and practices through the development of standardized sampling technologies and protocols and establishment of recognized thresholds
- Develop methods to analyze and model microbiome communities, including metabolic profiles, and take full advantage of post-genomic technologies, such as shotgun metagenomes, transcriptomes, proteomes, single cell genomes, metabolomes, and synthetic biology along with bioinformatic analysis pipelines
- Manipulate and bioengineer microbiome products that ensure the sustainable use of marine bioresources
- Ensure open access and benefit sharing in balance with agreements and negotiations to protect intellectual property, that is needed to enter into industry partnerships to meet Cross-Cutting Challenges

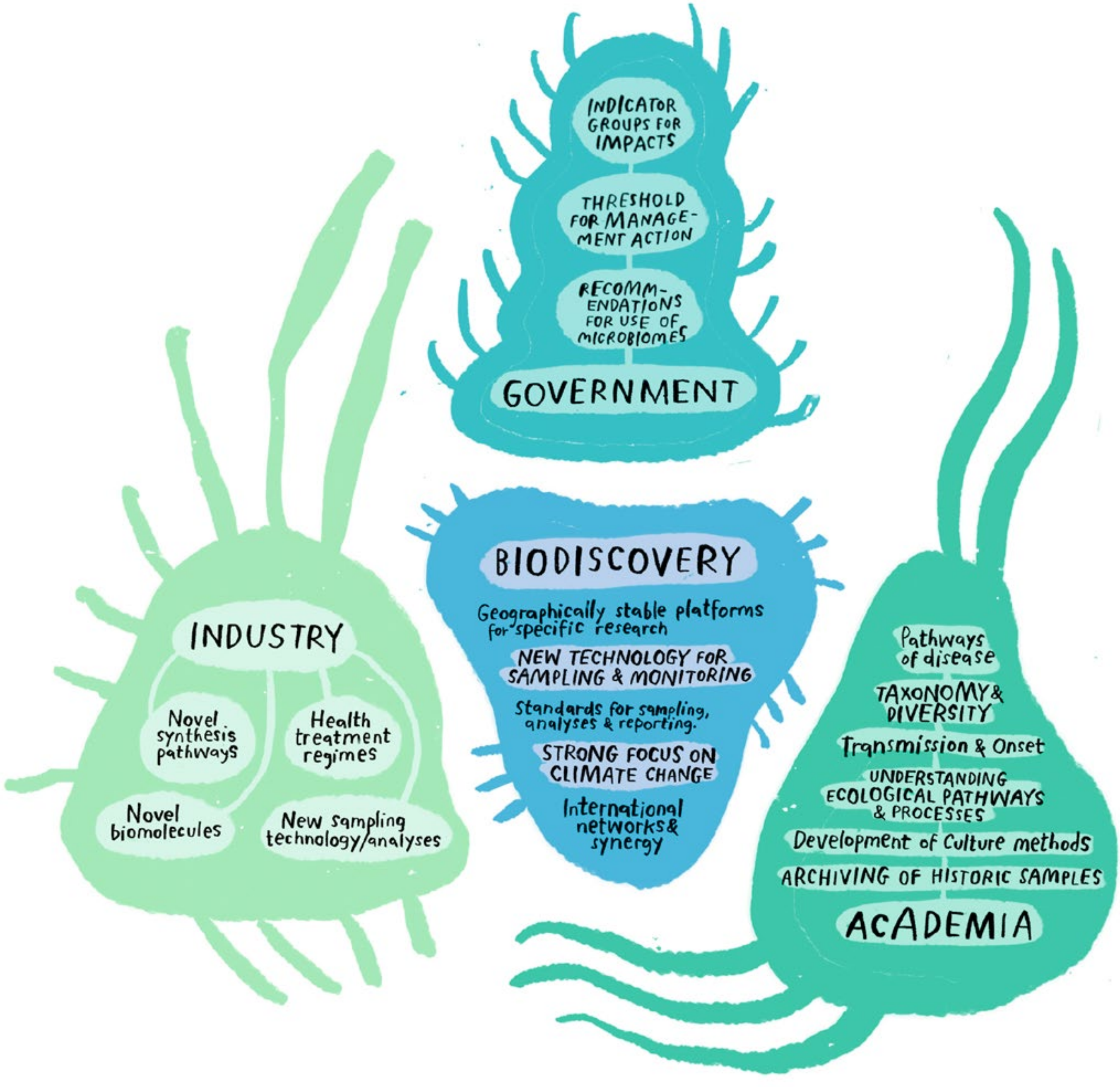
ACTION ITEMS

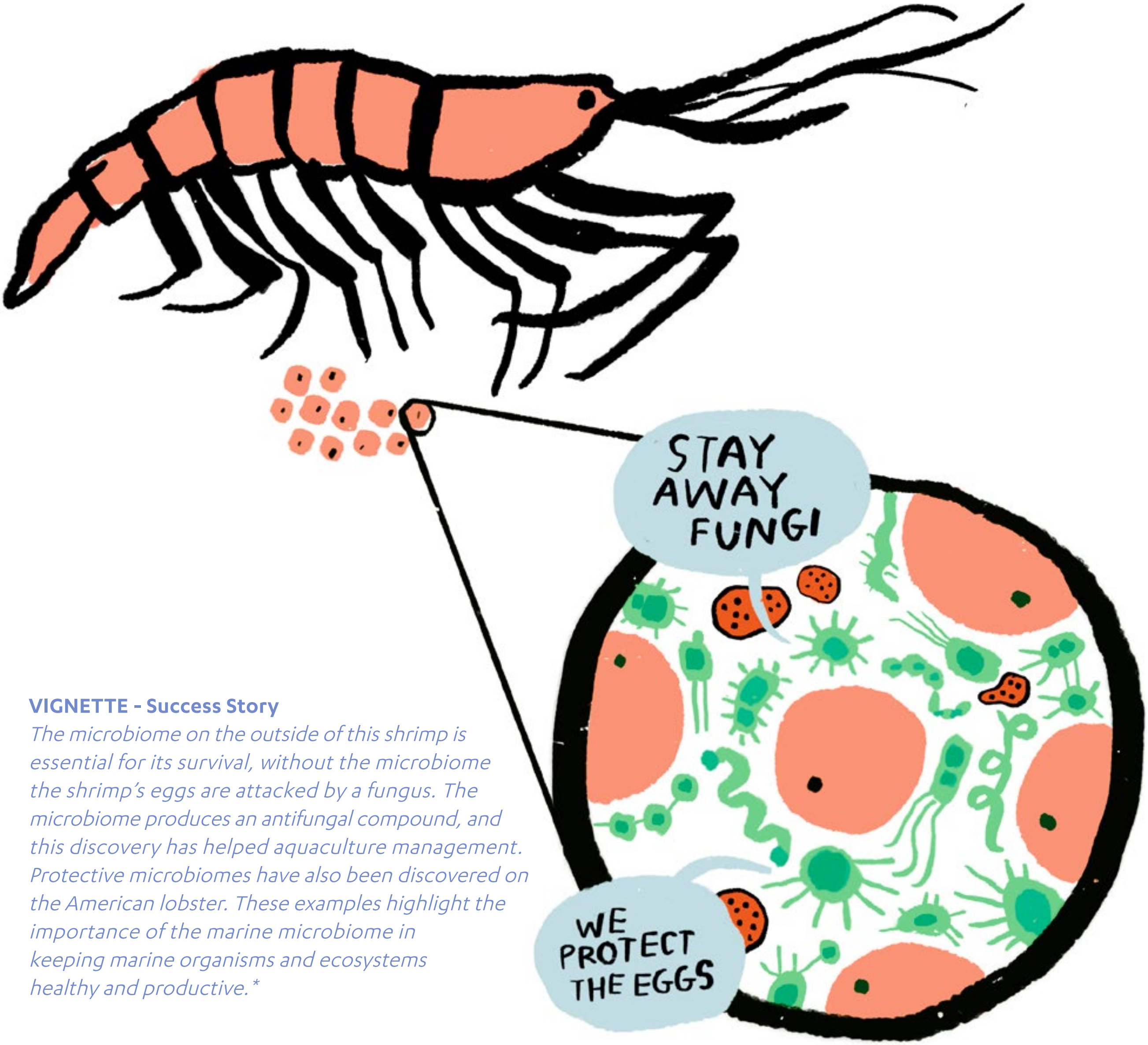
Short Term

- Identify champions to support the advancement of marine microbiome discovery
- Develop a portfolio analysis with an eye on creating connections and leveraging opportunities between government, academia, and industry, as well as using the input of special interest groups like NGOs, and the general public

Medium Term

- Implement demonstration project(s) using engaged stakeholders to model the biodiscovery process, including navigation of contractual obligations and connection to industry partners
- Provide access to technical training (bioinformatics, etc.) and opportunities that inspire entrepreneurship


INDICATOR GROUPS FOR IMPACTS
THRESHOLD FOR MANAGEMENT ACTION
RECOMMENDATIONS FOR USE OF MICROBIOMES
GOVERNMENT
BIODISCOVERY
Geographically stable platforms for specific research
NEW TECHNOLOGY FOR SAMPLING & MONITORING
Standards for sampling, analyses & reporting.
STRONG FOCUS ON CLIMATE CHANGE
International networks & synergy
INDUSTRY
Novel synthesis pathways
Health treatment regimes
Novel biomolecules
New sampling technology/analyses
Pathways of disease
TAXONOMY & DIVERSITY
Transmission & Onset
UNDERSTANDING ECOLOGICAL PATHWAYS & PROCESSES
Development of Culture methods
ARCHIVING OF HISTORIC SAMPLES
ACADEMIA



VIGNETTE - Success Story

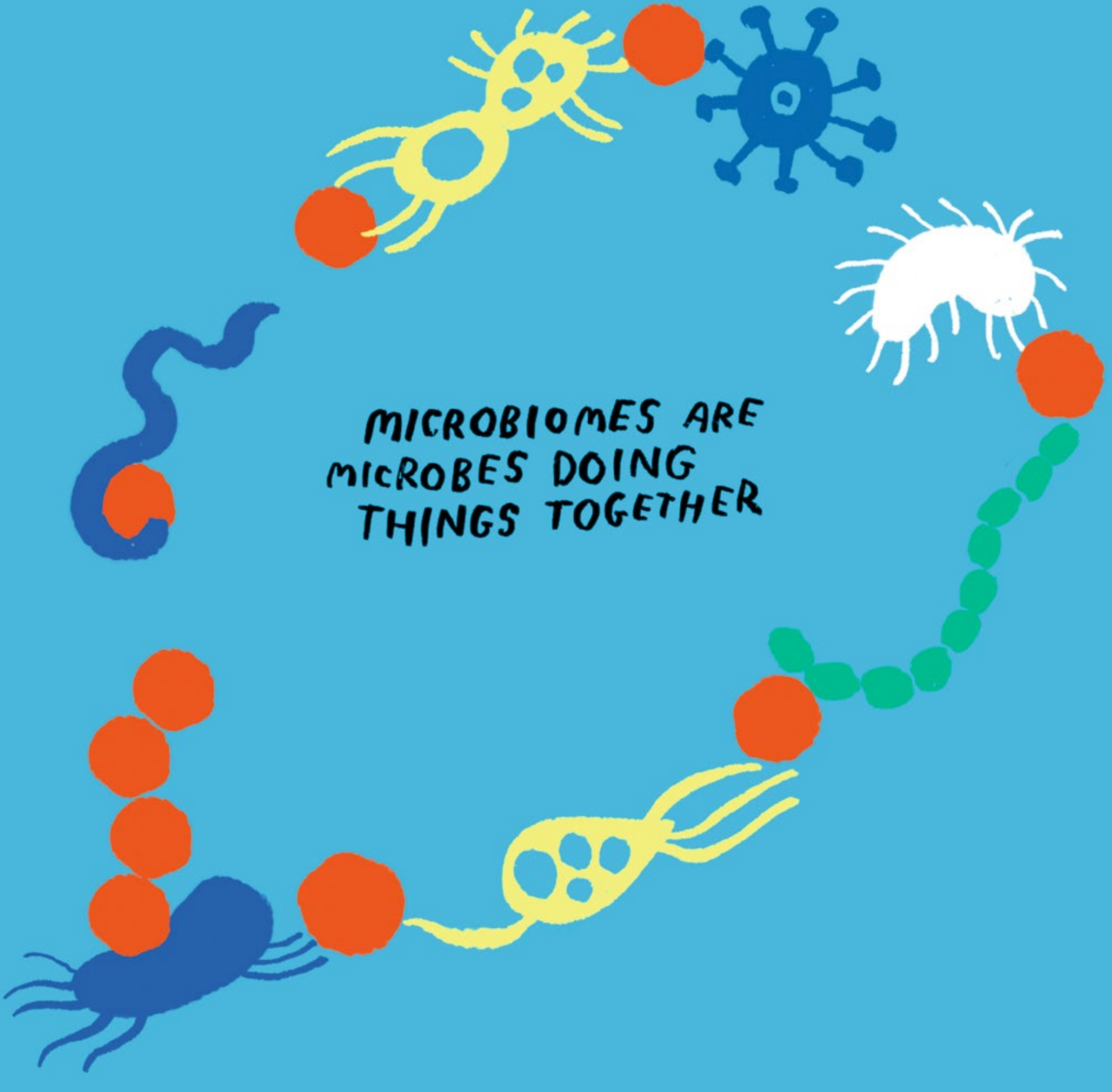
*The microbiome on the outside of this shrimp is essential for its survival, without the microbiome the shrimp's eggs are attacked by a fungus. The microbiome produces an antifungal compound, and this discovery has helped aquaculture management. Protective microbiomes have also been discovered on the American lobster. These examples highlight the importance of the marine microbiome in keeping marine organisms and ecosystems healthy and productive.**

Long Term

- Develop research projects to address priority topics to conduct the science and engineering needed to prime the research transition pipeline, with encouragement of small-medium enterprises
- Identify and develop guidelines and alliances to balance the need for open access to data and the need by industry to protect business interests in creating value from marine microbiomes through bioprospecting
- Communicate results to familiarize managers and policy makers about the microbiome and to develop management strategies that encompass ecosystems rather than single

Priority List of sites to investigate:

- Extreme environments: heat, cold, saline, pH, pressure
- Natural oil and gas seeps
- Impacted: oil, chemicals, livestock (antibiotic resistance, pathogens, virulence factors)
- Bioreactors (waste treatment, industrial)
- Marine aquaculture or other food production, including algae
- Sites with high microbial carbon capture and sequestration
- Environments at risk of disappearing


MICROBIOMES ARE
MICROBES DOING
THINGS TOGETHER

CROSS-CUTTING CHALLENGES

Vision Statement:

Addressing cross-cutting challenges will unlock the potential for a microbiome-based blue economy, leading to high quality food products, biological discoveries, and healthy marine ecosystems

Challenge 1

Demonstrate the socio-economic value of marine microbiomes

The socio-economic value of sustainable food production, biodiscovery, and climate change mitigation is widely recognized. Our challenge is to demonstrate how marine microbiomes contribute to these activities.

We must translate the science of marine microbiomes into investable propositions, such as

- discover and produce pharmaceutical products from marine microbiomes
- manipulate the gut and skin microbiomes of fish to enhance food production
- forecast changes in the cycling of carbon by ocean microbiomes and its impact on climate change[5]

Challenge 2

Increase our capacity to share infrastructures

A needs-based approach for microbiome research is required to address local and global scale challenges with the successful engagement of science, industry, policy, NGOs, civil society and citizens.

We must increase our capacity to mobilise and share existing infrastructures across these sectors in order to

- explore at basin scale, e.g. sampling from research, merchant, and citizen boats
- monitor at local scale, e.g. coordinating marine stations, oil platforms, and wind farms
- engineer solutions, e.g. sharing use of biobanks, analytical tools, mesocosms and bioreactors

[5] *"Cycling of carbon" refers to the uptake and respiration of CO2, its transfer to pelagic (water column) and benthic (seabed) food webs (e.g. supporting fish, corals, seaweed), or its sequestration in sediments.*

Challenge 3
Transfer technology across science and industry

The study of the human gut microbiome led to holistic health diagnostics and innovative treatments in just over a decade. Marine microbiomes offer the same potential to transform ocean science.

We must ride the technology wave and transfer its potential by

- rapidly adopting next generation genomics and imaging methodologies
- embarking genetic and bio-optical sensors on autonomous sampling vehicles
- using bioinformatics, artificial intelligence, and complex systems modelling

Challenge 4
Assess the risks and ethics related to microbiome science & technology

Solutions to local and global problems may involve manipulating abiotic conditions (e.g. nutrients) and modifying the genetic code of microbes in controlled or natural environments.

We must act responsibly and assess the risks and ethics of technological solutions, including evaluation of issues such as

- using genetically modified microbes to enhance food production
- modifying the composition of microbiomes to prevent harmful algal blooms
- fertilising the ocean to favour microbiomes that mitigate climate change

Challenge 5
Preserve bio-resources and share their benefits

The UN Convention on Biological Diversity (CBD) set out the Nagoya protocol on access to genetic resources and the fair and equitable sharing of benefits arising from their utilisation.

We must guide science and industry in addressing the CBD, fostering

- long-term preservation in biobanks
- proper documentation of rights for redistribution
- full traceability of their use and benefits

Challenge 6
Spark fascination about marine microbiomes

Communication about ocean science tends to focus on large-size, charismatic organisms such as whales, sharks, octopuses, lobsters or starfish. It is time to learn about the marine microbiomes.

We must contribute to ocean literacy, working with

- artists and aquariums on developing concepts for charismatic marine microbes
- schools and citizen science programmes linked to pleasure and sport sailing
- the World Microbiome Day to bring attention on marine microbiomes

Challenge 7
Develop standards and common methodologies

The study of marine microbiomes combines classical microbiological techniques with next-generation genomics and modeling, which generates a wealth of heterogeneous knowledge in need of integration.

We must adopt common methodologies that are

- coherent across exploration, monitoring and engineering activities
- adaptable to the capacity of the different sectors (science, industry & citizens)
- interoperable and fit for integrative science

Challenge 8
Adopt best practices and the FAIR principles for scientific data

Over the last decade, Europe, Canada and the U.S.A. developed number of research infrastructures aimed at making knowledge Findable, Accessible, Interoperable and Re-usable (FAIR).

We must promote research infrastructures and train science and industry in using

- data services, including ontologies, long-term preservation and interoperability
- cloud computing services that allow big data assembly and shared analysis pipelines
- discovery services such as text mining, linked publications and bibliometrics

Cross-cutting Research Infrastructures

	Genomic data	Cloud Computing	Open Access
Europe	elixir	egi	OpenAIRE
Canada	GenomeCanada	compute canada / calcul canada	CARL ABRC
USA	NCBI	Open Science Grid	COS Center for Open Science

COORDINATION & SUPPORT ACTIONS

The keystone to implementing AORA's marine microbiome roadmap is to support and coordinate the actions proposed by the three pillars and to address their cross-cutting challenges. The AORA proposes the creation of a Blue Microbiome secretariat that would work closely with the recently funded Food Microbiome CSA (https://www.microbiomesupport.eu/). It would support the UN Decade of ocean science for sustainable development[6] and the research and innovation projects that implement the Galway and Belém Declarations.

Tri-lateral Horizon 2020 projects with microbiome components			
2016-2020	AtlantOS	atlas	SponGES
2019-2023	TRIATLAS	iAtlantic	AquaVitae
2020-2024	MISSION ATLANTIC	AtlantECO	ASTRAL

Coordination and support actions include:

- engaging actors across science, industry, policy, advocacy and education sectors, and directly involving social scientists, economists and professional communicators
- organising training, mobility, mentorships and ambassadors programmes, particularly with the least developed countries, early career researchers and young professionals
- contributing to the UN Decade's (i) ocean literacy programme, (ii) clearing house mechanism for needs-based capacity development and technology transfer, and (iii) Digital Atlas for Ocean Science

[6] *On 5 December 2017, the United Nations proclaimed a Decade of Ocean Science for Sustainable Development, to be held from 2021 to 2030 (https://www.oceandecade.org/).*

Innovation Actions

Supporting Literature

For supporting literature and further information see http://www.atlanticresource.org

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ATLANTIC OCEAN RESEARCH ALLIANCE

Everything about microscopic life is terribly upsetting.
How can things so small be so important?
— Isaac Asimov

MAKING IT POSSIBLE

The Galway Statement on Atlantic Ocean Coopeeration between the European Union, Canada and the United States of America