Food and Agriculture
Organization of the
United Nations

NFIF/C1387 (En)

FAO
Fisheries and
Aquaculture Circular

ISSN 2070-6065

CURRENT AND FUTURE GENETIC TECHNOLOGIES FOR FISHERIES AND AQUACULTURE: IMPLICATIONS FOR THE WORK OF FAO

Cover image: © FAO/Image Kurt Arrigo adapted by William Perry.

FAO Fisheries and Aquaculture Circular No. 1387 NFIF/C1387 (En)

CURRENT AND FUTURE GENETIC TECHNOLOGIES FOR FISHERIES AND AQUACULTURE: IMPLICATIONS FOR THE WORK OF FAO

by

Friedman, K.J.
FAO Fisheries and Aquaculture Division

Bartley, D.M.
World Fisheries Trust (Canada) &
Michigan State University

Rodríguez-Ezpeleta, N.
AZTI Basque Research and Technology Alliance

Mair, G.C.
FAO Fisheries and Aquaculture Division

Ban, N.
University of Victoria

Beveridge, M.
FutureFish

Carolsfeld, J.
World Fisheries Trust (Canada)

Carvalho, G.
Bangor University

Cowx, I.
University of Hull

Dean, G.
Organic Ocean Seafood Inc.

Glazov, E.
Illumina Australia Pty Ltd

Leber, K.
Mote Marine Laboratory

Loftus, R.
IdentiGEN Ltd

Martinsohn, J.
European Commission Joint Research Centre

Olesen, I.
Nofima

Soto, D.
Interdisciplinary Center for Aquaculture Research

Van Eenennaam, A.L.
University of California

Vigar, J.R.J.
University of Toronto

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS
Rome, 2022

Required citation:
Friedman, K.J., Bartley, D.M., Rodríguez-Ezpeleta, N., Mair, G.C., Ban, N., Beveridge, M., Carolsfeld, J., Carvalho, G., Cowx, I., Dean, G., Glazov, E., Leber, K., Loftus, R., Martinsohn, J., Olesen, I., Soto, D., Van Eenennaam, A.L. & Vigar, J.R.J. 2022. *Current and future genetic technologies for fisheries and aquaculture: implications for the work of FAO.* FAO Fisheries and Aquaculture Circular. No. 1387. Rome, FAO. https://doi.org/10.4060/cc1236en

The designations employed and the presentation of material in this information product do not imply the expression of any opinion whatsoever on the part of the Food and Agriculture Organization of the United Nations (FAO) concerning the legal or development status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. The mention of specific companies or products of manufacturers, whether or not these have been patented, does not imply that these have been endorsed or recommended by FAO in preference to others of a similar nature that are not mentioned.

The views expressed in this information product are those of the author(s) and do not necessarily reflect the views or policies of FAO.

ISBN 978-92-5-136716-2
ISSN 2070-6065

© FAO, 2022

Some rights reserved. This work is made available under the Creative Commons Attribution-NonCommercial-ShareAlike 3.0 IGO licence (CC BY-NC-SA 3.0 IGO; https://creativecommons.org/licenses/by-nc-sa/3.0/igo/legalcode).

Under the terms of this licence, this work may be copied, redistributed and adapted for non-commercial purposes, provided that the work is appropriately cited. In any use of this work, there should be no suggestion that FAO endorses any specific organization, products or services. The use of the FAO logo is not permitted. If the work is adapted, then it must be licensed under the same or equivalent Creative Commons licence. If a translation of this work is created, it must include the following disclaimer along with the required citation: “This translation was not created by the Food and Agriculture Organization of the United Nations (FAO). FAO is not responsible for the content or accuracy of this translation. The original [Language] edition shall be the authoritative edition.”

Disputes arising under the licence that cannot be settled amicably will be resolved by mediation and arbitration as described in Article 8 of the licence except as otherwise provided herein. The applicable mediation rules will be the mediation rules of the World Intellectual Property Organization http://www.wipo.int/amc/en/mediation/rules and any arbitration will be conducted in accordance with the Arbitration Rules of the United Nations Commission on International Trade Law (UNCITRAL).

Third-party materials. Users wishing to reuse material from this work that is attributed to a third party, such as tables, figures or images, are responsible for determining whether permission is needed for that reuse and for obtaining permission from the copyright holder. The risk of claims resulting from infringement of any third-party-owned component in the work rests solely with the user.

Sales, rights and licensing. FAO information products are available on the FAO website (www.fao.org/publications) and can be purchased through publications-sales@fao.org. Requests for commercial use should be submitted via: www.fao.org/contact-us/licence-request. Queries regarding rights and licensing should be submitted to: copyright@fao.org.

PREPARATION OF THIS DOCUMENT

This publication offers insights into the likely implications of new genetic technologies on the fisheries and aquaculture sector over the next 10 years. An expert elicitation exercise was conducted by Drs D.M. Bartley and J. Carolsfeld with specialists in the fields of genetics, genomics, fisheries, aquaculture and conservation. The interview process requested experts to articulate the expected changes and likely responses the Food and Agriculture Organization (FAO) of the United Nations may consider, thus preparing FAO's Membership for such changes. Expert responses were collated into four key thematic areas: fishery stock management, genetic improvement and domestication, improved trade, marketing and traceability, biodiversity & ecosystems, in addition to the overarching theme of governance. The collation was returned to a subset of experts and FAO staff for further review, additional inputs and to refine the report, which is presented here. The thematic areas of work and the experts' suggestions are provided as a first step for FAO, helping to inform policy and practice surrounding the shifts in the availability, accessibility and impacts of genetic technologies for fisheries and aquaculture. Dr N. Rodríguez-Ezpeleta also provided text suggestions and boxed examples of how genetic technologies improve fisheries and aquaculture.

ABSTRACT

Within the last few decades, advances in genetic technologies have created powerful and efficient tools for fisheries stock identification, genetic improvement and domestication of aquaculture species and characterization of changes in aquatic life due to environmental or anthropogenic influences. Emerging genetic tools are improving our understanding of organisms in aquatic ecosystems, in terms of diversity, distribution, abundance, movement, function and adaptation, and are being applied in aquaculture facilities and across fishery and aquaculture value chains.

In this study expert[1] elicitation was used to examine and predict current and potential future (10 year) impacts of the application of these novel technologies in fisheries and aquaculture. Highlighting the need to prepare sectors for likely changes that will follow. All suggestions received were collated into themes, to provide a conceptual framework that partitions potential impacts, and calls for required action — action required on governance, management and practical application of these innovations at both a national and international level.

A range of fundamental shifts in fisheries and aquaculture were suggested as a result of the advancement and application of cost-effective genetic technologies. The advice highlighted both positive and negative impacts, including:

- increased understanding of genetics and basic biology that will provide better insight into how genes function in the organism, the production system and in the ecosystem;
- characterization of fishery stocks increasingly informed by genetic information rather than geo-politics, which will assist, but likely also challenge, traditional fisheries management;
- increased understanding by aquaculturists and breeders, of genes and gene sequences, with access to synthetic biology that will result in the creation of improved farmed types, and probably their privatization;
- ability of aquaculturists to produce aquatic species in more environments, more efficiently and according to market demand, stemming from the ability of growers to ensure farmed types more precisely meet local conditions and consumer preferences;
- increased ability for compliance in fisheries and aquaculture along the full production value chain, with the ability to identify fisheries and aquaculture products and their origin through more accurate and informative genetic traceability analyses;
- advancement of ecosystem studies, using a range of technologies including environmental DNA (eDNA), to improve ecosystem management, rehabilitation actions, and present potential challenges on how to characterize and manage synthetic biology.

Such technologies will provide a clearer view of the fundamental building blocks of aquatic life, resulting in novel actions and new opportunities. However, such advances will also challenge managers in terms of using these novel technologies, but also in responding to the implications of their use across value chains.

Expert advice on the impacts of genetic technologies were collated, including actions needed to address those impacts for management and conservation in fisheries and aquaculture. Within its mandate for fisheries and aquaculture, the role FAO will need to play in providing support for its Membership in addressing present and future issues is considered, although it was recognized that no one organization could address them all. This report outlines potential future steps for, and requirements of, international development, conservation communities, national governments, industry and civil society, with need to further support the fishery and aquaculture sector through transformations brought about by rapidly developing genetic technologies.

---

[1] Experts interviewed came from fisheries, aquaculture, quantitative and molecular genetics as well as food production and trade.

CONTENTS

TABLES

FIGURE

BOXES

ACKNOWLEDGEMENTS

The following experts are gratefully acknowledged for contributing their time and expertise in the interviews and in reviewing this document: Natalie Ban, Devin Bartley, Malcolm Beveidge, Gary Carvalho, Ian Cowx, Guy Dean, Evgeny Glazov, Kenneth Leber, Ronan Loftus, Graham Mair, Jann Martinsohn, Ingrid Olesen, William Perry, Tad Sonstegard, Doris Soto, Alison Van Eenennaam, and Justin Vigar.

GLOSSARY OF ABBREVIATIONS, ACRONYMS AND COMMON TERMINOLOGY

CKMR	Close-Kin Mark-Recapture
CITES	Convention on International Trade in Endangered Species of Wild Fauna and Flora
DNA	Deoxyribonucleic Acid
eDNA	Environmental DNA
GMO	genetically modified organism
GE	genetically engineered
GSI	genetic stock identification
ICCAT	International Commission for the Conservation of Atlantic Tunas
IUU	illegal, unreported and unregulated
RRI	Responsible Research and Innovations
SNP	single nucleotide polymorphism
SSB	spawning stock biomass

Term	Definition/explanation
Biodiversity / Biological diversity	The variability among living organisms from all sources including, *inter alia*, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems (Convention on Biological Diversity).
Close-Kin Mark-Recapture (CKMR)	A method based on the principle that an individual's genotype can be considered a "recapture" of the genotypes of each of its parents. Assuming the sampling of offspring and parents is independent of each other, the number of Parent-Offspring pairs genetically identified in a large collection of both groups can be used to estimate abundance (see Box 3, reference Bravington *et al.* 2016).
CRISPR	Acronym for "clustered regularly interspaced short palindromic repeats", a family of DNA sequences found in the genomes of organisms. Cas9 (or "CRISPR-associated protein 9") is an enzyme that uses CRISPR sequences as a guide to recognize and cleave specific strands of DNA that are complementary to the CRISPR sequence. Cas9 enzymes together with CRISPR sequences form the basis of CRISPR-Cas9 technology, and offers a biochemical method to efficiently cut and edit DNA (edit genes within organisms).
DNA sequencing	Detecting the sequence of the four bases (adenine, thymine, guanine, cytosine) as the code of genetic information.
DNA synthesis	Process of creating natural or artificial DNA molecules.
Domestication	Aquatic species are considered domesticated when they show the first results of selective breeding or, when no such evidence is found, after at least three successive cycles of reproduction (generations) under controlled conditions. Domestication is a process and when an organism is "domesticated" it can be interpreted differently by different scientists (Bilio, 2007; Teletchea 2021). FAO identifies three states of domestication among its definitions of farmed types (Mair and Lucente, 2020).

Term	Definition/explanation
Environmental DNA (eDNA)	Aquatic species leave traces of their DNA in surrounding waters through, for example, feces, saliva, urine and skin cells. This extra-organismal DNA can be collected from water samples and analyzed (Rees *et al.* 2014).
Effective population size (N_e)	The number of individuals that effectively participate in producing the next generation. Generally, the effective size of a population is considerably less than the census size. A group of 1000 males only would have an N_e of 0 because they alone could not produce the next generation (Harmon and Braude, 2010; Pearson, 2013).
Farmed Type	Farmed aquatic organisms that could be a strain, hybrid, triploid, monosex group, variety, wild type or other genetically altered form (FAO, 2019a).
Fish	In this document the word "fish" is used as a collective term, that includes fish, molluscs, crustaceans and any aquatic animal which is harvested.
Gene drive	A gene drive is a natural process and technology of genetic engineering, adding, deleting, disrupting, or modifying genes, and propagating particular genes throughout a population by altering the probability that a specific variant of a given gene will be transmitted to offspring (instead of the Mendelian 50 percent probability).
Gene edited organism	1. A farmed type created by the targeted insertion, deletion or replacement of DNA at a specific site in the genome that is inherited by its offspring (FAO, 2019a). 2. Genetic engineering techniques that involve DNA repair mechanisms for incorporating site-specific modifications into a cell's genome (FAO, 2022a).
Genetically modified organism (GMO)	1. Organisms that have been transformed by the insertion of one or more transgenes (FAO 2022a). 2. Genetic material is modified artificially to give it a new property (European Commission, 2022a). Also known as "living modified organism" (LMO), an organism whose characteristics have been changed by genetic engineering (contrasting classical selection experiments or naturally by mating and/or recombination, see IUCN (Redford *et al.* 2019)).
Genetic stock identification	The use of population genetic data to determine the stock composition of a mixed stock fishery or to identify an individual stock of aquatic species (Milner *et al.* 1985).
Genetic technologies	The term genetic technologies has many definitions. For use in this report, modern "genetic technologies" largely focusses on novel techniques for finding and "reading" genetic material, in addition to recombinant and other DNA manipulating technologies, such as genome engineering as part of synthetic biology. However, for comparative assessments, the report also touches on the use of conventional breeding practices that largely still dominate fisheries and aquacultures efforts in improving genetic fitness in aquatic animals and plants.
Genome	1. An organism's entire genetic make-up. The entire complement of genetic material (genes plus non-coding sequences) present in each cell of an organism, virus or organelle (Tave, 1995). 2. The complete set of chromosomes inherited as a unit from one parent (see FAO, 2022b).
Genotype	1. a) The genetic constitution of an organism. b) The allelic constitution at a particular locus, e.g. Aa or aa. c) The sum effect of all loci that contribute to the expression of a trait (FAO, 2022b). 2. The genetic make-up of an organism at the locus (or loci) that produces a specific phenotype (Tave, 1995).
Phenotype	The composite observable characteristics or traits of an organism. An organism's phenotype results from two basic factors: the expression of an organism's genotype (genetic code), and the influence of environmental factors (FAO 2022a).

Term	Definition/explanation
Stock	A group of individuals in a species occupying a well-defined spatial range independent of other stocks of the same species. Random dispersal and directed migrations due to seasonal or reproductive activity can occur. Such a group can be regarded as an entity for management or assessment purposes (FAO, 2019a).
Strain	A farmed type of aquatic species having relatively homogeneous appearance (phenotype), homogeneous behaviour, breeding history and/or other characteristics that distinguish it from other organisms of the same species in that country, and that can be maintained by propagation (FAO, 2019a).
Synthetic Biology	A further development and new dimension of modern biotechnology that combines science, technology and engineering to facilitate and accelerate the understanding, design, redesign, manufacture and/or modification of genetic materials, living organisms and biological systems (UN CBD, 2017).

Introduction

History and context of genetics in fisheries and aquaculture[2]

Rapidly advancing genetic technologies[3] have the potential to produce fundamental and transformational changes in the way living organisms are characterized and modified. The technological and theoretical explosion surrounding genetic technologies will impact how social and ecological systems are monitored and managed, while also impacting on how food is produced, marketed and traded, especially as the cost of these technologies reduce, making them more accessible. Utilising aspects of an organism's genetics is not a new phenomenon, as domestication of crops began over 10 000 years ago, and domestication of livestock began over 5 000 years ago. Aquaculture was thought to have started in earthen ponds in China 8 000 years ago, with an independent origin of aquaculture occurring in medieval Europe, and more recently, aquaculture has included genetic improvement and domestication of a wide range of aquatic species (Clutton-Brock, 2012; Harland, 2019). The production of farmed aquatic animals continues, growing at an average of 5.3 percent in recent years (2001–2018). Presently, this production mostly relies on altering the traits of wild species and their near relatives using traditional breeding.

Despite this, the scope applying novel genetic technologies is increasing. In aquaculture, current production mostly relies on farmed types that remain largely unchanged from their wild relatives, as the adoption of traditional selective breeding and other established genetic technologies is proceeding slowly. Only 10–15 percent of production is thought to be derived from well-managed breeding programmes (FAO, 2019a). FAO recently reported in its global assessment on aquatic genetic resources (AqGR) (FAO, 2019a) that countries are currently not taking full advantage of available genetic technologies, including their use in more traditional breeding programmes. Other reviews have echoed these sentiments, finding that genetic technologies used in fisheries and aquaculture could positively impact food security, economies, and conservation, but are not being taken up or fully utilized (Bernatchez *et al.* 2017). In the case of fisheries, where total global production has reached the highest level ever recorded at 96.4 million tonnes (2018 data, see FAO 2020), some inadvertent genetic modification of aquatic species has been recorded, caused by fisheries induced change (Hutchings and Kuparinen, 2019). Additionally, although not making up a significant part of global catches, restocking of fisheries can rely on artificial rearing and breeding of seed or juveniles, and can cause inadvertent genetic modification.

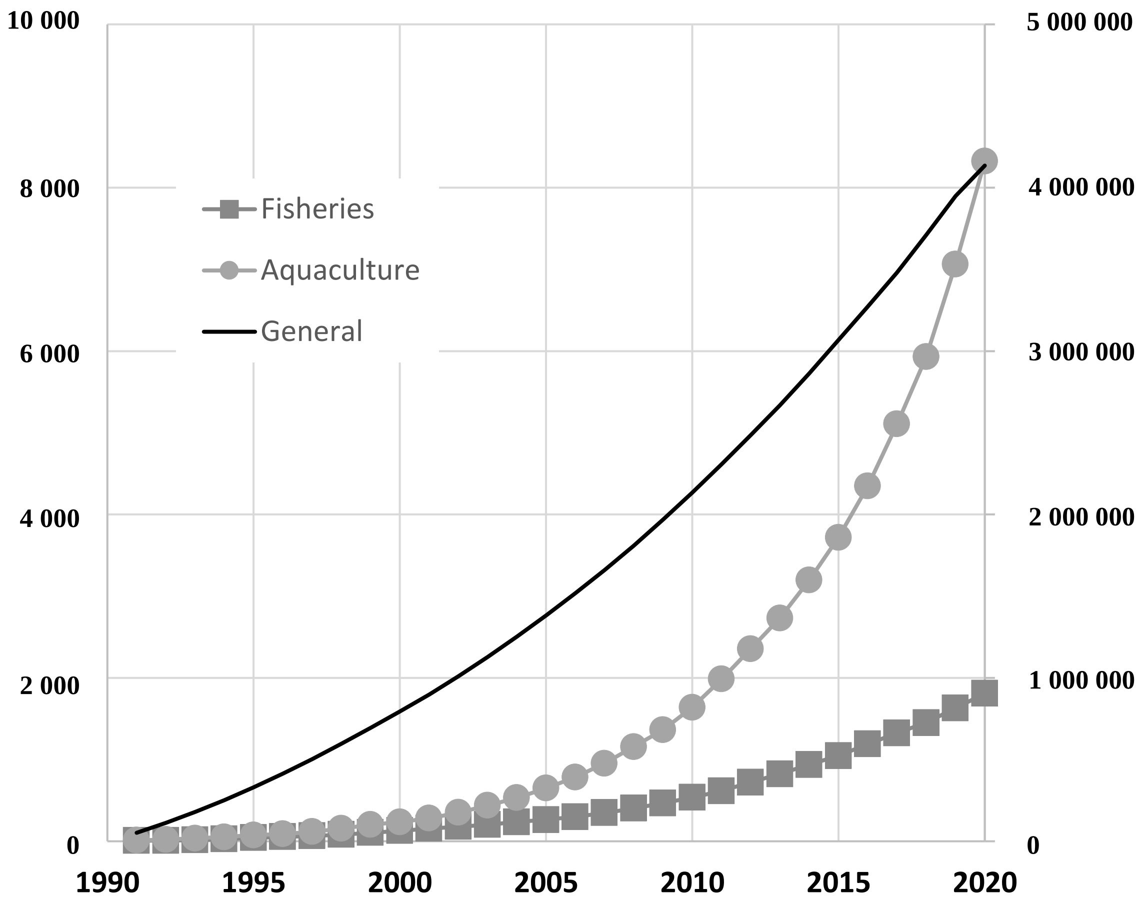
Genetic technologies offer extremely powerful and efficient tools for characterization of life and life traits, and a clearer vision of how genes, and by extension, organisms, interact with the environment (Bernatchez *et al.* 2017; ICES 2018; Ovenden *et al.* 2015). The intentional modification of genomes has been accelerating as we gain greater insight into the structure and function of genes, as well as greater insight into fundamental genetic processes. Many advances derive from applications of genome-wide sequencing and analyses (genomics) initially developed in the context of human health and medicine (Bernatchez *et al.* 2017). These are now coupled with a new generation of tools and rapidly evolving processes for gene editing. The fisheries and aquaculture community are now gaining access to a range of more powerful and informative tools for specific applications across individuals, species, farmed types, populations, communities and ecosystems. The research community's interest in understanding genetics and genetic technologies is represented by a rise in related scientific publications, which often foreshadows general application. This is especially true in the field of aquaculture but is also starting to make inroads into fisheries management (Figure 1). A growing interest in the advance of modern genetics in fisheries management and aquaculture is undoubtedly a precursor to greater adoption and adaptation of these technologies, which is leading to rapid innovation in practices on the ground.

---

[2] In this document the word "fish", where used, is used as a collective term that includes fish, molluscs, crustaceans, and any aquatic animal which is harvested.

[3] The term genetic technologies has many definitions. In this report the term, modern "genetic technologies" largely focusses on novel techniques for finding and "reading" genetic material, as well as recombinant and other DNA manipulating technologies, including genome engineering as part of synthetic biology. For comparative assessments, the report also refers to conventional breeding practices that still dominate fisheries and aquacultures efforts in improving aquatic organisms.

Figure 1. Cumulative number of genetic related papers published per year on fisheries assessment and management (squares) and on aquaculture (circles) (primary axis, left hand side)



Numbers were obtained by searching the terms "((fishery OR fisheries) AND (assessment OR management) AND (genomics OR genetics OR DNA OR gene or genome))" and "(aquaculture AND (genomics OR genetics OR DNA OR gene OR genome))" for the years 1991 to 2020 (both included) using primary literature in Web of Knowledge. Number obtained by searching using the term "(genomics OR genetics OR DNA OR gene OR genome)" overall published papers for the same period (general line) are provided on a second axis (right hand side) for comparison purposes.

In recent decades, the field of genomics has been transformed from a discipline seeking its first glimpses into genome sequences across the Tree of Life to a global enterprise with ambitions to sequence genomes for all of Earth's diverse life forms (see global databases figure in Economist, 2021). For aquatic species, representation, assembly quality, and annotation status is broadening, especially for global representation of aquatic species (primarily class Actinopterygii, see Fig. 1 of Hotaling, Kelley and Frandsen 2021). The genetic code of life, DNA, is now being routinely analyzed for a range of commercially important aquatic species. This information has enabled better identification and understanding of organisms, including their phenotypic expression, abundance and behaviour. More dynamically, the process of selective breeding for long-term genetic improvement and domestication is accelerating, albeit relatively slowly, for many important aquaculture species. Indeed, we are starting to see examples of genes being identified and selected for due to their link with a desired trait within some of the larger and more mature breeding programmes, such as in salmon breeding.

Furthermore, gene editing (addition, removal, modification, or replacement of genes in the genome of a living organism) is the subject of much research and has the potential to further enhance genetic improvement in aquaculture. Direct changes can be engineered so that new traits are passed to future generations or are only expressed in infertile offspring. In fisheries management, the value of understanding and using genetic information is also being increasingly recognized. It has been effective for stock delineation and for providing invaluable information for better characterizing exploited resources in market chains and identifying rare and endangered species. All of which is essential for promoting sustainable catch limits, traceability and legality across the full value chain.

Despite the advances, as genes, gene products and related technologies are commodified, the global community needs to carefully consider both potential future benefits and challenges (see Fig. 2 in Redford *et al.* 2019). The business of managing, capturing, producing, and marketing aquatic food will change in response to access to novel genetic technologies and associated, previously unavailable, information. As genetic information and capacity to work in these fields becomes increasingly valued, and tradable, there will be greater need for consultation on agreed access and use of AqGR, including relevant sequence data, and the sharing of benefits derived from them. Additionally, improved understanding of the risks and benefits of new genetic technologies is also still required, as accurate awareness of the drawbacks or limitations of these technologies is considered low (Prince and Berkman, 2018), with widespread misinformation in circulation (Ovenden *et al.* 2015; Bernatchez *et al.* 2017; Prince and Berkman, 2018). Improved governance of, and support for the safe and orderly use of, these technologies and their products should therefore be given priority.

Aquatic genetic resources have attracted an increasing amount of commercial interest, as indicated by the emerging patent activity in this area (WIPO, 2019; Blasiak *et al.* 2018). International instruments addressing these issues include the *Convention on Biological Diversity* and the *Nagoya Protocol on Access to Genetic Resources and the Fair and Equitable Sharing of Benefits Arising from their Utilization to the Convention on Biological Diversity.* An international legally binding instrument, currently being negotiated under the United Nations Convention on the Law of the Sea (UNCLOS) on the conservation and sustainable use of marine biological diversity of areas beyond national jurisdiction (BBNJ), might also address benefit-sharing of marine (AqGR).

Genetic technologies are becoming more powerful and have great potential to promote the sustainable use and thus better conservation of the world’s aquatic biodiversity for food and aquaculture. The progressive advance from traditional genetics, to genomics, where genome-wide sequences can be explored more effectively, has significantly increased the power and range of tools available. For example, in aquaculture, genetic improvement technologies, which, in addition to selective breeding (including genomic selection), also include hybridization, chromosome set manipulation (ability to read and write the genetic code, put it in digital form and translate it back into synthesized life), sex control, transgenesis and gene editing, are all becoming more accessible and advanced in their application.

In fisheries management, genetic stock identification (GSI) permits assignment of individuals back to their population of origin, which can, but not necessarily does, coincide with geographic origin. This is crucial for fisheries stock assessment, which can evaluate fisheries resources based on natural populations rather than on artificial units described by geopolitical realities. Additionally, there is a wider range of applications that can be used by scientists, fishery managers and aquaculturists that rely solely on DNA extracted from small quantities of tissue, e.g. fin clips, museum specimens, processed food, stomach contents (van Zinnicq Bergmann, 2021), sediment or water samples (eDNA), in order to identify species, species’ origin, abundances and trophic webs, among other applications (D’Alessandro and Mariani, 2021).

What is the scope for FAO to assist countries with the transition because of genetic advances in fisheries and aquaculture?

There is general scope for wider understanding and application of these technological advances (Gjedrem *et al.* 2012; Gjedrem and Rye, 2018; Ovenden *et al.* 2015; FAO, 2019ab). FAO, a specialized agency of the United Nations, has the role to support countries in their efforts in making food production systems productive, equitable and sustainable. FAO and related international and national agencies, business and civil society institutions need to prepare for the associated opportunities, risks and benefits that these genetic technologies will provide, to ensure appropriate and equitable application.

At the request of members of the Commission on Genetic Resources for Food and Agriculture, FAO has prepared, in response to the needs and challenges identified in the global assessment, a Global Plan of Action for the Conservation, Sustainable Use and Development of Aquatic Genetic Resources for Food and Agriculture (FAO, 2022c). The focus is on species that are farmed, and their wild relatives and is based primarily on current genetic technologies. The plan of action includes several strategic priorities that relate to monitoring the use of genetic technologies, characterization of farmed types of AqGR and raising awareness of the properties, risks and benefits of the likely changes that are coming with genetic technologies.

The purpose of the study presented here is to provide a clearer picture of the available opportunities and issues that the application of genetic technologies offers, so that governments and the international community can make better use of these innovations in the next 10 years. It seeks to characterize the myriad of issues in a way that summarizes where current, or near future, genetic technologies are likely to impact fisheries and aquaculture. It identifies areas where FAO is best placed to act, where it is most needed, and where it can address opportunities and concerns to provide advice and support to its 194 Member Nations.

Methods

This study used expert elicitation (Hemming *et al.* 2018) to assess current and future (10 year) impacts of the application of genetic technologies on the fisheries and aquaculture sectors and characterize the major thematic "areas of work" with related sub tasks.

The expert elicitation process consisted of a series of long-form one-on-one interviews with 14 experts and their teams in the fields of food production, fisheries, aquaculture, and in population, quantitative and molecular genetics. The identification of the experts interviewed was based on the authors' knowledge of the field and professional associations developed over the course of their careers. Preliminary expressions of interest were sought and those experts that responded positively were then scheduled to be interviewed (Annex 1. See Letter of inquiry and timeline).

To structure the interviews and help the experts consider what kinds of information was required from such a large field of topics, they were presented with several potential areas where advances in genetics could impact fisheries and aquaculture (see Annex 1.). They were asked to provide their views on these key areas and the full range of topics, and not just the experts' specific area of expertise. Experts therefore provided responses on potential arising impacts and the actions needed to address them.

The interviews were conducted between November 2018 to June 2019. Information was collected and synthesized and returned for revision by experts between December 2019 and January 2020. Once all the interviews were completed, the responses were grouped and tabulated into thematic areas that grouped inputs into a conceptual framework of likely changes. In writing the report, experts were offered further opportunity to have input to the structure and content of the descriptions of opportunities, challenges and their implications for fisheries and aquaculture. A substantive literature review provided further insight, in the form of examples that reflect ongoing work and progress in the use of genetic technologies. A final revision in 2021/2022 allowed the experts, along with experts at FAO with expertise in this field, to upgrade the study by updating and adding to the report's content, as well as identifying examples to illustrate change that is underway.

Results

The experts characterized many shifts from “business as usual” in four fundamental thematic areas in the fishery and aquaculture sector that are likely to arise from the increased application of existing genetic technologies and the emergence of novel technologies. The four thematic areas where genetic technologies will have a major influence on understanding, policy and practice include:

i) fishery stock management;
ii) genetic improvement and domestication;
iii) trade, marketing and traceability; and
iv) biodiversity conservation and maintenance of ecosystem function.

The experts identified a range of expected shifts from “business as usual” under each of the four thematic areas (Table 1) to give insight into what needs to be done to prepare for and address those opportunities/challenges. Interviewees predominantly identified fundamental shifts in ii) genetic improvement and domestication of aquatic life, and in iv) biodiversity and ecosystem impacts, in relation to advances in genetic technologies. The description and addition of advice within the thematic areas does not ignore the reality that information on tasks or impacts within a thematic area are not always likely to be discreet to that area, as overlaps do occur. For example, genetic sterilization of farmed types will benefit the industry by producing organisms with more desirable traits for aquaculture (related to point ii) (Table 2) but is also likely to improve biosecurity by reducing potential impacts of escaped farmed types breeding in the wild (related to point iv) (Table 5). Similarly, improved understanding of stock structure (related to point i) (Table 3) will impact trade through better labeling (related to point iii) (Table 4) and biodiversity through improved fishery management (related to point iv) (Table 3).

Along with text descriptions and boxed examples there are 10 tables which summarize the input from the experts. Table 1 gives examples of fundamental shifts in fisheries and aquaculture, whereas Tables 2 to 5 display examples of improvement and challenges across each of the themes. Table 6 highlights fundamental shifts, items to be monitored and questions to be addressed across the four thematic areas. Tables 7 to 10 complete the report by suggesting potential actions for international coordination and support for each of the four themes.

Shifts in governance were also identified by all the experts interviewed as a “cross-cutting” area of change that will be essential to optimize the benefits and limit challenges that arise from the adoption of new genetic technologies. Some examples of anticipated changes will be related to management of transboundary stocks where significant reform and action will be needed at local, national, regional and international levels. Importantly, governance will need to address potential risks posed by genetic technologies and oppose certain practices, while providing new opportunities for proper and responsible use of their potential. Amongst other things, continued funding for research, development and oversight of genetic technologies in fisheries and aquaculture will likely need to be given greater attention.

Table 1. Examples of fundamental shifts in fisheries and aquaculture resulting from adoption and increased use of genetic technologies

	Existing situation	Fundamental shift	Implications for management & conservation
Fisheries stock management	Fisheries management predominantly based on species and historical political or geographic classification. Stock assessment rarely informed through use of genetic population profiling, while potentially biased historical and current data used for abundance estimation. Data gaps on species of low abundance.	Fisheries assessment and management units defined using accurate species identification, genetic stock identification and knowledge on biological populations acquired through understanding of inter and intra-specific genetic diversity, including evolution and connectivity. Fisheries stock assessment will increasingly use genetic technologies to elucidate close-kin relationships in estimation of spawning stock biomass, gain understanding of natural mortality (i.e. from genetic analyses of stomach contents) and improve abundance and distribution of data-poor stocks that are increasingly enumerated through analysis genetic material, e.g. use of eDNA.	• Improved baseline of genetic information collected on target and non-target species; • Management units used for stock assessment and management defined using information on genetic relationship analyses enabling definition of biological units, including transboundary stocks; • With change in species and stock characterization (target and indirectly affected by fishing) routine species and population tagging and monitoring will change; • More accurate predictions of responses to natural and anthropogenic pressures due to better stock definition; • More accurate spawning stock biomass estimates derived from close-kin mark recapture methods; • Fisheries restocking practices improved as hatchery reared stock will have appropriate genetic makeup; • Rebuilding and risk assessment of depleted stocks benefiting from using knowledge on demographic connectivity obtained through genetic technologies; and • Countries claim of sovereign rights over fishery stocks more accurately supported by science.

Table 1. (continued)

	Existing situation	Fundamental shift	Implications for management & conservation
Genetic improvement and domestication	Many species are cultured, of which major production volumes come from a few. Most species are only recently domesticated with poor genetic management in aquaculture commonplace. Relatively few developed farmed types with slow and uneven adoption of genetic improvement.	Aquaculture able to achieve sustainable and efficient production from better genetic management, as well as using improved farmed types (particularly those traits that are hard or costly to record/improve in traditional breeding programmes), all at less cost and faster pace than traditional breeding approaches.	• Genetic basis of desirable or harmful traits identified; • Farmed types bred more inexpensively and quickly to suit a wider range of consumer requirements – including through the use of synthetic biology; • Farmed types bred to grow more quickly, with greater quality, accepting alternative diets (e.g. diets with less fishmeal or fish oil and replacement nutrients); • Farmed types bred to suit a wider range of conditions in more environments, while also becoming more suitable for culture environments to improve their welfare; • Improvement in traits that are hard to improve using traditional genetic technologies, e.g. fillet quality; • Patenting and intellectual property protection over useful gene sequences; and • Raising consumer awareness on the benefits of genetic improvement in aquaculture, while adhering to Environmental, Social and Governance (ESG) standards

Table 1. (continued)

	Existing situation	Fundamental shift	Implications for management & conservation
Trade, marketing and traceability	Fisheries and aquaculture products often misidentified across the supply chain or marketed under misleading or incorrect labelling. Product substitution not uncommon.	Informative, easy to use and cost-effective genetic analysis of fisheries and aquaculture products across the value chain with unambiguous species identification, often to place of origin, based on genetic information.	• Increased traceability of species and farmed type/stock of origin in trade; • Improved ability to discriminate between farmed and wild organisms; • Certification and informative labelling of fisheries and aquaculture products based on genetic characterization; and • Increased consumer trust based on compliance with forensic standards.
Biodiversity conservation and maintenance of ecosystem function	Ecosystem studies, management and rehabilitation based on traditional technologies that often require extensive sampling and monitoring of ecosystems with limited scope to increase lost genetic diversity.	Ecosystem studies, management and rehabilitation informed by knowledge of how genes function in an organism and the environment, as well as using genetic analyses of biodiversity, trophic structure and ability to recreate ecosystem components according to desired genetic resources, including interactions between farm escapees and native populations.	• Increased ability to detect and determine the abundance of rare species of high conservation concern; • Populations of rare, threatened and endangered species managed based on effective population size; • Clearer choices on interventions to maintain species, population and ecosystem resilience resulting in a refocusing of conservation effort; • More powerful models for how threatened and endangered species respond to natural and anthropogenic changes; • Rebuilding of rare, threatened and endangered stocks using genetic technologies and knowledge of potential base population genetics; and • Increased understanding of movement of species, especially species of conservation concern, and commodities, potentially to place of origin.

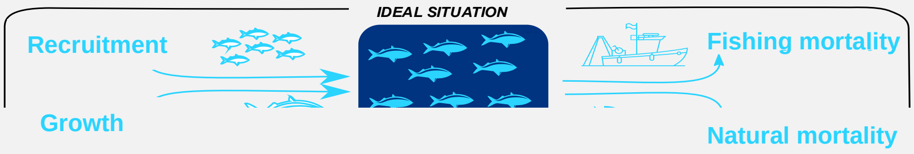
Impacts and required action: “Improved fisheries stock management”

Improved fisheries stock information for management and conservation, at lower cost, will be possible through use of improved genetic technology. Improvement includes a more accurate definition of stock delineation based on the understanding of genetic connectivity, that is, knowing the biological reality rather than administrative or geographic boundaries. In doing so, key stock assessment measures such as age and size at maturity, distribution of size structure, abundance estimates and fecundity can be better aligned to a discrete reproductive unit, or biological population. Genetic technologies are allowing us to see the impacts of fishing, from different exposure to fishing exploitation (Petrou *et al.* 2021; Gandra *et al.* 2020; Therkildsen *et al.* 2019; Pinsky and Palumbi 2014), to proving, in some cases, that fishing has not caused stock collapse (Atlantic cod, see Pinsky *et al.* 2021). In the case of re-defining fishery stocks based on their genetics rather than geographical range, such work is confirming previous assumptions, such as Skipjack tuna (*Katsuwonus pelamis*) in the Pacific being a single stock (Anderson *et al.* 2020). In other cases, however, previous assumptions are being challenged, such as with Haddock (Berg *et al.* 2020), cod (Kristensen *et al.* 2021) and others, a more complex picture is emerging (see Box 1, Box 9 and Box 12).

Box 1. Genetic technology and tools for fishery stock delineation

Why does stock definition need to be based on genetic connectivity rather than geopolitical delineators?

Fisheries stock assessment assumes that **stocks** have intrinsic parameters (e.g., growth, recruitment, mortality, fishing mortality) that are independent of immigration or emigration rates, that is, that they represent natural **populations**, composed of sexually interbreeding individuals that possess a common gene pool.



In some cases, what is considered a fishery stock can be misaligned with a fish population. This can result in more than one population assessed as one stock, one population considered as several stocks, or more complex scenarios.

Inaccuracy of averaged parameter estimations can lead to local depletion if fishing mortality is disproportionate in the more vulnerable population.

Ignored unidirectional movement in/out of the stock, or presence of higher/lower productivity areas, can lead to incorrect stock status assessment.

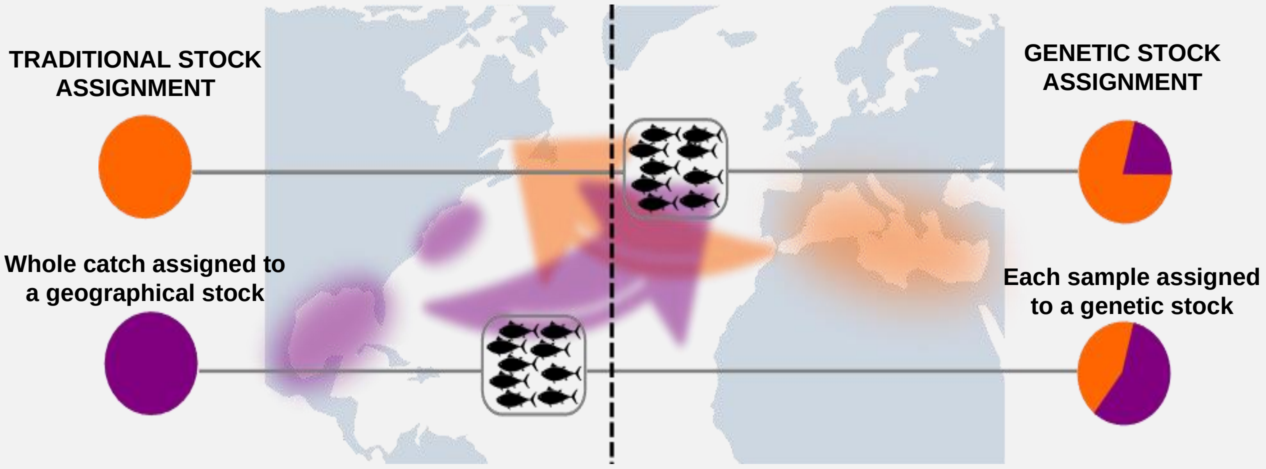
Ignoring genetic structure in stock assessment can potentially cause misinterpretations of stock status, leading to incorrect management advice and decisions, thus increasing the risk of inappropriate Total Allowable Catch allocations, local depletion and, ultimately, loss of sustainable yield.

Baseline information and monitoring of commercial fishery stocks and stock enhancements will be essential to improve the match between management units (often spatial and inappropriate) and biological units (genetic and more real). They will also be essential in assessing the impacts of fishery management. New and refined tagging opportunities, catch discrimination and assessments made through genetic stock identification (GSI) may identify novel genetic information, including on genetic changes caused by fishing (Yorisue *et al.* 2020). Because of this management may be required to redefine of stocks based on the new genetic/biological units. This, in turn, would allow assignment of catches to stock of origin for mixed stocks, as well as new fishery models considering population genetic information such as connectivity, migration and genetic diversity. Following the delineation of biological stocks, existing fisheries data can be re-aggregated according to revised spatial units, thereby providing a direct estimate of the biological and economic cost of any ongoing mismatch between biological and management units (see Box 2).

Box 2. Example of using GSI for stock delimitation for fisheries stock management

How to delimitate fish stocks, even when no obvious geographic boundaries exist?

Tuna case study: The Atlantic bluefin tuna is managed as two stocks (western and eastern) separated by the 45° W meridian and is based on the presence of two main spawning grounds (**Western Atlantic** and **Mediterranean**). Genetic and otolith studies show spawning site fidelity, but tagging studies indicate that population mixing occurs outside of the spawning grounds. Traditional stock assessments assign catches to stocks based on capture location, but a recently developed genetic-stock identification tool allows researchers and managers to assign catches to each genetic stock.



The GSI tool is being used by The International Commission for the Conservation of Atlantic Tunas (ICCAT) in their Management Strategy Evaluation process to better reflect mixing and thus develop more effective and efficient management actions.

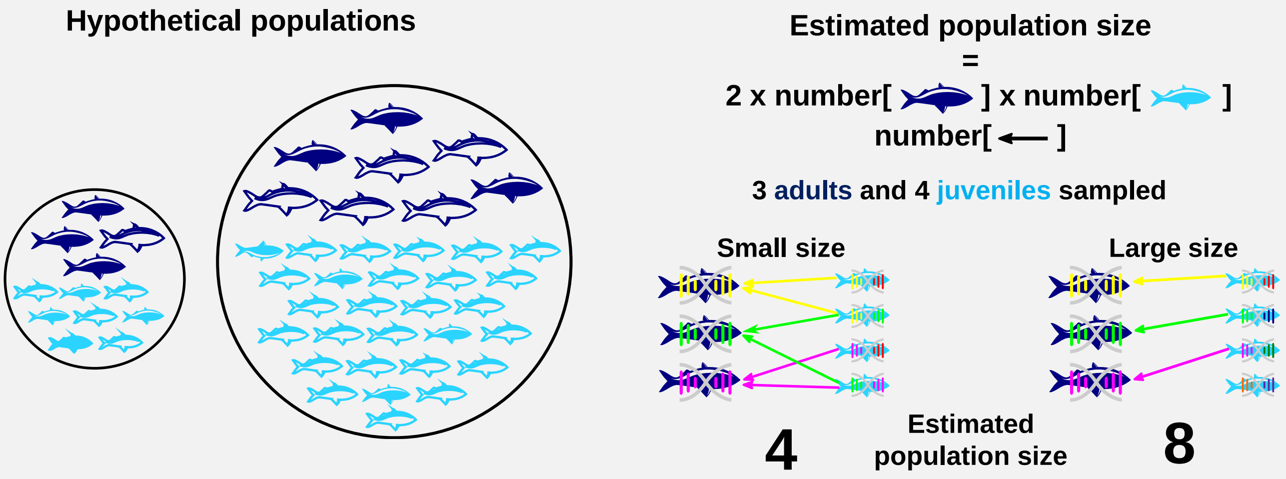
Further reading (see references):
Rodríguez-Ezpeleta et al. (2019). Frontiers in Ecology and the Environment 17: 439-444

Other emerging genetic-based approach applied to fisheries management is tagging (DeHaan *et al.* 2008; Andreou *et al.* 2012; Ovenden *et al.* 2002) and aging (Mayne *et al.* 2021) of individual fish, and the use of genetic information for estimation of population size through close-kin mark recapture (CKMR, see Box 3), and even taking water and sediment samples to sample eDNA present (Rourke *et al.* 2021; Shelton *et al.* 2022, also see passive eDNA work of Bessey at al. 2021). Such approaches offer novel assessments of fisheries populations and biomass that can offer advantages over traditional sampling, as they are not dependent on costly fishery independent surveys and remove much of the bias of catch per unit effort (CPUE) derived stock abundance estimates.

Box 3. Genetic tools and estimating fishery spawning stock biomass through use of kinship measures. The CKMR has been successfully integrated in the Southern bluefin tuna stock assessment, providing estimations of a key parameter for management, the absolute abundance of adults, while avoiding the expense of independent surveyor tag-release programmes, and the interpretational problems of fishery catch rates (see Box 4)

Can we improve accuracy of spawning stock biomass estimates using genetic tools?

Close-Kin Mark Recapture (CKMR) is the collection of genetic material to achieve an abundance estimation. It is based on the principle that in a bigger population, the probability of finding related (kin) pairs in a random sample is smaller. These **kin are found using genetic analyses** of material collected from live or dead fish (e.g. fin clips). It can then be determined if two samples are parent-offspring, sibling, half-sibling or grandparent-grandoffspring pairs.



Realistic applications of CKMR are more complex and require the integration of species-specific characteristics (e.g., longevity, fecundity, genetic connectivity, growth), as well as developing appropriate logistics for sample collection and genetic analyses. CKMR often requires hundreds to thousands of samples so that enough kin pairs are found.

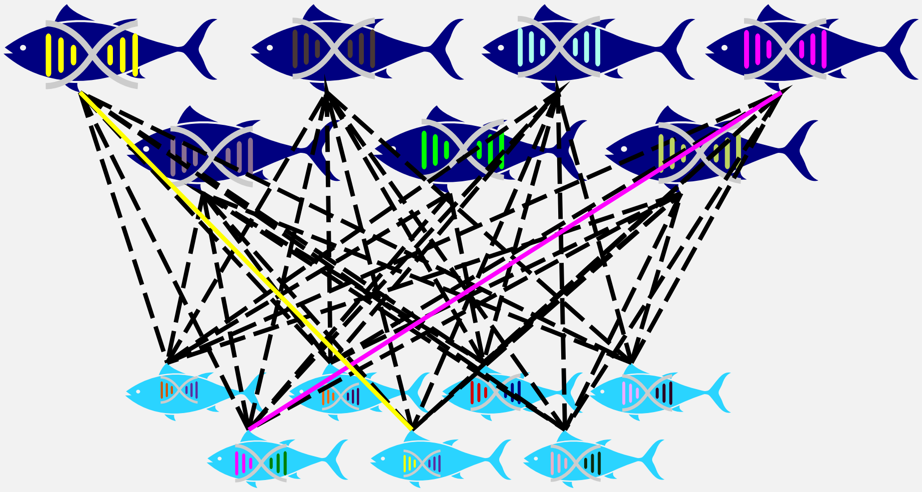
CKMR could be a "game changer" in fish stock assessments as it offers a more accurate spawning stock biomass estimate, compared to the CPUE method, which depends on catch selectivity and quality of the reports provided by fishermen.

Further reading (see references):
Bravington et al. (2016). Statistical Science 31: 259-274
Bravington et al. (2016). Nature Communications 7: 13162

Box 4. Example of using CKMR for stock assessment of commercial fishery stocks of conservation concern

Can Close-Kin Mark Recapture (CKMR) be used in stock assessment for biomass estimation?

Southern Bluefin tuna case study: The Southern Bluefin tuna is highly migratory, depleted and of uncertain recovery potential status, largely due to low levels of confidence on its stock status. The abundance index used for this species, based on fishery derived catch per unit effort (CPUE) data, suffers from inaccuracies due to changes in fishing practices and issues related to reporting.



To better estimate abundance in Southern Bluefin tuna, the CKMR method was applied, using genotyped samples of **5,755 adults** and **7,443 three-year-old juveniles**. From all the possible adult-juvenile pairs, 45 parent-offspring pairs were found, resulting in a more precise and higher estimated abundance than previous CPUE based estimates – information that was used to improve the stock assessment and predictions for management.

The CKMR method is being used by the Commission for the Conservation of Southern Bluefin Tuna (CCSBT) for its stock-rebuilding plan.

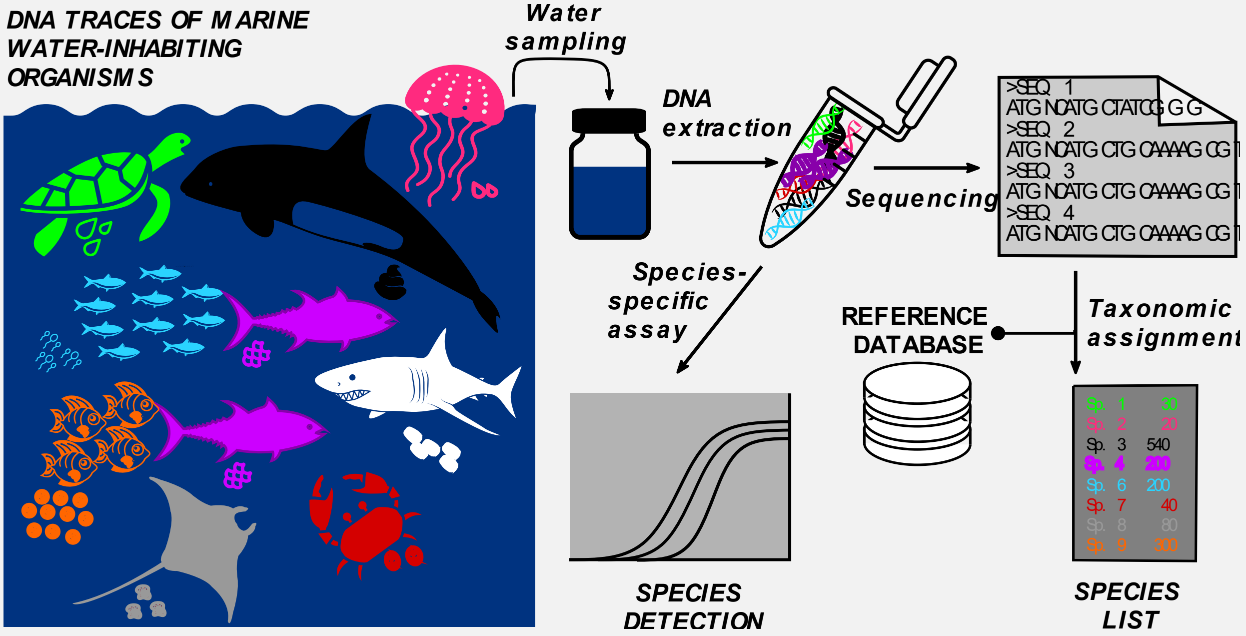
Further reading (see references):
Bravington et al. (2016). Nature Communications 7: 13162

Another emerging genetic-based approach is the estimation of distribution and abundance through eDNA (see Box 5), which can provide information about the organisms inhabiting an aquatic environment without needing to see or sample them directly (Pikitch 2018; Fernández *et al.* 2021). This is achieved either by assessing the presence (and abundance) of a particular species or by providing a general overview of the community and can even examine the long-term dynamics of populations by quantifying genetic material in sediment sequences spanning hundreds of years (Kuwae *et al.* 2020).

Box 5. Genetic tools and ecosystem measures using traces of aquatic life found in water

Can we improve assessments of aquatic diversity by sampling DNA without seeing/sampling organisms?

Environmental DNA (eDNA) refers to DNA present in the environment originating from organismal traces (e.g. tissue, cells, mucus) in water. The collected eDNA can be investigated via a species-specific assay (e.g. qPCR, ddPCR), to determine if a given species' DNA is in a sample, as well as its quantity. eDNA can also be investigated using sequencing, where, for example, a conserved genetic region in all target species is sequenced and compared against a reference database (metabarcoding). Sequencing identifies entire communities and can provide estimates of relative abundance.



Studies have shown that eDNA presence/absence and abundance can correlate with survey-based estimates. Therefore, eDNA can be used as a proxy of marine biodiversity.

eDNA is a cost-effective alternative that can be easily integrated into scientific surveys for assessing marine organismal distribution, diversity and abundance. It offers additional, more timely, information for policy makers, particularly in relation to depleted stocks and difficult to reach environments.

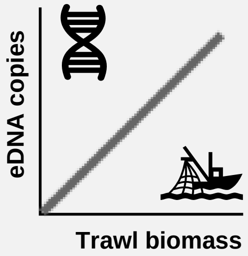
Further reading (see references):
Gilbey et al. (2021). Marine Policy 124: 104331
Rodriguez-Ezpeleta et al. (2021). Molecular Ecology Resources 21: 1405-1409

Application of eDNA approaches directly to fisheries management is less mature compared to genetic-based stock delimitation or CKMR. Traditionally, standardized Catch Per Unit Effort (CPUE) data obtained from commercial catches or scientific surveys are used for estimating biomass and spatial distribution of fishery stocks. Yet, such surveys are costly, and CPUE data suffers from bias such as selectivity and misreporting (Kleiber and Maunder, 2008). Recent studies have shown that eDNA can be used as a proxy for estimating biomass in addition to distribution of commercial fishery stocks (see Box 6).

Box 6: Examples of using eDNA for fisheries assessments and management

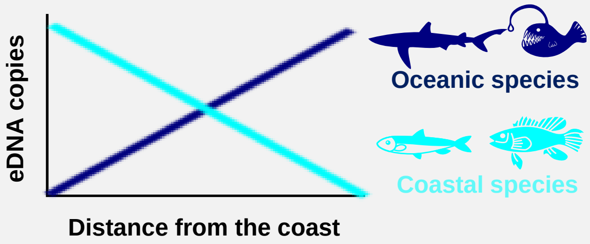
Can eDNA provide accurate biomass estimations of commercial fish species?

Genetic technologies can move us beyond standardised Catch Per Unit Effort (CPUE) data obtained from commercial catches or scientific surveys for estimating biomass and spatial distribution of fish stocks.



The Atlantic cod case study: A recent survey on Atlantic cod around the Faroes found that the number of eDNA copies from Atlantic cod obtained from filtered water samples correlated with biomass estimates obtained from a demersal trawl survey. Additionally, there was an overall 80 percent concordance between trawl and eDNA cod detection, with good spatial conformity between the two approaches.

The Bay of Biscay case study: A recent survey on the Bay of Biscay has shown that eDNA is spatially distributed and that the eDNA from coastal, shallow water species is more abundant in coastal stations, whereas eDNA from open ocean, deep water species is more abundant in oceanic stations.



eDNA monitoring can provide valuable abundance and spatial distribution information in a more cost-effective and low impact manner for marine (but also inland) fisheries. These findings reinforce the opportunities for incorporating eDNA based approaches into fish stock assessments

Further reading (see references):
Salter et al. (2019). Communications Biology 2: 461
Fraija-Fernandez et al. (2020). Ecology and Evolution 10: 7560– 7584
Weldon et al. (2020). Environmental DNA 2: 587-600

The use of genetics in fishery management, stock identification, CKMR, eDNA and others would likely incur additional costs at first, although these costs would rapidly decline as genetic analyses became more mainstream, which, together with the associated benefits of a genetics-informed fisheries management, would make the use of genetic technologies more cost-effective in the long-term. Nevertheless, to foster adoption by fisheries managers, robust and practical validation of these tools will be required to show that these technologies can lead to better fishery management, and result in actions that ensure sustainable exploitation of resources.

The potential negative impacts of, and resistance to, changing the fisheries assessment process along with fishery management policies will need to be evaluated, considered in policy decisions, and mitigated. For example, new fishing regulations based on genetic stock structure may impact socio-cultural and legal agreements of fishers accustomed to traditional stock boundaries with their associated regulations. These impacts may not be appropriate or accepted. Additionally, not all fisheries or governmental bodies will be able to afford to apply the technologies. There are extensive information requirements in establishing baselines, continued monitoring of the genetic structure and diversity of fishery resources, which requires re-skilling and re-tooling. Finally, subsistence fisheries are difficult to manage at present and Illegal, Unreported and Unregulated (IUU) fishing will continue to present challenges, but even here novel genetic technologies are, and will, make inroads (see Trade and marketing below).

Table 2. Examples of improvement and challenges resulting from changes in understanding of *fishery stock management (including on stock structure and assessment)*

General impact	Specific changes
Improved stock productivity and sustainability in capture fisheries	Ability to genetically tag individual fish, and confidently assign species and stocks to catches, improving focus fishing on target resources and avoiding fishing of non-target species and stocks
	Non-lethal aging of fish through genetic assessment rather than counting aging rings on otoliths (Mayne *et al.* 2021).
	Improved estimates of stock abundance which can support traditional stock assessment model estimates
	Potential to identify new genes in wild stocks that are beneficial for other applications (e.g. aquaculture and pharmaceuticals)
	Cost effective release strategies for stock-enhancement with hatchery-produced seed or juveniles based on the genetic characteristics of the stock in the receiving environment/fishery
	Refined placement of fishery reserves and their management due to information being informed by genetic assessments rather than geopolitical delineators alone
Improved conservation of aquatic species	Improved identification of threatened, vulnerable or over-fished stocks, as well as under-utilized stocks in fishery management
	Genetically altering plants to produce fish meal/fish oil equivalents, or genetically altering farmed fish to accept higher levels of plant-based diets, which could reduce pressure on, or spare wild populations as a target for aquafeed production
	Possibility to reconstruct depleted populations of important farmed types/stocks through selecting individuals best adapted to specific conditions
	Reduced chance of escapees from aquaculture establishing in wild populations due to genetic sterilization or reduced survivability in the wild
Risks and challenges to be addressed and mitigated	The need to renegotiate/change fishing regulations based on new information on stock range informed by genetic information rather than geopolitical delineators alone
	Resistance of fishers to new fishery monitoring requirements or management regimes
	Initial increases in sampling requirement of fishery resources with related costs for novel genetic assessments
	Need to design, build and maintain central databases providing general access to harmonized and quality checked genetic information
	Genetic tagging and diagnostic technologies may not be available to all fisheries or governmental bodies, or there may be lacking competence and capacity to apply and exploit these technologies, giving some fisheries or governmental bodies an advantage
	Uncontrolled use of engineered gene drives, posing a risk to the loss of natural variation of traits, or introduction and proliferation of unwanted traits

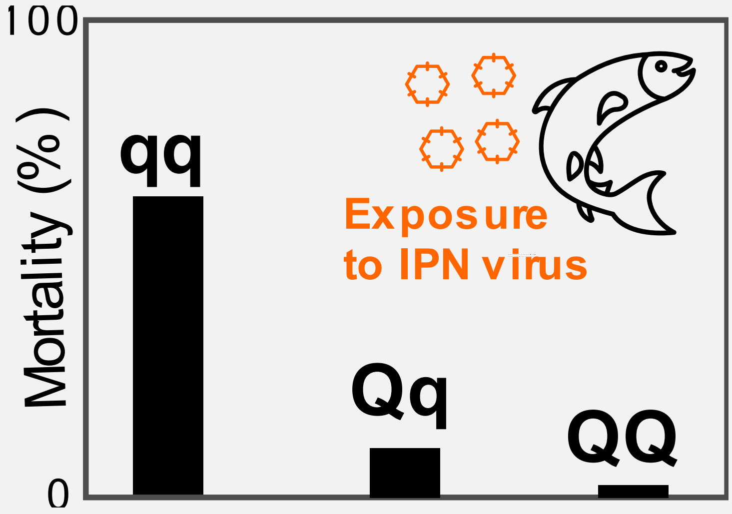
Impacts and required action: *"Genetic improvement and domestication"*

Genetic improvement and domestication was the most frequently cited thematic area when discussing impacts of current and forthcoming advances in genetic technologies. Applications of novel genetic technologies are already having an impact, including the increased use of genetic marker systems for pedigree analysis in breeding programmes and at least one application of marker assisted selection (See Box 7). One major impact of the increased use of genomic selection, which is already visible in a small number of aquaculture sectors, is the increased efficiency and profitability of the aquaculture industry. This is achieved by complementing and improving the efficiency of traditional breeding programmes, which to date have largely been based on phenotypic and behavioural selection for traits.

Box 7. Discovery of a quantitative trait loci (QTL) for a major disease of farmed salmon paves the way for faster selection in resistance, and ultimately its eradication from aquaculture breeding lines

Can marker assisted selection improve breeding programmes?

The discovery of a genetic marker in Atlantic salmon led to dramatic reductions in incidence of the disease in aquaculture. A decade ago, infectious pancreatic necrosis (IPN) was the leading viral diseases in European salmon aquaculture. Mortality of young salmon shortly after introduction to sea cages averaged 25 percent, which resulted in significant economic losses. In the late 2000s, researchers discovered a genetic marker that explained over 80 percent of genetic variation for resistance to IPN, but it was only present in a small proportion of salmon.



Individuals with the IPN resistance marker (**Q**) had their mortality after exposure to the IPN virus reduced. By developing an assay to detect this marker in individual broodstock across many different farmed types of salmon, breeding almost exclusively from resistant individuals was possible. However, emerging evidence of new IPN variants, causing mortality even in resistant farmed types, is making it unclear whether this approach will represent a long-term solution. It is possible that the markers will need to be adapted or new ones identified.

By using marker assisted selection, the industry has been able to integrate selection for a virus resistance marker in on-going breeding programmes, commercialising virus infection resistant salmon.

Further reading (see references):
Houston et al. (2010). Heredity 105: 318-327
Hillestad et al. (2021) Front. Genet: 2172

Box 8. Integration of genomic selection into on-going aquaculture breeding programmes

Will genomic selection be transformative in aquaculture?

Genomic selection is particularly useful for traits that are difficult to measure in live animals such as product quality traits (e.g. filet colour, flesh composition, dress out yield and multiple disease resistance traits). Advances in high-throughput genotyping enables detailed gene mapping, using high-density SNP arrays. Detailed gene mapping then allows the prediction of breeding values of selection candidates based on their genotypes for several genome-wide markers associated with a wide array of key traits. Genomic selection also accelerates the efficiency of selection. Selection based on gene markers can be carried out much earlier in an animals' life than phenotypic selection, as phenotypic traits may only become apparent at, or beyond, sexual maturity.

Is genomic selection already being used in commercial breeding programmes?

Breeding of Atlantic salmon is the most advanced global aquaculture sector in terms of selective breeding, with several private companies providing breeding services to the industry. Many breeding companies have developed their own SNP arrays for genomic selection. As a result, inclusion of genomic selection for a range of commercially important traits in now becoming a routine procedure. A few other species, including Blue catfish, European seabass and gilthead seabream are also developing enhanced breeding programmes.

What are the challenges for widespread adoption of genomic selection?

There is no doubt that genomic selection improves the efficiency and expands the traits being improved in selective breeding programmes. However, genomic selection can only be applied in the context of on-going and structured family-based breeding programmes. Whilst these are ubiquitous now in Atlantic salmon breeding, such programmes are only commonplace in a small handful of species, mostly high-value species in high-income economies. FAO has demonstrated that aquaculture lags behind terrestrial agriculture in the application of breeding programmes, and its uptake needs to be significantly accelerated. Until this happens, the opportunities for applying genomic selection, especially for major aquaculture species such as carps and tilapias, remain relative few. In addition, whilst the costs of high throughput genotyping have come down significantly in recent years, costs can still be prohibitive for application in some lower value species and in lower income economies.

Further reading (see references):
Boudry et al. (2021). Aquaculture Reports 20:100700

Greater resource efficiency (see Table 2), such as feed, land and water, in combination with the reduced use of antibiotics and hormones, is a foreseen result of aquaculturists being able to select for desirable genes, as well as being able to target deleterious genes for removal (deletion) or reduction in expression (knockdown) (Wargelius *et al.* 2016). For example, based on an organism's genetic profile, diets can be formulated to better match specific dietary requirements. Conversely, growth or survival on a "favourable diet" (e.g. one with no inputs from capture fisheries) can be used as a criterion to select individuals with genotypes compatible with that diet. Production planning and development of economic models based on knowledge about the potential of an organism to function under different culture conditions and environments offers further savings. Similarly, modelling and assessing the impacts of stock enhancement will be more accurate when informed with knowledge on the genotypes of both the stocked and recipient populations.

There are genetic technologies on the horizon which may be more impactful than others (see Box 10). However, these potential improvements will only be realized if basic research and development continues, genetic information is made available, and there is investment in commercialization of genetic technologies. Useful genotypes can be identified, and information on those genotypes can be relayed to industry and regulators. Similarly, useful variants can be identified based on their genetic profile and prioritized for use in aquaculture or conservation. Well-designed and long-term selective breeding programmes based on phenotypic data, which carefully manage and conserve genetic diversity, are a necessary starting point before adding new technologies such as gene editing. As such, traditional breeding programmes, not well explored in this publication, will continue, and will need on-going investment.

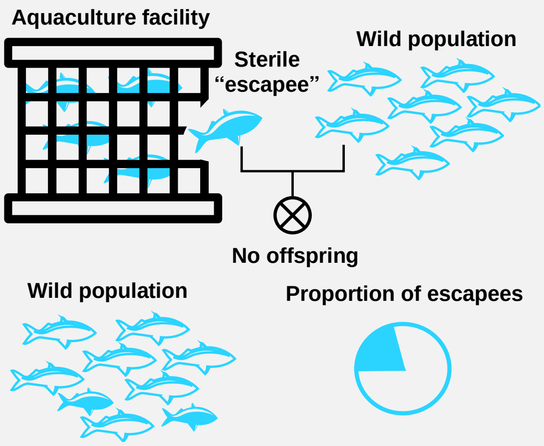
No one entity or actor will be able to ensure the positive impacts of genetic technologies in aquaculture are realized. Industry, regulators and the international community should seek partnerships with advanced scientific and civil society organizations to develop and share information on genetic technologies and their impacts. Hatchery operators, aquaculturists, regulators and consumers will also be vital, and need to be well informed, while a broad range of voices need to be part of setting breeding objectives and strategies of farmed types, which will likely include many more traits than just faster growth. Objectives such as long gut-lengths to help utilize plants-based feeds, disease resistance, or sterile grow-out organisms. Clear objectives will help ensure development investment targets as well as practical and legal solutions that are well accepted in the market.

The combination of traditional and new genetic technologies will yield distinct benefits, but may also come with elements of increased risk. Escapes of genetically selected or modified farmed types (see Box 9) was emphasized by many of the interviewed experts as a known risk. There may be trade-offs between the use of improved farmed types and protecting native biodiversity, that will need to be reconciled at appropriate scales from local to international. The establishment of best management practices based on risk/benefit analysis will be essential to limit unintended negative consequences from genetic improvement of aquatic plants and animals in aquaculture.

Box 9. Genetic tools for reducing risks of escapes

How can genetic technologies improve biosecurity?

Farmed fish, crustaceans and molluscs will invariably escape from aquaculture facilities. Such "escapees" have impact on local biodiversity, fisheries, aquaculture facilities as well as the people that depend on these resources for livelihood or enjoyment. Application of genetic technologies can address these issue in two ways:



Increased biosecurity of farmed types: If a farmed type escapes into the wild, but cannot reproduce, there is less chance of long-lasting environmental harm. Farmed types can be made sterile, or have greatly reduced fertility, through the addition of a chromosome set (triploids) or through hybridization. Genome editing may also offer more innovative ways of achieving sterility.

Identification of escaped organisms in the wild: Because farmed types generally have different genotypes to their wild relatives, genotyping allows you to determine the proportion of escapes into the wild. In addition to escapes, it also allows for estimates of introgression between farmed and wild types, which can be used to inform fishery management decisions to protect native species.

Genetic tools are valuable in managing escapes from aquaculture by either reducing or detecting them

Further reading (see references):

Forseth et al. (2017). ICES JMS 74:1496-1513
Van Eenennaam et al. (2011). Nature Biotechnology 29:706-10
Bartley et al. (2001). Reviews in Fish Biology and Fisheries 10:325-337

Risks should be addressed immediately to promote transparency and allow for engagement in constructive and informed dialogue. For example, public opposition to genetically modified organisms (GMOs) is one of the main challenges to the progressive use of genetic modification of animals and plants in the context of food production (Nep and O'Doherty, 2013). The risks of this technological advance should be addressed openly and in a constructive manner. Responsible Research and Innovations (RRI, see Felt, 2018) is an approach that can be taken in relation to considering genetic modification of animals and plants prior to moving forward with use of such publicly sensitive technological innovations. RRI ensures that a broad range of likely stakeholders (e.g. researchers, citizens, policy makers, business, third party organizations) work together during the whole process of research and innovation to better align both the process and its outcomes with the values, needs and expectations of society. Although a main aim of this study was to look at impacts of new technologies, participants of the interviews advised that low-tech, robust and proven selective breeding techniques should not be pushed aside in a rush towards new and potentially more risky technologies; tremendous gains can be made with increased use of the existing technologies of mass, index and family selection, which generally also effectively conserve genetic diversity for the future.

Consumers should be made aware of the potential advantages of genetic technologies, including their ability to increase production, which is particularly important when faced with problems such as feeding an ever-increasing human population. Indeed, there are some potential applications of genetic technologies that have potentially profound positive impacts on how we manage animals and plants in aquaculture, while also ameliorating the risk that aquaculture poses to biodiversity (see Box 10). However, above all, monitoring and documenting the progress, as well as the pitfalls, of genetic technologies in aquaculture should be a standard component of industry’s obligation, and of public oversight. Reasoned debate and reasonable science-based regulations will be essential to keeping the technologies from going “underground” (See Governance section below).

Box 10. Two game changing genetic technologies that have the potential to transform aquaculture

What are the upcoming applications of genetic technologies that could be game changers for sustainable aquaculture development?

Development of the ability to selectively sterilize plants and animals

Presently, the most practical method for sterilizing animals in culture is to create triploids (see Box 9). It is practiced commercially in a few species such as salmonids and oysters but can have negative impacts on product quality and hardiness. A more effective mechanism for mass producing sterile farmed types could provide benefits in aquaculture at three levels:

i. preventing sexual maturation during culture, removing the negative impacts of maturation on growth of somatic tissue and increasing product quality in some species;
ii. enabling protection of intellectual property for breeding companies; and
iii. limiting the impacts of escapes and releases which could not then form self-recruiting feral populations or interbreed with wild relatives.

A gene known as dead end (dnd) has been targeted using gene editing to induce sterility in salmon. preventing the formation of germ cells (Wargelius et al. 2016). To be widely applicable this “knock-out” technique would ideally be reversible and such techniques have been developed for the model fish species medaka and zebrafish. Alternative approaches can achieve similar goals and further research is needed but the potential applications are so broad and significant that related R&D is likely to proceed quickly. However, a major challenge facing the application of gene editing will be the systems under which its use is regulated, which vary between jurisdictions (see Box 13).

Genetic markers to analyse the impact of genetic management in major seed supply systems

Much of the seed being produced in aquaculture today, especially for lower value species important to food security, and in developing countries, is subject to little or no genetic management. Without effective monitoring we can only make subjective assessments of the long-term impact of genetic management systems on the genetic quality of seed. Lack of attention to genetic management has long-term negative implications through genetic drift, loss of genetic diversity and accumulation of Inbreeding, resulting in reduced performance. In addition, in some species groups, uncontrolled hybridization can lead to introgression of species and loss of key characteristics of pure species (e.g. in major carps). Species specific marker systems (based on SNPs), that can be used to quantify levels of genetic variability and detect hybrid introgression, would enable monitoring of the genetic status of farmed types throughout the supply chain (even using wild relative stocks as a benchmark). Such monitoring would identify genetic management bottlenecks permitting corrective measures to be taken before genetic variation is irrevocably lost. Wide applications of such monitoring could play a huge role in enhancing the sustainable use of genetic resources in aquaculture and ensure the long-term quality of seed.

Further reading (see references):
Gratacap et al. 2019. Trends in Genetics 35(9) 672-684.
Yang et al. 2022. Reviews in Aquaculture 14(1) 178-191.

Table 3. Examples of improvement and challenges resulting from changes in *genetic improvement and domestication*

General impact	Specific changes
Better farmed types	Ability to select and design organisms for better production with desired genetic profiles e.g. for improved growth rate, conversion efficiency, quality, welfare and disease resistance
	More reliable and easier production of monosex groups
	Ability to tailor diet for a specific genetic profile of a species or farm type
	Improved animal welfare when organisms are genetically adapted to culture environment
	Improved animal and plant health through selection for disease resistance including selection of specific genetic markers that confer resistance (see Box 7); vaccines based on genetic characteristics of specific species, strains or varieties
	Improved management of genetic variability in seed supply systems for sustainable use of genetic resources for the long-term
	Identification of wild stocks that have beneficial genes for aquaculture organisms
Better environmental protection	Less use of hormones, antibiotics and other costly or harmful inputs in aquaculture due to *inter alia* genetic disease resistance and improved conversion efficiency of genetically improved farmed types
	Sparing of vulnerable wild populations of food fish currently used for animal feeds through genetically altering plant crops to produce fish meal/fish oil equivalents
	Bioreactors of improved cell culture for replacing unsustainable production of fish and other animal meat
	Reduced chance of escapees from aquaculture establishing in nature due to improved genetic sterilization or reduced survivability in the wild
	Facilitated genetic traceability of farm escapees in support of risk assessments, environmental monitoring, control and enforcement.
	Reduced pressure on capture fisheries as consumer demand is supplied by more efficient aquaculture
	Reconstruction of lost species or important farmed types/stocks through improved broodstock selection based on genetic resources
	Identification of wild stocks that have beneficial genes for aquaculture or reconstructing lost stocks
	Improved modeling of the impacts caused by stocking or accidental escapes based on genetic principles and genetic resources of stocks
	Better decisions by resource and hatchery managers on stocking into the natural environment and aquaculture production using risk assessment which incorporates genetic information
Improved uptake of aquaculture	Help areas develop viable aquaculture and become less reliant on imports when cost effectiveness, production and biosafety are improved through genetic technologies that more accurately match a farm type to the local conditions and environment
	Help aquaculture develop in places where there are strict environmental regulations
Risks to be addressed and mitigated	Potential of increased genetic or ecological impact of escapees on the natural environment, unless rigorously controlled. Additionally, “cocktail effects” from a mix of many gene edited organisms, also interacting with other anthropogenic changes of the environment, may be unpredictable
	Possible consumer resistance to genetic manipulation if not effectively executed and communicated through RRI processes
	Advanced or expensive technologies push out small–scale farmers and fishers that cannot afford the new technologies or farmed types and therefore cannot compete in the marketplace
	Traditional farmed or natural biodiversity is marginalized or lost in favour of apparently more productive improved farmed types
	Limited access to AqGr due to privatization through patenting and intellectual property protection over useful gene sequences by big and powerful enterprises

Impacts and required action: "Improved marketing and traceability of fisheries and aquaculture products in the supply chain"

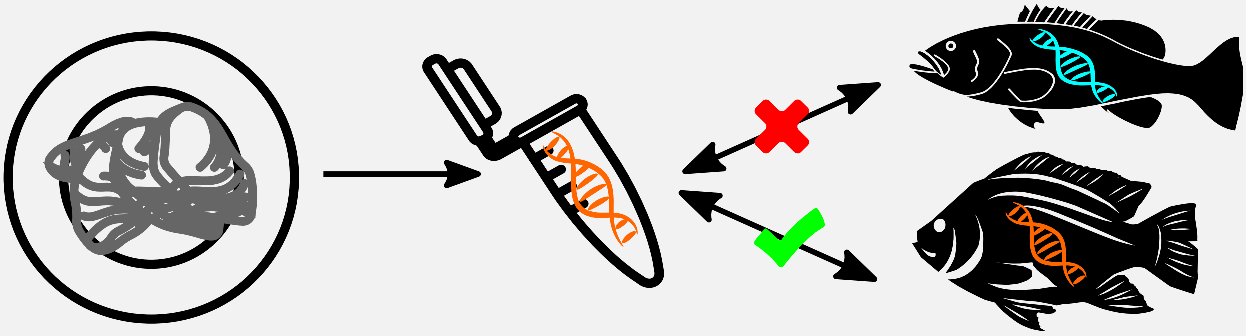
Aquatic food and aquatic food products are some of the most internationally traded food commodities with 67 million tonnes, or 38 percent of total fisheries and aquaculture production, traded internationally in 2018 (FAO, 2020). The fisheries and aquaculture sector is highly vulnerable to food fraud given its complexity, the price differential between lookalike species, and the multiplicity of species and their corresponding value chains. Consumers are becoming strong advocates for responsible fisheries and aquaculture, and accurate genetic information on the aquatic food they consume will improve their ability to make informed choices, thus increasing consumer confidence and trade.

Yet, it is very difficult to identify by sight frozen fillets of different species, e.g. tilapia and grouper, and even more so, following processing. Studies in the United States of America and the European Union have shown that the aquatic food sector is in the top two or three food sectors most vulnerable to fraudulent activity. However, in the case of differentiating commodities to species level with genetic analysis, the difference is clear (see SeaTraces, 2022) and genetic techniques have enabled the detection and reporting of misidentification and deliberate mislabeling of aquatic food in the major aquatic food markets of the world, e.g. United States of America and the European Union (Nielsen *et al.* 2012). They are also used to identify difficult to identify commodities in transit, when they are considered to potentially be sourced from species under CITES provisions (e.g. sharks and eels, see Cardeñosa *et al.* 2018ab; 2019). While some of the experts interviewed felt that deliberate deception of this kind is infrequent, others highlighted that the potential to detect such deception is already affecting practices of IUU, including the poaching and fishing of species at risk. Ideally these new technologies, once widely practiced, will significantly reduce IUU.

To facilitate responsible trade and marketing of aquatic food and food products, identification of useful genetic markers and standard practical genetic protocols for identifying aquatic species, and maybe eventually stocks and farmed types, will need to be developed. The International Barcode of Life project (IBOL, 2022) has standards at the species level, but this would not be sufficient for identification of populations. More sensitive genetic markers, such as single nucleotide polymorphisms (SNPs), can identify individuals back to population or origin (Nielsen *et al.* 2012; and see also the FishPopTrace project (European Commission, 2022b)). This level of identification could identify escaped farmed types or help identify product derived from IUU fishing, e.g. fishing of endangered stocks (see Box 11).

Box 11. Using genetic tools for compliance

Can genetic technologies help to prevent, deter and eliminate Illegal, Unreported and Unregulated (IUU) fishing and seafood fraud?



Traceability in fisheries value chains is essential to identify mislabeling as well as to detect and reduce IUU fishing and food fraud. Genetic methods are becoming a favoured tool that is standard in seafood product traceability, but efforts are still needed to agree on standardised procedures. Work is also still required to establish the mechanisms for implementing genetic traceability in seafood labelling and authentication. Several international initiatives have made significant advances in this respect, such as the LabelFish, SeaTraces and FishPopTrace projects.

LabelFish: This project has detected worrying levels of mislabeled seafood products in six European countries. It has highlighted the importance of harmonizing systems for seafood authentication, ensuring that commercial names reflect the species in question, so that the sector can implement full traceability.

FishPopTrace: This project focused on the study of intraspecific variability to develop geographic origin traceability tools. These tools are to be used in seafood origin authentication and in population stability assessment.

SeaTraces: This project focused on the establishment of standardised procedures for species identification that will be transferred to official laboratories. In addition to this, it led to the development of new tools for identification of specimens to geographic origin, as well as wild versus farmed origin. Information generated from the project was communicated to stakeholders, industry and consumers.

Genetic traceability tools are essential for ensuring species and origin traceability in the context of fighting against IUU and food fraud, for which the development and implementation of standardized procedures is paramount

Further reading (see references):
Keep.eu (2021) https://keep.eu/projects/5412/LABELFISH-EN/
SeaTraces (2022) https://www.seatraces.eu/
European Commission (2022b) https://fishpoptrace.jrc.ec.europa.eu/

Labelling of farm products that have been subject to genetic technologies can be controversial, and requirements for labelling are evolving. For example, in the United States of America the labelling of bioengineered food is now mandatory following the approval of a transgenic salmon (Agricultural Marketing Service, 2018). Although the interviewed experts were not unanimous on this issue, and competence, technology, regulation and organization of capacity for accurate and informative labelling of genetically altered organisms and products may need to be developed.

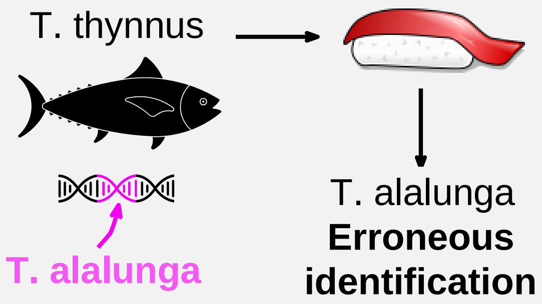
The Nagoya protocol (Secretariat of the Convention on Biological Diversity, 2011) seeks to ensure sovereignty of the nations' genetic resources, including prior informed consent and fair sharing of the benefits arising from the use of genetic resources with the country of origin. This may be facilitated using genetic information. Separately, there is the need to harmonize international trade policies to minimize trade barriers that arise from misinformation on genetic characteristics of fisheries and aquaculture products, or on the technologies that produce them. It is expected that increased labelling requirements will be implemented, and retailers/consumers should be informed on how labels are used and misused. Advances in genetic identification, or traceability using genetic markers, will offer opportunities for informative monitoring of fisheries and aquaculture products along the supply chain, increased transparency of the process and increased consumer/regulator confidence.

Governments and the private sector should be involved in facilitating identification, labelling and monitoring of fisheries and aquaculture products. In addition, they should be increasing the efficacy and cost effectiveness of using genetic tools in a transparent way, where they add value. However, harmonization of characterizations where aquatic products have undergone change using genetic technologies is needed to facilitate ongoing data collection and reporting programmes.

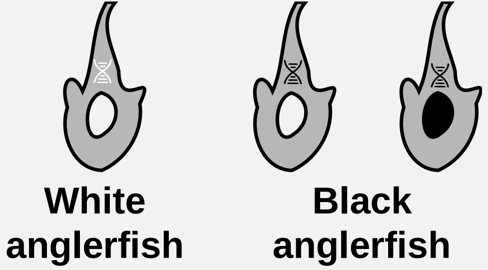
As stated above, accurate, generally understood and accessible information related to genetic modification will likely be required for labelling, marketing and monitoring of fisheries and aquaculture products. Accurate information will also greatly facilitate fishery management and genetic improvement in aquaculture. Therefore, the establishment of a global database that is readily accessible with genetic and biological data could be a long-term goal for the sustainable development and biodiversity conservation communities. A potential database could include evolutionary history (which is crucial for species assignment; see Box 12), life history traits and growth rates linked to DNA sequences, genes, effective population size, genetic diversity estimates, genetic descriptors of stock and farmed types, and stock distribution. Work on collating information of genetic resources in aquaculture is already being conducted by differing institutions. For example, FAO has developed a prototype of a global information system on AqGR, known as AquaGRIS (Aquatic Genetic Resources Information System) (FAO, 2022d), which has the capacity to record phenotypic and genetic data on farmed types of aquatic species.

Box 12. Reliability of compliance assessment using genetic tools

What are the risks of relying on genetic identification tools in IUU and seafood fraud detection, and how reliable are genetic tools for compliance?



Example of possible issues - genetic introgression: Genetic introgression is the transfer of genetic material from one species into the genome of another. For example, it has been documented that about 2–3 percent of Atlantic bluefin tuna individuals possess identical mitochondrial sequences to albacore tuna due to introgression. Thus, if mitochondrial genes are used for species identification, which is often the case, misleading conclusion could be drawn.



Example of equivocal diagnostic based on morphological characters: In some cases, traditional morphological characteristics used for species identification could be incorrect. As an example of a species diagnostic character, white and black anglerfish can be separated based on the dark peritoneum found on black anglerfish, and thought not to be present on the white anglerfish. However, it has recently been discovered that some white anglerfish can have a black peritoneum, and so genetic testing has shown peritoneum colour is an unreliable diagnostic feature.

The use of genetic tools for species identification in the context of IUU and food fraud prevention requires an understanding of the species' evolutionary context and could help update morphological species identification characters

Further reading (see references):
Díaz-Arce et al. (2016). Mol. Phy. Evol. 112: 202-207
Aguirre-Sarabia et al. (2021) Evol. Appl. 14: 2221-2230

Although the interviewed experts did not explicitly identify "consumers" as an area to be impacted by genetic technologies, nearly all stated that consumer awareness, education and acceptance of genetic technologies were essential for the expanded use of genetics in food production. Consumers will certainly benefit from having clear and accessible information on safe aquatic products and commodities (animals and plants). To facilitate consumer acceptance of new technologies, benefits (e.g. less expensive and more readily available fish) are passed on to consumers as well as to the private industry. RRI processes of new technologies are essential for this.

Table 4. **Examples of improvements and challenges resulting from changes in *trade, marketing and traceability* across the value chain**

General impact	Specific changes
Improved trade in fisheries and aquaculture products	More accurate and confident identification and traceability of fisheries and aquaculture products
	Improved trade in fisheries and aquaculture products when conflicting and inappropriate regulations and trade barriers are eliminated
Improved labelling of fisheries and aquaculture products	More accurate labelling of fisheries and aquaculture products to species and geographic and/or stock origin, and, in some cases, method of production, i.e. farmed or fished
	Improved traceability of fisheries and aquaculture products along the supply chain based on genetic markers, including the tracing and identification of farm escapees in the context of risk assessments, environmental monitoring, control and enforcement
	Increased consumer awareness and confidence in fisheries and aquaculture products due to improved accuracy in labelling, e.g. species identification, origin of product, and identification to a stock or fishery that is sustainably fished
	Improved ability to identify escapees from aquaculture facilities
Reduced IUU fishing	Improved species/stock identification and tracing tools for inspectors to monitor and enforce measures to identify illegal catch or misreported names of species
Risks to be addressed and mitigated	Misinformation on genetic technologies that spread mistrust and inappropriate trade regulations
	Consumer resistance to genetic improvement technologies
	Risk of using a set of markers that lead to misinterpretation of the evolutionary history e.g. a set of populations could belonging to the same species when using one genetic marker but if high-resolution markers (e.g. SNPs) were used, they could, in reality, belong to two different species
	Marginalization of farmers, fishers, or countries that cannot afford genetic technologies, tracing and labelling which may become mandatory to participate in markets

Impacts and required action: *"*Biodiversity and ecosystem functions*"*

Genes function within organisms, organisms function within and across populations, populations function within and across communities and communities function within and across ecosystems. Genetic technologies can inform and have an influence on all levels of this hierarchy. Ongoing development of next-generation sequencing technologies and the availability of data on genomes is advancing the field of conservation genomics. There is now an increased number of markers to enable more accurate estimation of effective population sizes and migration rates (Funk *et al.* 2012; Leitwein *et al.* 2020; Bourgeois and Warren 2021).

We will soon have a wider range and more complete understanding of the genome sequences of species, as well as from many individuals within species. In addition, ecosystem understanding will also be clearer through environmental genomics (Cordier *et al.* 2020). Access to this information will transform our ability to determine the amount, distribution and functional significance of genetic variation in natural populations (Segelbacher *et al.* 2021).

Basic research on gene identity, function and regulation is progressing rapidly and can be directly applied to producing better farmed types, to understanding how organisms and ecosystems function, and even to designing *de novo* organisms. This has implications on how we approach actions to help restore the components and functions of biodiversity or increase the vitality and resilience of systems under sustainable management, noting that climate change is presenting a significant challenge to on-going management (Gurgel *et al.* 2020). Novel tools are also used in real time to make rapid species identification and place of origin determinations using diagnostic tools to facilitate the return of trafficked specimens back to the wild at timescales relevant to their survival (see, Cardeñosa *et al.* 2021).

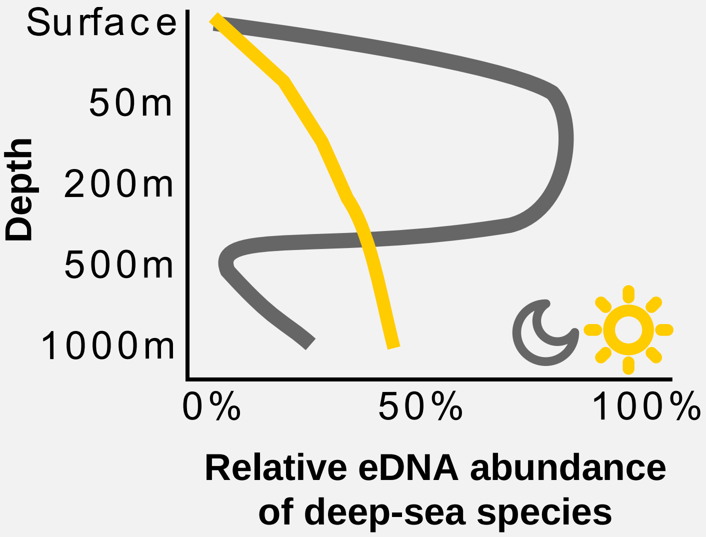
As previously mentioned, aquaculture's environmental impact will be reduced through increased biosecurity if farmed types are sterile and cannot reproduce in the wild, or by producing farmed types that are less able to survive outside of the culture environment. Nevertheless, several of the experts stressed that policies should still mandate adequate physical barriers to avoid escapees entering the natural environment and introgression from farmed escapees (Bolstad *et al.* 2021; Lorenzen, Beveridge and Mangel 2012).

Other impacts from aquaculture effluent, such as pathogens, may be identifiable and traceable using eDNA. eDNA can also be used to detect endangered or invasive species, as well as to study species composition in unexplored, traditionally hard to sample, ecosystems such as the mesopelagic realm (see Box 13). Examining eDNA in water bodies tells us what species, or potentially even stocks or farmed types, are present, which is useful for understanding aquatic life, but it also reveals variation in environmental structuring that might not always be obvious.

Box 13. Can genetic tools help us reach into the unknown — is eDNA suitable for studying underexplored and threatened ecosystems?

Can genetic tools help us explore aquatic life across poorly documented ecosystems?

Exploring the deep-sea through eDNA: The deep sea is the largest, least explored ecosystem on Earth. The average depth of the ocean is over 3500 metres and 99.7 percent of the ocean's volume is below 500m, which is assumed to harbour about 90 percent of total fish biomass. Noting the need for additional and alternative sources of protein for human consumption, especially as feed supply for aquaculture, a quest for exploitation of this ecosystem has attracted interest. Yet, due to the role deep-sea organisms play in carbon sequestration and trophic connectivity, it is urgent that we gain a better understanding of this ecosystems' biodiversity and function, to inform its management in the future.



Fundamental knowledge gaps include identifying animals that inhabit the deep-sea, how they are spatiotemporally distributed and factors that control their distribution. This information is lacking due to the inaccessibility of deep-sea ecosystems, but a recent study has shown that eDNA, vertically distributed along the water column, can provide information on the species inhabiting this unexplored ecosystem, including their diel migratory behaviour. For example, eDNA abundance of mesopelagic fish, known to present a diel migratory behaviour, is higher in shallower depths during the night and higher in deeper depths during the day.

Genetic tools are also helping us better understand cryptic or nocturnal species, and species in muddy or inaccessible waters.

eDNA sampling and sequencing is a powerful approach in improving our knowledge of fishes inhabiting the dark ocean before this relatively pristine ecosystem is further impacted

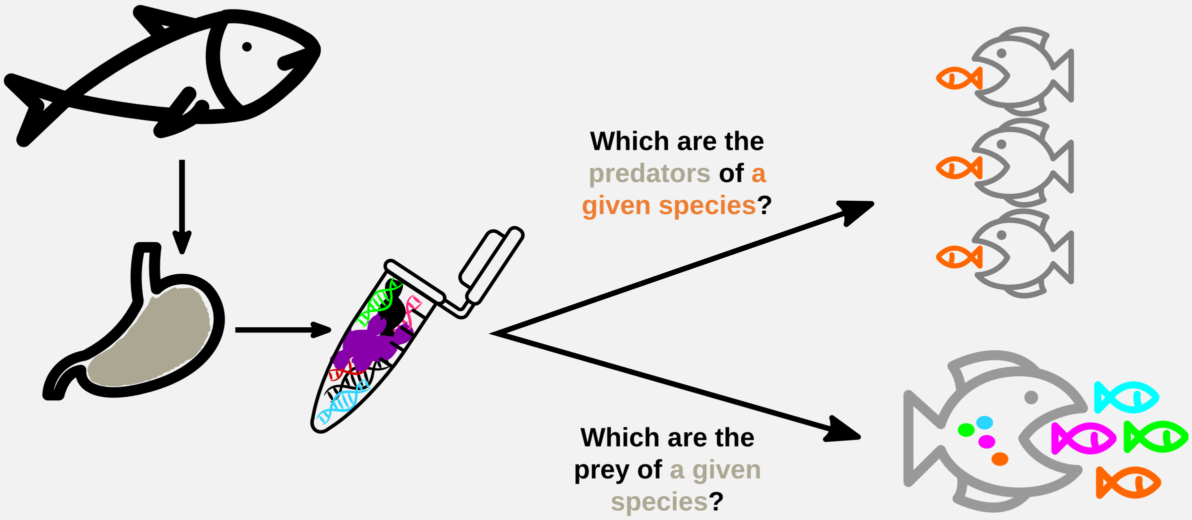
Further reading (see references):
Canals et al. (2021). Limnology and Oceanography Letters 6: 339-347
Fernández et al. (2020). Environmental DNA. 3:142-156
Costello et al. (2021). Environ. Sci. Technol. 44: 8821-8828

There is a demand that fisheries management is ecosystem based, i.e. that all components of the ecosystem and the interactions among them are considered for development of management procedures. This requires understanding of what life is present, and their interconnection across trophic webs so that information about connectivity can be included in ecosystem models. Metabarcoding of eDNA is already proving useful in giving us a broad appreciation of what species are present (Russo *et al.* 2021; Miya, Gotoh and Sado 2020) and even a relatively good assessment of their relative abundance (Yates *et al.* 2020; Spear *et al.* 2020). In addition, we are using other genetic tools to examine their interconnection across trophic webs (see Box 14).

Box 14. Genetic tools and ecosystem function

Can genetic tools give insights into ecosystem function - such as trophic connectivity studied through stomach content genetic analyses?

Understanding the trophic web of an ecosystem through the study of predator-prey relationships is key for an accurate application of ecosystem and multispecies models, as well as for estimating natural mortality. These data and models are required to anticipate responses to fishing pressures and to make good predictions about the status of fisheries stocks and ecosystems. Traditionally, food web studies have been made through the visual identification of stomach contents, which is a tedious and expensive activity. In addition to this, it is has limitations for (semi)digested preys, early life stages or gelatinous organisms that lose their distinguishing features on ingestion.



Genetic methods offer an alternative, allowing for a broader, more accurate and cost-effective characterisation of stomach contents. This can be achieved by either focusing on which are the predators of a given prey species, using species-specific assays, or by assessing the diet composition of a predator species using sequencing.

Stomach content DNA analysis is a powerful approach in understanding ecosystem function by allowing a cost-effective analyses of trophic networks

Further reading (see references):
Cuende et al. (2017). Journal of Sea Research 130: 204-209
Günther et al. (2021) PeerJ 9: 311757

With the ability to identify species through very small tissue samples and from small sample sizes, genetic monitoring of various aspects of the ecosystem will be able to provide qualitative and quantitative information on trophic structure, diet of commercially important species, pathogens, and on rare or endangered species. Identification of isolated and locally adapted stocks (Berry 2019) can indicate the presence of stocks more vulnerable to overexploitation. Furthermore, their potential adaptive distinctiveness may prove to be of special value for the species if environmental conditions change across the species range, even adaptation in relation to pollution (Reid *et al.* 2016).

Genetic technologies are being used to examine what genes are important for adaptive divergence, for past and present evolution in aquatic species (Brennan *et al.* 2018; 2019), and what population sizes should be considered as critically endangering long-term conservation (Frankham, Bradshaw and Brook 2014). New species, new stocks and potentially new genes with beneficial traits can be identified using genetic screening (Nature 2022). New species, or species with new characteristics, can be engineered through synthetic biology to enhance ecosystem function or to replace lost ecosystem services (Table 5). For example, CRISPR based engineered gene drive technologies can rapidly spread genetic changes through populations of sexually reproducing organisms (Oye *et al.* 2014). Engineered gene drives may be transformative in pushing forward genetic engineering. Gene-drives, which also occur in nature, can be used to change the prevalence of specific genes in a population or ecosystem over several generations at a rate different to that expected through Mendelian probability. At present, gene drives are not used in fisheries or aquaculture. However, within the next 10 years they could be used to control invasiveness and adapt populations to climate change, facilitating species recovery efforts by spreading genes rapidly through wild or aquaculture populations. For RNA-guided gene drives based on CRISPR to serve as a general method for spreading altered traits, both its capabilities, but also its limitations, require development of novel precautionary strategies to control the spread of gene drives and reverse genomic changes. That way, we can benefit from favorable change, while limiting unforeseen undesirable impacts (Esvelt *et al.* 2014).

Table 5. Examples of improvements and challenges resulting from changes in understanding of *biodiversity and ecosystem functions*.

General impact	Specific changes
Improved management and conservation of ecosystems	Revision of recommendations for population viability thresholds linked to conservation measures for species characterized as having a critically small population size
	Clearer understanding of trophic structure of stocks and species, and their diet, based on genetic identification of feed and prey organisms
	Reduced chance of escapees from aquaculture establishing in nature due to improved genetic sterilization or reduced survivability in the wild
	Improved understanding and identification of species at risk, based on genetic detection tools, including on their effective population size
	Better understanding of epidemiology and identification of pathogen sources based on their genetic character
	Lowering environmental impacts of aquaculture on wild stocks through efficient aquaculture production, lowering drug use and effluents because of genetically improved farmed types
	More components of the ecosystem, not just the fishery, managed based on genetic information
	Improved understanding and assessment of interaction between farmed types and their wild relatives based on genetic information of both
	Improved capacity to identify, manage and monitor rare, invasive and cryptic species as well as aquaculture escapees
	Improved and quantifiable estimates of impacts from fisheries and aquaculture, e.g. impact on environment from escapes, from antibiotics and from other forms of effluents from aquaculture, even over large geographic areas
Improved ability to restore ecosystem services	Improved ecosystem functioning through establishment of gene-drives to re-establish lost components of an ecosystem or establish new components
	Improved ability to restore ecosystems through use of synthetic biology recreating lost components of a stock, species or of an ecosystem
	Improved ability to identify suitable aquatic species or stocks for transplantation or introduction into new or degraded ecosystems
Risks to be addressed and mitigated	Unknown ecosystem and social-cultural impacts of developing and releasing genetically engineered or transplanted organisms
	Loss of biodiversity in countries that cannot afford genetic technologies or improved genetic resources to protect biodiversity
	Unregulated use of genetic technologies to engineer organisms that are released into the wild with undesirable or unknown consequences

Implications for changes in "Governance"

Effective governance was an overarching theme, where actions and impacts are foreseen by the experts interviewed. Governments put regulations in place to ensure the safety and health of their citizens. Yet current institutions, policies and management practices may not be sufficiently well structured, or do not have adequate capacity to address and manage change brought about by the introduction and use of novel genetic technologies and their products. As often they require new, complicated, and sometimes unclear pathways before adoption. These pathways include general awareness raising of what is coming, agreed sharing arrangements of the tools and genetic information standards and data, as well as setting up of systems for their management. This needs to take place to facilitate an environment for innovation, although harmonized rules for how to characterize and control/manage the products and trade of these technologies is also needed.

As an example, genetic technologies such as gene transfer and gene editing have the potential to create farmed types that challenge traditional regulatory production or trade management frameworks (see a tiger puffer fish and a red sea bream, both developed in Japan, Nature 2022). The case of AquAdvantage, genetically engineered (GE) Atlantic Salmon in the United States of America is revealing (see Box 15). In 1995 when approval was being sought for farming a GE salmon, it was unclear how the product of the technology should be classified and treated, as a potential disease, a new drug, or just a new farmed type? The United States of America Food and Drug Administration (FDA) has now decided that such products should be treated similarly to a new "drug" and should be tested and regulated as such (Van Eenennaam *et al.* 2021).

Similar debates are ongoing as to whether gene edited organisms are GMOs and to what threshold of change requires their reclassification and product labelling. The European Union considers products of gene editing as GMOs (Adamse *et al.* 2021), whereas in other countries, such as Brazil, similar products are not considered GMOs (Vieira *et al.* 2021). Such classification has very significant implications for regulation and thus uptake, therefore Governments need to be prepared with clear, transparent regulations developed from participatory processes. New genetic technologies will face new and perhaps challenging regulations, and citizen review and acceptance of this process and the technology are essential, as is the transparent participation of the private sector.

As such, governance structures (e.g. policies, laws, agencies and organization to enforce laws on national and international levels) will also be needed to undergo necessary fundamental review and potential shifts to establish an overall framework of good governance that can be harmonized across jurisdictions.

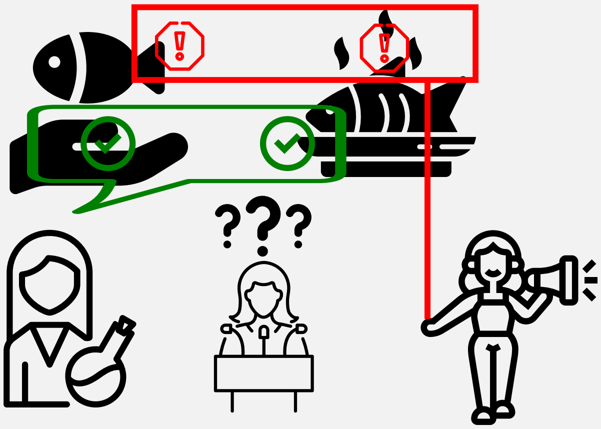
Increased ethical and regulatory policies governing use of genetic technologies and their products will be an ongoing need in the next few decades, and potential access restrictions to genetic technologies and their products is likely. As knowledge on the composition and function of genes becomes a valuable resource, conflicts over sovereignty, ownership and intellectual property protection are likely to arise. Combined with consumer and small-scale producer resistance, this may lead to conflicting, inconsistent and/or polarized policies and practices on the use of genetic technologies and their products, including on the use of different farmed types in different areas.

In addition to issues surrounding intellectual property, the need for advances in method standardization and in adopting common procedures will require also require active engagement, globally. As this is a new and rapidly evolving field stakeholders can be confused by apparently contradicting information provided by scientists and the media, which in most cases results from a mix of reporting from technical studies in terms of geographical or temporal coverage. Thus, management decisions will need to be based on a broad review of scientific evidence to encourage consensus, and when possible, the methodologies (and genetic markers) used should be standardized using initiatives such as that of the European Committee for Standardization (CEN, 2022).

Box 15. Promise and challenge of utilising advanced genetic technologies: AquAdvantage Atlantic salmon

Transgenic salmon and the problem of regulation - what is the need for novel regulation of transgenic fish?

AquAdvantage Atlantic salmon, transgenic for the Chinook salmon growth hormone gene under the control of a promoter from an antifreeze gene of the ocean pout, is an example of a genetically engineered and commercialised food fish. Genetically engineered (GE) individuals carrying this gene reach market weight 40 percent sooner, require 25 percent less feed and have a lower carbon footprint than individuals not carrying the transgene.



Aquaculturists, consumers and the environment can benefit if missing or complex regulatory structures, misinformation and political hurdles can be overcome. After over two decades of delivering data to the United States of America Food and Drug Administration (FDA) and its advisory bodies on the efficacy and safety of the GE salmon, AquaBounty received notice that the FDA concluded: there was no evidence that genetic engineering was unsafe to the fish; consumption of the GE fish posed no more harm to the consumer than “normal” salmon and, therefore, GE salmon was “equivalent” to other Atlantic salmon on the market.

However, as the government review process was ongoing, special interest groups opposed to GE salmon distributed contested information that GE salmon had higher levels of growth hormone and lower levels of omega-3 fatty acids. Complex political arguments arose in 2015 that blocked the sale of the GE salmon in the United States of America. Finally in 2019, 10 years after the FDA ruled the salmon was safe for people and the environment, commercial sale was authorised. AquaBounty estimated that lack of an appropriate regulatory environment, misinformation and politics cost the company USD 8.8 million in regulatory fees/costs and over USD 20 million in maintaining the GE salmon from 1995 to final approval for sale.

Gene editing presents similar opportunities to improve efficiency and protect the environment. However, the problems and pitfalls surrounding the regulation of such innovation is an ongoing challenge for governments and aquaculturists alike

Further reading (see references):
Du et al. (1992). Bio-Technology 10: 176-81
Tibbetts et al. (2021) Aquaculture 406-7: 141-52
van Eenennaam & Muir (2011). Nat. Biotech 29: 706-10
van Eenennaam et al. (2021). Annu. Rev. Anim. Biosci. 9: 453-478

However, in the long-term good governance based on genetic principles, internationally accepted principles,[4] transparency, open communication, inclusive communication, as in RRI processes, will increase food security, secure livelihoods, provide consumer trust, public trust, acceptance, promote responsible fisheries and aquaculture, and conserve aquatic biodiversity. Conflicts that arise should be possible to resolve based on scientifically based principles, accepted international practices and inclusive dialogues with relevant stakeholders. However, this will require the active engagement of appropriate fora, holistic approaches and facilitation of such discussions and conflict resolutions that take place as part of RRI processes.

A main fundamental shift required for improved governance of genetics in fisheries and aquaculture is bringing science and regulators more closely together in policy and practice. This was noted by almost all experts interviewed and will entail breaking down barriers between scientists, fishers, resource managers, aquaculturists, and policy makers, including raising the level of knowledge in the public about the risks and benefits of genetic technologies. Furthermore, improving experts' and scientists' ability to contribute to RRI processes is critical, and implies increased competence, understanding and skills in holistic, transdisciplinary, action and system-oriented research and cooperation.

Conversely, acrimonious debate, inconsistency and overly restrictive regulations have the potential to stifle innovation or drive new technological approaches underground, away from proper oversight. Although bound by confidentiality commitments, several of the interviewed experts revealed that genetic editing is already being conducted without appropriate government or industry oversight. International attention was recently focused on one such example where human embryos were genetically edited to be resistant to HIV infection leading to the birth of twin girls carrying the edits. This experiment garnered widespread criticism due to a lack of knowledge or agreement by proper scientific and government authorities (Normile, 2018).

As a first step, the international community should strive to reach agreement on harmonized terminology related to genetic technologies and reference to them in production, trade and the environmental fora. Accurate terminology and standardized usage of terms are necessary for proper policy development, management, trade, information exchange and consumer awareness. Unfortunately, these necessities are often lacking for terms relating to genetic resources and modern genetic technologies. It is understandable that as new technologies are able to create new "farmed types"[5] (e.g. new strains and genetically improved organisms), and are applied to more fishery management situations (e.g. genetic stock identification), there could be some confusion or discrepancies in how countries classify and therefore regulate the products of modern biotechnology (e.g. GMOs, gene edited organisms and newly identified genetic stocks). These discrepancies can lead to barriers to business and trade, hindering sustainable development of AqGRs, as well as potentially hindering biodiversity conservation through inappropriate policies or actions.

FAO is working to support its Members in addressing such issues, initially through the development of the State of the World's Aquatic Genetic Resources for Food and Agriculture (FAO, 2019a). Standardization and harmonization of terminology to describe genetic resources was deemed an essential precursor to the development of AquaGRIS, a global information system on AqGR and descriptions in AquaGRIS are based on defined farmed types (Mair and Lucente, 2020). More generally, FAO address terminology and definitions through a FAO Fisheries and Aquaculture Glossary (FAO, 2022e), a Glossary of biotechnology for food and agriculture (FAO, 2022b) and the AGROVOC thesaurus (FAO, 2022a), although definitions of genetics related terms are not always harmonized among these resources.

---

[4] For example the Convention on Biological Diversity, FAO Code of Conduct for Responsible Fisheries, the small scale fisheries guidelines and the governance of tenure guidelines.

Some basic definitions are still not well described. For example, FAO glossaries have no definition of "effective population size" or what a "domesticated" organism is. Other information sources need continual updating to ensure standardization and harmonization continues in the face of novel technologies, techniques and products. The term GMO is defined by FAO, the European Union and others. However, as of January 1, 2022 the Food and Drug Administration (FDA) in the United States of America has discontinued the use of the GMO label on food and has replaced it with "bioengineered food". In this case FAO biotech glossary defines bioengineering as "the use of artificial tissues, organs and organ components to replace parts of the body that are damaged, lost or malfunctioning", which is clearly not well aligned to the usage the FDA has intended. FAO is working to standardize and update definitions across various platforms, but considering the above, more rigorous and dedicated work is needed immediately.

Definitions and explanations for common terminology used in this paper are found in the glossary. This represents a small subset of terminology that needs to be standardized, harmonized and brought into common usage to enhance understanding as well as promote good policy. Once a standard terminology is accepted, policies on the use of genetic technologies would benefit from being standardized globally. That is not to say that the entire world should adopt the same policies, but the basis for national policy development should be consistent and based on scientific principles, RRI and national priorities. Such decisions would also need to decide on whether policies are focused on product-based regulation, processed based regulation, or a combination of the two, considering any uncertainties associated with the product and process regarding genetically improved farmed types (Pullin *et al.* 1999).

Policies may also need to be created or modified to address genetic information, technologies and materials as valuable resources and how to ensure fair and equitable access to them. Policies will need to address intellectual protection and patenting of genetic material and associated information, while also ensuring access and benefit sharing, accounting for agreements under the Convention on Biological Diversity (CBD) and national priorities (Hoban *et al.* 2021). Policies will also need to address equity and accountability, i.e. who bears the cost when use of genetic technologies or their products adversely impact society or the environment. Similarly, policies regarding public support to use genetic technologies that lead to improved ecosystem services (e.g. reduced tax to farmers from applying environmental friendly seed or genetically marking farmed types for better traceability in the environment) may be considered.

New technologies, new gene products and access to information regarding their use will require improved capacity and resources; capacity and resources that may not be available in poor areas, or to small-scale fishers and aquaculturists. The use of traditional farmed types may be threatened by farmed types genetically improved by new technologies. Governance structures will need to address how all sectors of society can equitably access and benefit from the use of genetic technologies.

The use of genetic technologies will not provide a complete solution ("silver bullet") for meeting increased food and conservation demands in the coming decades and there is no one "best" genetic technology. Genetic technologies provide an additional tool, or tools, to be used with other established practices depending on local circumstances. Trade-offs will be necessary to feed the planet because technological innovations may have complex impacts on stakeholders' conflicting interests. Although complete certainty on the risks/benefits of genetic technologies is impossible, policy makers and consumers may accept technologies that give major and valuable benefits when the risk or level of negative impacts is low. RRI processes may arrive at such mutual understanding and acceptance, and hence lead to successful implementation of new genetic technologies.

Governments alone will not be able to regulate all the complexities associated with new genetic technologies in the supply chain. Therefore, the fisheries and aquaculture industry along with major food producers and retailers need to intervene to help ensure proper identification, labeling and traceability. In addition to this, they need to help facilitate an open and constructive dialogue with the public and consumers on the products that they are purchasing, ensuring that sustainable production processes are followed.

How might FAO Members benefit from having a thematic characterization (framework) in which to consider the implications of current and future shifts in genetic technologies and their impact on fisheries and aquaculture.

A draft framework for determining the key areas for FAO to consider when assessing the implications that advances in the application of genetic technologies could have on the fisheries and aquaculture sector emerges from the elicitation process. These key areas of impact and the description of needed actions are a preliminary review that can assist in structuring thinking around how to respond to the rapid shifts in policy and practice that are to come. The themes presented here are by necessity broad due to the nature of the innovations and the global mandate of FAO and other international organizations, but can become more specific when applied at national and more local levels (e.g. see considerations for integrating genomics into U.S. Endangered Species Act decision making, Funk *et al.* 2018). If the thematic description is helpful, it may simplify the approach FAO *et al.* need to take when considering the adoption, use and impact of genetic technologies across fisheries and aquaculture (Table 6).

Table 6. Assessment of questions to be addressed across thematic areas due to current and predicted future genetic technologies for fisheries and aquaculture

Fundamental shift	Items to be monitored or assessed	Key questions
Fishery stock management	Baseline level of genetic characterization of stocks	What will be measured, how to negotiate change based on new stock structure information, and what is sufficient resolution of genetic understanding for effective management?
	Fishery management structured on genetic makeup of stocks	Are laws in different countries consistent, will certain groups be disadvantaged, e.g. small scale fishers?
	Efficacy of management	What traditional fishery management can be adapted or transitioned to benefit from the adoption of novel genetic approaches?
	Impacts of enhancement with hatchery raised farmed types on fisheries and the environment	Is stock enhancement based on genetic characterization of recipient wild population effective (i.e. are native stocks negatively impacted)?
	Transition of aquaculture away from reliance on forage fish for aquafeeds	How will forage fisheries, terrestrial agriculture, and the marine ecosystem be impacted?
Genetic improvement and domestication	Efficacy and cost effectiveness of genetic technologies	Where and how are the use of genetic technologies cost effective when compared to traditional breeding techniques?
	Proven traditional genetic breeding technologies	Is there an appropriate balance in the use of traditional and new technologies? Are they being displaced or effectively integrated with new technologies?
	Industry uptake	How to bring industry to the table and is industry complying with legislation and being transparent?
	Uptake of novel technologies and their products by rural and developing areas	Are technologies, and improved farmed types available, and what are the barriers for general uptake?
	Consumer acceptance	What is the level of acceptance of genetically improved farmed types and their products, and does this differ for different technologies?
	Environmental impact	Is there an acceptable level of risk in relation to the benefits? What is known about environmental impacts?

Table 6. (continued)

Fundamental shift	Items to be monitored or assessed	Key questions
Improved trade, marketing and traceability	Useful genetic markers	Are there sufficient standards for markers and markers to be informative?
	Uptake of genetic labeling	Is it widespread and understood, and are they being shared and used in a harmonized fashion?
	Protocols on genetically identifying fisheries and aquaculture products	Are they based on reliable science and accepted by traders and consumers?
	Industry acceptance	What is the level of acceptance of genetically improved farmed types, and does it vary between farmed types? Is industry complying with regulations?
	Knowledge on evolutionary history of species (hybridization, introgression) that might hinder genetic identification	Is there enough awareness raising and knowledge?
	Technical barriers to trade based on genetic information	Are these legitimate and how can they be mitigated?
Biodiversity & ecosystems	Can we better identify vulnerable components of endangered populations and assist in better targeting conservation activity?	What is the threshold for loss of genetic diversity, and can conservation policy and actions better target species / areas of need based on genetic information?
	What is the impact of genetically improved organisms on biodiversity and enabling ecosystems	What are the impacts and is there an acceptable level of risk in relation to the benefits?
	Impact of farming genetically improved farmed types on the environment	What is the acceptable level of impact from aquaculture (including escapees and effluents) and their environmental impact?
	Use of genetics in ecosystem rehabilitation and restoration	Is it effective in rehabilitation and restoration as well as cost effective?
	Use of genetics to explore new ecosystems, such as mesopelagic and deep sea	How does it compare to traditional tools in effectiveness, and is it cost-effective?
Overarching theme of Governance	Policies at national and international level on the use of genetic technologies, as well as management and control of their products	Are they relevant to change that novel technologies bring, are they consistent and equitable, and based on science?
	Standardization of terminology	Is terminology standard and widely used?
	Standardization in methodology	Are methodologies and approaches standardized?
	Privatization and sharing of information and products of gene technology	What balance is needed to promote innovation and sustainability, preventing some groups of society/countries from not accessing the benefits of genetic technologies?
	Conflict and conflict resolution	Are conflicts increasing and how can they be mitigated through negotiation to harmonize standards and norms?
	Establishment of platforms or fora for stakeholder engagement and sharing	Where do they exist and where are they needed, and what form should they take?
	Capacity to use genetic technologies and their products	What capacity is needed, does it exist and how can it be improved?
	Access and benefit sharing	Would genetically engineered products dominate markets or create more barriers for traditional/organic farmers? Are the benefits of genetic resources accessible and shared equitably?

Discussion

Given the wide range of genetic technologies being established and improved, combined with the suggested potential impacts that were highlighted by the interviewed experts, it is clear that these technologies will increasingly be applied to fisheries and aquaculture. The application of a new generation of tools will bring many positive opportunities for sustainable development. However, it is also clear that significant changes to policies and established practices will be needed, in addition to the need for raising awareness and effective communication, to realize and optimize positive impacts of implementation while avoiding or mitigating negative ones.

Not all expert interviewees responded identically in their suggestions for needed actions to address expected impacts. The responses were very likely influenced by their specific field of expertise, e.g. if we had interviewed more experts in biodiversity conservation there probably would have been a higher number of responses prioritizing biodiversity impacts. None-the-less, the experts were all well-versed on the broad issues of genetic technologies and their impacts, and in the final publication of their advice, timely edits were added that recognized new research and advances. Thus, we feel that the responses are indicative of the fishery and aquaculture sector in general. Perhaps the biggest difference among the responses was whether to choose a small subset of commercially important species to focus on or to include a wide range of species in this study and in the Boxes. It is not the purpose of this paper to debate the responses of the experts, some are controversial, and some require significant resources to achieve. Rather it is to provide a wide view of the future role of genetic technologies in fisheries and aquaculture; specific actions must be decided in other fora depending on the nature of the technology, species, impacts and needs.

The results of these interviews are consistent with other reviews on the application of genetic technologies to fisheries and aquaculture (Casey *et al.* 2016; ICES 2018; FAO 2019a) and aquatic systems more generally (D'Alessandro and Mariani 2021; Djurhuus *et al.* 2020; Danovaro *et al.* 2016). The National Oceanic and Atmospheric Administration (NOAA) examined how techniques such as high-throughput DNA sequencing and subsequent bioinformatics analyses can aid national priorities in fisheries management, aquaculture development, food and water safety, species and habitat conservation, consumer protection, and natural products discovery (NOAA 2020). The IUCN (Redford *et al.* 2019) in their scoping document made an assessment of synthetic biology and biodiversity conservation generally, while Ovenden *et al.* (2015) discussed the application and value of genetics for capture fisheries under the following themes: i) species identification, ii) fisheries stock structure, iii) resolving mixed-stock fisheries, iv) DNA as a biomarker for age, v) ecosystem monitoring, vi) estimating harvest rates and abundance, vii) genetic diversity, population abundance and resilience, viii) evolutionary responses to fishing, ix) genetic effect of stock enhancement, x) detection of pathogens and invasive species and xi) product provenance and fisheries surveillance. Scoping documentation is accompanied by documents from authorities outlining their future implementation strategies for the adoption and use of these technologies (Genome British Columbia, 2019).

While in less detail, the experts interviewed by FAO cited all these themes. Developments in biotechnology, genetics, ethical, legal and social aspects in aquaculture have been discussed by Myhr *et al.* (2012), Olesen *et al.* (2009, 2011), Rosendal *et al.* (2014), Forsberg *et al.* (2017) and Braarud Hansen *et al.* (2018). Additionally, more in-depth examination of domestication, trade and ecosystem functioning would be worthwhile to provide a level of analysis similar to that of Ovenden *et al.* (2015). Like many experts interviewed here, Olesen *et al.* (2015) stressed the value of improved application of traditional technologies such as selective breeding in aquaculture enhanced with new genomic technologies, where appropriate.

What has not been widely reported previously, in the resource management and academic press, is the need for appropriate policies and oversight of new, powerful and relatively easy to implement genetic technologies (e.g. gene editing), to ensure that they are used appropriately, avoiding their movement "underground" to avoid burdensome regulations (Smalley 2018). Experts interviewed for this study (names omitted by request) reported that new and powerful technologies such as gene editing are already being used without proper oversight. This presents a challenge to national and international institutions that want to promote the responsible use of new technologies while ensuring proper environmental and ethical risk analyses.

Given the potential for genetic technologies to impact positively on fisheries and aquaculture, several reviews have noted the lack of their implementation (Bernatchez *et al.* 2017, Casey *et al*. 2016 and FAO 2019ab). These reviews concluded that there is no longer a need to demonstrate the usefulness of genetics in fisheries and aquaculture, but rather a means to remove the barriers to their wider application is required. One major barrier is cost. Are the technologies a cost-effective selection strategy (ICES 2018)? Several of the interviewed experts stated that validation and cost-effectiveness studies on the use of genetic technologies should be conducted. Another barrier is inertia, as often procedures (e.g. fisheries assessment) have been performed similarly, using the same kind of data, for decades; meaning that the introduction of new data and adapting previous models would require significant effort, and resources should be provided for this.

Another major barrier is a lack of understanding and confidence in the technologies by potential users. Interviewed experts stressed the importance of lessening the "gap" among scientists, regulators and food producers and creating a common understanding of genetic principles, risks and benefits. Coupled with this is a danger that the application of genetics will be technology driven rather than by the immediate needs of the sector. Often, implementation of fundamental genetic management and improvement practices such as traditional selective breeding compete for the same resources as the development of new generation technologies, many of which cannot actually be applied if basic breeding programmes are not in place. Casey *et al*. (2016) noted: "discussions on the use of genetics and genomics for fisheries management are often driven by the remarkable technological progress in this field, rather than imminent needs emerging from policy frameworks". They also noted, "a focus on technology rather than policy and management needs is prone to widen the gap between science and policy, governance and management, thereby further impeding the effective integration of genetic and genomic information into the fisheries management decision making process".

Reflecting on this trend, publication of genetic technologies overall has increased substantially in the last decade (Figure 1.). It is expected that more publications describing the use, opportunities, risks and results of adopting genetic technologies will be forthcoming, and continue to provide knowledge of how genes function in an organism and in the environment. Emerging genetic technologies provide potential solutions for restoration of fishery stocks, but in their delivery we must consider whether to proactively match target species to present or predicted future environmental conditions, opening up the possibility of boosting resistance to future stress in degraded habitats in the face of environmental and climate change (Coleman *et al.* 2020).

The role of FAO

The application of genetic technologies in fisheries and aquaculture is extensive and on-going. In this assessment, FAO could not and did not attempt to cover all aspects of this rapidly advancing field. For example, much work on genetic technologies investigating gene expression (transcriptomes) (Chandhini *et al.* 2019) and host-associated microbial communities (microbiomes) (Perry *et al.* 2020) has also been conducted in the context of fisheries and aquaculture. However, as the specialized agency of the UN for fisheries and aquaculture, FAO has a mandate to address global fisheries and aquaculture issues, including through its Committee on Fisheries and other related FAO initiatives (e.g. The Commission on Genetic Resources for Food and Agriculture – CGRFA).

FAO avoids taking any position on potentially controversial issues such as the application and governance of genetic technologies. However, FAO does have a role to play in presenting issues relating to technologies in agrifood systems that are pertinent for discussions within and among Members (for example, FAO is currently preparing an issues paper on Gene Editing Technologies for efficient, inclusive, resilient and sustainable agrifood systems). Such papers provide an overview of the potential implications of new developments in modern biotechnology for sustainable agriculture development, with a focus on low and middle-income countries.

FAO will continue to support its members in the establishment and implementation of global governance frameworks, including the provision of information on which these are run, as well as guidance for fisheries and aquaculture management, conservation and utilization of aquatic species. FAO, through its strategic, normative and technical programmes can support its members in building capacity in research and development, creating reliable sources of information as well as in providing the forum for development of global agreements that result in the sustainable use and management of aquatic resources for enhanced food security and nutrition.

Regarding AqGR, FAO, in consultation with the COFI Advisory Working Group on Aquatic Genetic Resources and Technologies, developed a Framework of Essential Criteria that can guide countries to manage their AqGR. This general framework will complement the material presented here and provides guidance on information and databases, governance, policy and planning, infrastructure and equipment, capacity building and training, and enabling the private sector (FAO, 2018a). Casey *et al.* (2016) examined the range of available technologies and prioritized those that were most useful to the European Union's Common Fishery Policy. Taking these examples and the report that overviews the scope of the changes ahead, FAO members may choose to instruct the Secretariat to complete a similar process, noting their needs, FAO's mandate, and comparative advantage. Several elements of the framework presented in this paper are already covered in the Global Plan of Action of the Conservation, Sustainable Use and Development of Aquatic Genetic Resources for Food and Agriculture, adopted by FAO Council in December, 2021 (FAO, 2022c).

FAO is well placed to support Members in responding to some of these impacts directly, for example, where new information sources are needed and where national and international policies need to be negotiated, established or revised. Addressing other opportunities, as well as impacts, will require strengthened partnerships with research and development agencies, the International Council for the Exploration of the Sea (ICES), WorldFish of the Consultative Group on International Agriculture Research (CGIAR), agencies with a mandate related to international trade, e.g. World Trade Organization (WTO), academia and advanced scientific institutions, and NGOs, e.g. the International Union for Conservation of Nature (IUCN) and World Wildlife Fund for Nature (WWF). Following on from recommendations of the ICES Working Group on the Application of Genetics in Fisheries and Aquaculture (ICES 2018) and the Intergovernmental Working Group on Aquatic Genetic Resources for Food and Agriculture (FAO, 2018b), non-technical reviews and summaries for policy makers of the risks and benefits of using genetic technologies in fisheries and aquaculture may be needed. Therefore, FAO, could establish partnerships to facilitate the production and dissemination of non-technical reviews and policy summaries that help to ensure orderly roll-out in regards these complicated issues.

As an “honest broker”, FAO would be well placed to facilitate the convening of discussions on these issues, and in production of technical and policy guidance where requested to do so. FAO has been successful at developing guidance and international guidelines on a variety of important subjects in fisheries and aquaculture:

- Ecolabelling of products from marine/inland capture fisheries (FAO, 2009; FAO, 2011a)
- Aquaculture certification (FAO, 2011b)
- Small scale fisheries (FAO, 2015)
- Governance tenure (FAO, 2022f)

Furthermore, FAO, at the request of COFI, established an Advisory Working Group on Aquatic Genetic Resources and Technologies (FAO, 2022g). Members of the Advisory Working Group are appointed by the Director-General based on scientific and technical excellence and taking into consideration diversity and complementarity of scientific backgrounds and observing, as appropriate, the principle of equitable geographical representation and gender representation. Experts participate in the Advisory Working Group in their personal capacity as experts and do not represent the position of the government of which they are an official, or of the organization with which they are associated. This group advises FAO on matters concerning AqGR, technologies, and enhancing international cooperation on aquatic genetic resource management (FAO, 2022h). It is therefore well positioned to support FAO to guide nations towards responsible development, management and oversight of genetic technologies.

FAO Commission on Genetic Resources for Food and Agriculture established an Inter-governmental Technical Working Group on Aquatic Genetic Resources and Technologies (FAO, 2022i). The Working Group, consisting of 28 Members Nations of FAO elected at each regular session of the Commission, has the task to (i) review the situation and issues related to AqGR for food and agriculture and advise/make recommendations to the Commission on these matters; (ii) consider the progress made in implementing the Commission’s programme of work on AqGR for food and agriculture as well as any other matters referred to the Working Group by the Commission; and (iii) report to the Commission on its activities.

Under the Commission’s guidance, in 2019, FAO launched the first global assessment of AqGR (FAO, 2019a). In response to the report, the Commission, in consultation with the Intergovernmental Technical Working Group recommended the development of a Global Plan of Action (FAO, 2022c) which was based on the outcome of various expert consultations. FAO has also produced technical guidelines on genetics in support of the Code of Conduct for Responsible Fisheries (FAO, 2008; FAO, 2018b) and is developing a series of further guidelines to support the implementation of the Global Plan of Action for the Conservation, Sustainable Use and Development of Aquatic Genetic Resources for Food and Agriculture. The development of international guidelines is usually preceded by expert consultations and consultations of FAO Members nations.

Given the rapid advances in genetics and the great opportunities, combined with the potential for inappropriate application and consumer resistance, it may be opportune for FAO to build on this preliminary expert review to begin the process of convening an expert consultation and a technical consultation on the appropriate use and oversight of genetic technologies in fisheries and aquaculture. Potential actions for FAO to consider in regards to *Genetic improvement and domestication*, *Fisheries management and knowledge of fishery stock structure*, *Marketing and traceability of fisheries and aquaculture products in the supply chain*, and *Biodiversity and ecosystems* are described, and support for the proposed actions for development and management are summarized in Table 7 to Table 10.

Conclusion and outlook

A wide range of positive and challenging impacts to fisheries and aquaculture are expected from technical advances, decreased cost and increased accessibility of genetic technologies. Significant changes in established practices, research and innovation processes including communication and resulting policies will be necessary to realize and optimize positive impacts from these changes, while avoiding or mitigating negative ones. With this realization, there is a reformation of global objectives for the use, management and protection of genetic diversity under the Convention on Biological Diversity (Hoban *et al.* 2021).

The application of genetic technologies in fisheries and aquaculture is extensive and on-going. Due to FAO's mandate in global fisheries and aquaculture, it should support Members in the development of information resources, information tools and global governance frameworks, where requested. As a first step, the questions arising and actions identified in this study (Table 6 to Table 10), should be well communicated across FAO Membership, for example, through the Commission, COFI and its sub-committees on aquaculture and trade, to provide a foundation for policy makers to assist them in framing the discussion on next steps. Once submitted, this could be discussed at venues such as FAO Committee on Fisheries, FAO Commission on Genetic Resources for Food and Agriculture and by relevant experts in the international scientific community working on aquaculture and fisheries. This may result in FAO and partners being requested to complete follow-up actions to assist Members (see suggested actions in Table 7 to Table 10), and their focus would depend on the instruction received from FAO Members and on financial and human resources made available for delivery of those requirements.

Table 7. Potential actions for international coordination and support for countries to facilitate cooperation and advancement due to new genetic technologies, focusing on fisheries

	Key framework partition	Support for development	Support for management
Fisheries Fisheries management informed by improved species characterization, status assessments and information of exploitation impacts on the environment		**Fishery stock understanding**	
	Fisheries management informed by genetic intra and inter species characterization and understanding of population structure, genetic diversity and abundance	Promote capacity for describing and monitoring aquatic genetic resources	Develop revised fishery management plans based on genetic stock structure Use genetic technologies to monitor the presence and abundance of populations
		Refine FAO fishing areas by adding genetic stock information to species distribution areas	Provide guidelines on rebuilding depleted populations with genetically appropriate fish
			Provide a forum for negotiations of fishing rights based on new genetic delimitation of stocks
		Genetic improvement & domestication	
	Hatchery enhancement and restocking based on genetic criteria and reference points	Promote broodstock management and hatchery genetic tagging of seed or juveniles to be stocked	Provide training and guidelines on broodstock management Provide guidelines on hatchery releases of genetically appropriate stocks
	Market and value chains		
	Fishery stocks identified and marketed based on genetic stock structure	Develop standard genetic descriptors of species and stocks	Incorporate genetic descriptors into ecolabelling and certification schemes
	Biodiversity and ecosystem function		
	Ecosystem components and their function in fisheries defined through genetic analysis	Promote capacity to identify and genetically describe key ecosystem components	Assist fishery managers in developing reference points for ecosystem components other than target species of fisheries

Table 8. Potential actions for international coordination and support for countries to facilitate cooperation and advancement due to new genetic technologies, focusing on aquaculture

	Key framework partition	**Support for development**	**Support for management**
Aquaculture Aquaculture production of improved farmed types more inexpensively and quickly – including through use of synthetic biology	**Fishery stock understanding**		
	Aquaculture and associated restocking of wild populations takes place in accordance with genetic stock structure in capture fisheries	Promote hatchery genetic tagging of seed or juveniles to be stocked	Provide guidelines on how to manage hatcheries to produce genetically appropriate seed or juveniles for release
	Genetic improvement and domestication		
	Beneficial and harmful genetic resources and genetic technologies identified	Provide training and capacity building, e.g. manuals and online courses, including various learning material such as videos etc. on both traditional and new genetic improvement technologies	Provide guidelines on risk assessment and RRI processes on the use of genetic technologies
		Provide guidance on acceptable genetic technologies and risk analysis vs potential benefits	Provide guidelines on long-term genetic improvement programmes
		Develop or improve databases on genes and genetic resources	Provide resources for development and hosting of information systems
	Farmed species identified by genetic characters or genetic markers throughout the supply chain	Develop standard genetic descriptors to differentiate farmed from wild stock products	Incorporate genetic descriptors into ecolabelling and certification schemes
			Develop consumer awareness, education and two-way dialogue programmes on products of modern biotechnologies as, for example, parts of RRI processes
	Biodiversity and ecosystem function		
	Useful genes and genotypes identified from wild populations and ecosystems for development in aquaculture	Develop standard genetic descriptors to identify aquaculture escapes and effluents based on genetic descriptors, e.g. eDNA	Develop guidelines on monitoring ecosystems around aquaculture facilities based on genetic characters e.g. eDNA
		Develop access and benefit sharing arrangements for screening aquatic ecosystems for useful genetic resources	Develop guidelines and policies for conservation, bioprospecting and mining wild genetic resources

Table 9. Potential actions for international coordination and support for countries to facilitate cooperation and advancement due to new genetic technologies, focusing on trade, marketing and traceability

Trade Informative, easy to use and cost-effective identification of fisheries and aquaculture products across the value chain	**Key framework partition**	**Support for development**	**Support for management**
	Fishery stock understanding		
	Fishing directed to optimize economic return based on genetic stock structure and commercial value of specific genetic stocks	Amend species distribution maps based on genetic characters for origin of fishery products	Assist in identifying markets for fishery products
	Genetic improvement & domestication		
	Farmed types produced more efficiently and to better meet consumer demands	Promote consumer and government awareness of the benefits and risk of genetic technologies in aquaculture through RRI processes etc.	Incorporate best farming practices into aquaculture and monitor and report to oversight agencies
	Market and value chains		
	Genetic information used throughout the supply and value chains	Develop easily monitored and consistent genetic markers for aquaculture products	Incorporate genetic characters into certification and ecolabelling schemes.
		Develop monitoring of supply chains	Promote regular monitoring of supply chains
	Biodiversity and ecosystem function		
	Globally significant biodiversity and ecosystems identified by genetic information	Genetically characterize globally significant biodiversity	Promote policies and practices (and set harvest limits) that protect biodiversity based on genetic information

Table 10. Potential actions for international coordination and support for countries to facilitate cooperation and advancement due to new genetic technologies, focusing on biodiversity and ecosystem function

Conservation Ecosystem studies, management and rehabilitation informed by knowledge of how genes function in an organism and the environment	**Key framework partition**	**Support for development**	**Support for management**
		Fishery stock understanding	
	Stocks assessed using genetic descriptors, diversity, and effective population size, and rehabilitated as necessary using genetic information	Promote knowledge that assists improved understanding of genetic principles behind conservation of populations	Promote long-term education, that supports research and capacity in application of genetic technologies
	Populations of rare, threatened, or endangered species managed based on effective population size not number	Develop genetic reference points to conserved biodiversity	Manage fisheries with an ecosystem approach that looks at more than fishery stocks
		Genetic improvement & domestication	
	Genetic technologies used to reduce impacts of escapes of farmed types on environment	Develop capacity in using genetic technologies and RRI processes	Monitor use and efficacy of genetic technologies used in biodiversity conservation
	Genetic technologies including synthetic biology used to recreate or recover important biodiversity or ecosystem services lost	Develop descriptors of ecosystems and their status based on genetic parameters	Monitor efficacy of genetic technologies in ecosystem/biodiversity conservation
		Market and value chains	
	Protected biodiversity better identified through genetic analysis, e.g. cryptic species, juveniles, larvae and eggs identified by genetic analysis	Promote use of genetic identification and analysis in the supply chain and for all life history stages of aquatic biodiversity	Develop guidelines and capacity in using genetic information in the supply chain and in ecolabelling and certification schemes
		Biodiversity and ecosystem function	
	More powerful models of how threatened and endangered species respond to natural and anthropogenic changes	Promote guidelines, including the advantages, on using genetic identification of globally significant biodiversity in conservation	Link with IGO and NGOs to develop and monitor use of genetic descriptors in biodiversity conservation
	Clearer choices on interventions to maintain species, populations and ecosystems resilience resulting in a refocusing of conservation effort	Develop suite of genetic technologies and their risks and benefits when used in conservation of biodiversity	Link with IGO and NGOs to develop and monitor use of genetic descriptors in biodiversity conservation

References

Aguirre-Sarabia, I., Díaz-Arce,N., Pereda-Agirre, I. *et al.* 2021. Evidence of stock connectivity, hybridization and misidentification in white anglerfish support the need of a genetics-informed fisheries management framework. *Evol. Appl.,* 14(3):2221-2230.

Anderson, G., Lal, M., Stockwell, B., Hampton, J., Smith, N., Nicol, S. & Rico, C. 2020. No population genetic structure of skipjack tuna (*Katsuwonus pelamis*) in the tropical western and central Pacific assessed using single nucleotide polymorphisms. *Front. Mar. Sci.,* 7:570760. https://doi.org/10.3389/fmars.2020.570760

Andreou, D., Vacquie-Garcia, J., Cucherousset, J., Blanchet, S., Gozlan, R.E.& G. Loot. 2012. Individual genetic tagging for teleosts: an empirical validation and a guideline for ecologists. *J. Fish Biol.,* 80:181-194.

Bartley, D., Rana, K., & Immink, A.J. 2001. The use of inter-specific hybrids in aquaculture and fisheries. *Rev. Fish Biol. Fish.,*10(3):325-337

Berg, P.R., Jorde, P.E., Glover, K.A., Dahle, G., Taggart, J.B., Korsbrekke, K., Dingsør, G.E., Skjæraasen, J.E., Wright, P.J., Cadrin, S.X., Knutsen, H., & Westgaard, J. 2021. Genetic structuring in Atlantic haddock contrasts with current management regimes. *ICES J. Mar. Sci.,* 78(1), 1-13. https://doi.org/10.1093/icesjms/fsaa204

Berger, A.M., Deroba, J.J., Bosley, K.M. *et al.* 2021. Incoherent dimensionality in fisheries management: consequences of misaligned stock assessment and population boundaries. *ICES J. Mar. Sci.,* 78(1):155-171

Bernatchez, L., Wellenreuther, M., Araneda, C., Ashton, D.T., *et al.* 2017. Harnessing the Power of Genomics to Secure the Future of Seafood. *Trends Ecol. Evol.,* 32:665-680. https://doi.org/10.1016/j.tree.2017.06.010

Berry, O., Richards, Z., Moore, G., Hernawan, U., Travers, M., & Gruber, B. 2019. Oceanic and coastal populations of a harvested macroinvertebrate *Rochia nilotica* in north-western Australia are isolated and may be locally adapted. *Mar. Freshwater Res.,* 71:782-793. https://doi.org/10.1071/MF19172

Bessey, C., Jarman, N., Simpson, T., Miller, H., Stewart, T., Keesing, J., Berry, O. 2021. Passive eDNA collection enhances aquatic biodiversity analysis. *Comm. Biol.,* 4(1):236. https://doi.org/10.1038/s42003-021-01760-8.

Bilio, M. 2007. *Controlled reproduction and domestication in aquaculture*. Aquaculture Europe 37. 10p. https://issuu.com/easonline/docs/domestication_bilio/8

Blasiak, R., Jouffray, J.B., Wabnitz, C.C.C., Sundström, E., & Österblom, H. 2018. Corporate control and global governance of marine genetic resources. *Sci. Adv.,* 4(6):eaar5237. https://doi.org/10.1126/sciadv.aar5237.

Bolstad, G. H., Karlsson, S., Hagen, I.J., Fiske, P. *et al.* 2021. Introgression from farmed escapees affects the full life cycle of wild Atlantic salmon. *Sci. Adv.,* 7(52): eabj3397. https://doi.org/10.1126/sciadv.abj3397

Boudry, P., Allal, F., Aslam, M.L., Bargellonid, L., Bean, T.P., *et al.* 2021. Current status and potential of genomic selection to improve selective breeding in the main aquaculture species of International Council for the Exploration of the Sea (ICES) member countries. *Aquac. Rep.* 20(15):100700. https://doi.org/10.1016/j.aqrep.2021.100700

Bourgeois, Y.X.C., & Warren, B.H. 2021. An overview of current population genomics methods for the analysis of wholegenome resequencing data in eukaryotes. *Mol. Ecol.,* 30(23):6036-6071.

Bravington, M.V., Grewe, P.M., Davies, C.R. 2016. Absolute abundance of southern bluefin tuna estimated by close-kin mark-recapture. *Nat. Commun.* 14(7):13162. https://doi.org/10.1038/ncomms13162

Bravington, M., Skaug, H.J., & Anderson, E.C. 2016. Close-Kin Mark-Recapture. *Stat. Sci.,* 31(2):259-274. https://doi.org/10.1214/16-STS552

Brennan, R.S., Healy, T.M., Bryant, H.J., La, M.V., Schulte, P.M., & Whitehead, A. 2018. Integrative population and physiological genomics reveals mechanisms of adaptation in killifish. *Mol. Biol. Evol.,* 35(11): 2639-2653. https://doi.org/10.1093/molbev/msy154

Brennan, R.S., Garrett, A.D., Huber, K.E., Hargarten, H. & Pespeni, M.H., 2019. Rare genetic variation and balanced polymorphisms are important for survival in global change conditions. *Proc. R. Soc. B.,* 286(1904): 20190943. https://doi.org/10.1098/rspb.2019.0943

Canals, O., Mendibil, I., Santos, M., Irigoien, X., *et al.* 2021. Vertical stratification of environmental DNA in the open ocean captures ecological patterns and behavior of deep-sea fishes. *Limnol. Oceanogr.,* 6:339-347.

Cardeñosa, D., Chapman, D.D. 2018a. *Shark CSI: The Application of DNA Forensics to Elasmobranch Conservation*. In: Shark Research: Emerging Technologies and Applications for the Field and Laboratory. CRC Press.

Cardeñosa, D., Quinlan, J., Shea, K.H., Chapman, D.D. 2018b. Multiplex real-time PCR assay to detect illegal trade of CITES-listed shark species. *Sci. Rep.*, 8(1):16313.

Cardeñosa, D., Gollock, M.J., Chapman, D.D. 2019. Development and application of a novel real-time polymerase chain reaction assay to detect illegal trade of the European eel (*Anguilla anguilla*). *Conserv. Sci. Pract.*, 1(5):e39.

Cardeñosa D., Chapman, D.D., Robles, Y.L., Ussa, D.A., Caballero, S. 2021 Rapid species and river of origin determination for matamata turtles (*Chelus* sp.) using real time PCR: Facilitating rapid return of trafficked specimens back to the wild, Aquatic Conservation: *Marine and Freshwater Ecosystems*. https://doi.org/10.1002/aqc.3613.

Casey, J.,E. Jardim J., & T.H. Martinsohn. 2016. The role of genetics in fisheries management under the E.U. common fisheries policy. *J. Fish Biol.*, 89:2755–2767. https://doi.org/10.1111/jfb.13151

CEN. 2022. Making standards for Europe. https://www.cencenelec.eu/

Chandhini, S., & Kumar, V.J.R. 2019. Transcriptomics in aquaculture: current status and applications. *Rev. Aquac.*, 11(4):1379-97.

Clutton-Brock, J. 2012. *Animals as Domesticates. A World View through History*. Michigan State University Press. ISBN-13: 978-1-61186-0283.

Coleman, M.A., Wood, G., Filbee-Dexter, K., Minne A.J.P., Goold, H.D., Vergés, A., Marzinelli, E.M., Steinberg, P.D., & Wernberg, T. 2020. Restore or Redefine: Future Trajectories for Restoration. *Front. Mar. Sci*., 7:237.

Cordier, T., Alonso-Sáez, L., Apothéloz-Perret-Gentil, L., Aylagas, E., Bohan, D.A., Bouchez, A., Chariton, A., Creer S., Frühe, L., Keck, F., Keeley, N., Laroche, O., Leese, F., Pochon, X., Stoeck, T., Pawlowski, J., Lanzén, A. 2020. Ecosystems monitoring powered by environmental genomics: A review of current strategies with an implementation roadmap. *Mol. Ecol.,* 30(13):2937-2958. https://doi.org/10.1111/mec.15472

Costello, M.J., Cheung, A., & De Hauwere, N. 2021. Surface area and the seabed area, volume, depth, slope, and topographic variation for the world's seas, oceans, and countries. *Environ. Sci. Technol*., 44(23):8821-8828.

Cuende, E., Mendibil, I., Bachiller, E., Álvarez, P., *et al.* 2017. A real-time PCR approach to detect predation on anchovy and sardine early life stages. *J. Sea Res.,*130:204-209. https://doi.org/10.1016/j.seares.2017.06.009

D'Alessandro, S. & Mariani, S. 2021 Sifting environmental DNA metabarcoding data sets for rapid reconstruction of marine food webs. *Fish. Fish*., 22(4): 822-833. https://doi.org/10.1111/faf.12553

Danovaro, R, Carugati., L. Berzano, M., *et al*. 2016. Implementing and Innovating Marine Monitoring Approaches for Assessing Marine Environmental Status. *Front. Mar. Sci.,* 3:213. https://doi.org/10.3389/fmars.2016.00213

DeHaan, P.W., Jordan, G.R. & Ardren, W.R. 2008. Use of genetic tags to identify captive-bred pallid sturgeon (*Scaphirhynchus albus*) in the wild: improving abundance estimates for an endangered species. *Conserv. Genet.,* 9:691-697.

Díaz-Arce, N., Arrizabalaga, H., Murua, H., Irigoien, X. & Rodríguez-Ezpeleta, N. 2016. RAD-seq derived genome-wide nuclear markers resolve the phylogeny of tunas. *Mol. Phy. Evol.,* 102: 202-207. https://doi.org/10.1016/j.ympev.2016.06.002

Djurhuus, A., Closek, C. J., Kelly, R. P., Pitz, K. J., Michisaki, R. P., Starks, H. A., Walz, K. R., Andruszkiewicz, E. A., Olesin, E., Hubbard, K., Montes, E., Otis, D., Muller-Karger, F. E., Chavez, F. P., Boehm, A. B. & Breitbart, M. 2020. Environmental DNA reveals seasonal shifts and potential interactions in a marine community. *Nat. Commun.,* 11(1):1-9. https://doi.org/10.1038/s41467-019-14105-1

Du S.J. Gong, Z., Fletcher, G.L., Shears, M.A., *et al.* 1992. Growth enhancement in transgenic Atlantic salmon by the use of an "all fish" chimeric growth hormone gene construct. *Biotechnol. J.*, 10:176-181.

Economist. 2021. *Cracking the code. The sequencing of genetic material is a powerful conservation tool*. June 19th 2021 Edition.

Esvelt, K.M., Smidler, A.L., Catteruccia, F., & Church, G.M. 2014. Concerning RNA-guided gene drives for the alteration of wild populations. *eLife,* 3:e03401.

European Commission. 2022a. Genetically Modified Organisms. https://food.ec.europa.eu/plants/genetically-modified-organisms_en

European Commission. 2022b. FishPopTrace. https://fishpoptrace.jrc.ec.europa.eu/

FAO. 2008. *Aquaculture development. 3. Genetic resource management. FAO Technical Guidelines for Responsible Fisheries.* No. 5, Suppl. 3. Rome. 2008. 125p. http://www.fao.org/3/a-i0283e.pdf

FAO. 2009. *Guidelines for the ecolabelling of fish and fishery products from inland capture fisheries*. Rome. ISBN 978-92-5-006932-6.

FAO. 2011a. *Guidelines for the ecolabelling of fish and fishery products from marine capture fisheries.* Rome. ISBN 978-92-5-006405-5.

FAO. 2011b. Technical guidelines on aquaculture certification. Rome. ISBN 978-92-5-006912-8.

FAO. 2015. *Voluntary Guidelines for Securing Sustainable Small-Scale Fisheries in the Context of Food Security and Poverty Eradication*. Rome. ISBN 978-92-5-108704-6

FAO. 2018a**.** *Aquaculture Development 9. Development of aquatic genetic resources: A framework of essential criteria*. TG5 Suppl. 9. Rome. 88 pp. Licence: CC BY-NC-SA 3.0 IGO. http://www.fao.org/3/CA2296EN/ca2296en.pdf

FAO. 2018b. *Second Session of the Ad Hoc Intergovernmental Technical Working Group on Aquatic Genetic Resources for Food and Agriculture*. Rome. https://www.fao.org/fi/static-media/MeetingDocuments/AqGenRes/ITWG/2018/MX047en.pdf

FAO. 2019a. *The State of the World's Aquatic Genetic Resources* for Food and Agriculture. *FAO Commission on Genetic Resources for Food and Agriculture assessments*. Rome. ISBN 978-92-5-131608-5.

FAO. 2019b. *ABS Elements: Elements to facilitate domestic implementation of access and benefit-sharing for different subsectors of genetic resources for food and agriculture – with explanatory notes*. Rome. 84 pp Licence: CC BY-NC-SA 3.0 IGO. https://www.fao.org/policy- support/tools-andpublications/resources-details/fr/c/1201566/

FAO. 2020. *The State of World Fisheries and Aquaculture 2020. Sustainability in action*. Rome. https://doi.org/10.4060/ca9229en

FAO. 2022a. *AGROVOC Multilingual Thesaurus*. Rome. https://agrovoc.fao.org/browse/agrovoc/en/

FAO. 2022b. *Glossary of biotechnology for food and agriculture*. Rome. https://www.fao.org/3/Y2775E/y2775e07.htm

FAO. 2022c. *Global Plan of Action for the Conservation, Sustainable Use and Development of Aquatic Genetic Resources for Food and Agriculture*. Commission on Genetic Resources for Food and Agriculture. Rome. https://doi.org/10.4060/cb9905en

FAO. 2022d. *Database of Farmed types in Aquaculture. In: Food and Agriculture Organization of the United Nations [online]*. Rome. Database version 1-2022. https://www.fao.org/fishery/aquagris/home

FAO. 2022e. *Fisheries and Aquaculture Glossary*. Rome. https://www.fao.org/fishery/en/glossary/en

FAO. 2022f. *Voluntary guidelines on the responsible governance of tenure of land, fisheries and forests in the context of national food security.* Rome. ISBN 978-92-5-107277-6

FAO. 2022g. *Advisory Working Group on Aquatic Genetic Resources and Technologies*. https://www.fao.org/aquatic-genetic-resources/activities/awg/en/.

FAO. 2022h. *Terms of reference of the advisory working group*. https://www.fao.org/3/bs237e/bs237e.pdf

FAO. 2022i. *Aquatic biodiversity: underpinning aquatic food security*. https://www.fao.org/aquatic-genetic-resources/working-groups

Agricultural Marketing Service. 2018. National Bioengineered Food Disclosure Standard. *Federal Register*. 83:245. https://www.federalregister.gov/documents/2018/12/21/2018-27283/national-bioengineered-food-disclosure-standard

Felt, U. 2018. *Responsible Research and Innovation*. Routledge Handbook of Genomics, Health and Society (2nd ed.). Routledge. ISBN 9781315451671.

Fernández, A.P., Marques, V., Fopp, F., Juhel, J.B., *et al.* 2020. Comparing environmental DNA metabarcoding and underwater visual census to monitor tropical reef fishes. *Env. DNA,* 3:142-156.

Forsberg, E., Braarud Hanssen, A., Nielsen, H.M., & Olesen, I. 2017. The Misalignment of Views Between the Patent System and the Wider Society. *Sci. Eng. Ethics,* 24:1551-1576. https://doi.org/10.1007/s11948-017-9956-5

Forseth, T., Barlaup, B.T. Finstad, B., Fiske, P., Gjøsæter, H., *et al.* 2017. The major threats to Atlantic salmon in Norway. *ICES J. Mar. Sci.,* 74(6):1496-1513. https://doi.org/10.1093/icesjms/fsx020

Fraija-Fernandez, N., Bouquieaux, M.C., Rey, A., Mendibil, I., *et al*. 2020. Marine water environmental DNA metabarcoding provides a comprehensive fish diversity assessment and reveals spatial patterns in a large oceanic area. *Ecol. Evol.,* 10:7560-7584.

Frankham, R., Bradshaw, C.J.A., & Brook, B.W. 2014. Genetics in conservation management: revised recommendations for the 50/500 rules, Red List criteria and population viability analyses. *Biol. Conserv.*, 170:56–63.

Funk, W.C., McKay, J.K., Hohenlohe, P.A., & Allendorf, F.W. 2012. Harnessing genomics for delineating conservation units. *Trends Ecol. Evol.*, 27:489-496. https://doi.org/10.1016/j.tree.2012.05.012

Funk, W.C., Forester, B.R., Converse, S.J. Darst, C., & Morey, S. 2019. Improving conservation policy with genomics: A guide to integrating adaptive potential into U.S. Endangered Species Act decisions for conservation practitioners and geneticists. *Conserv. Genet.*, 20:115-134. https://doi.org/10.1007/s10592-018- 1096-1

Gandra, M., Assis, J., Martins, M. R., & Abecasis, D. 2020. Reduced Global Genetic Differentiation of Exploited Marine Fish Species. *Mol. Biol. Evol.* 38:1402-1412. https://doi.org/10.1093/molbev/msaa299

Genome British Columbia. 2019. A genomics strategy for British Columbia's fisheries & aquaculture sector. https://www.genomebc.ca/wp-content/uploads/2019/08/0112.001.002_Fisheries-Aquaculture-Sector-Strategy_FINAL.pdf

Gilbey, J. Carvalho, g., Castilho, R., Coscia, I., Coulson, M.W., *et al.* 2021 Life in a drop: Sampling environmental DNA for marine fishery management and ecosystem monitoring. *Mar. Policy,* 124:104331.

Gjedrem, T., & Rye, M. 2018. Selection response in fish and shellfish: a review. *Rev. Aquac*., 10 (1):168-179. https://doi.org/10.1111/raq.12154

Gjedrem, T., Robinson, N., Rye, M., 2012. The importance of selective breeding in aquaculture to meet future demands for animal protein: a review. *Aquaculture,* 350:117-129. https://doi.org/10.1016/j.aquaculture.2012.04.008

Gratacap, R.L., Wargelius, A., Edvardsen, R.B. & Houston, R.D., 2019. Potential of genome editing to improve aquaculture breeding and production. *Trends Genet.*, 35(9):672-684.

Günther, B., Fromentin, J., Metral, L., & Arnaud-Haond, S. 2021. Metabarcoding confirms the opportunistic foraging behaviour of Atlantic bluefin tuna and reveals the importance of gelatinous prey. *PeerJ*, 9:e11757. https://doi.org/10.7717/peerj.11757

Gurgel, C.F.D., Camacho, O., Minne, A.J.P., Wernberg, T., & Coleman, M.A. 2020. Marine Heatwave Drives Cryptic Loss of Genetic Diversity in Underwater Forests. *Curr. Biol.,* 30:1-8.

Hanssen, A.B., Forsberg, E-M., Nielsen, H.M., Kettunen, A. & Olesen, I. 2018. The unacknowledged uncertainty of biopatenting; a case study of the AquaBounty patent in the European patent system. *Proceedings of the World Congress on Genetics Applied to Livestock Production*, 11.988. 7 pp.

Harland, J. 2019. The origins of aquaculture. *Nat. Ecol. Evol.,* 3(10):1378-79. https://doi.org/10.1038/s41559-019-0966-3

Harmon, L.J., & Braude. S. 2010. *Conservation of Small Populations: Effective Population Sizes, Inbreeding, and the 50/500 Rule*. Pp 125-138. In: An Introduction to Methods and Models in Ecology, Evolution, and Conservation Biology. Edited by: Stanton Braude and Bobbi S. Low. https://doi.org/10.1515/9781400835454

Hemming, V., Burgman, M.A., Hanea, A.M., McBride, M.F., & Wintle, B.C. 2018. A practical guide to structured expert elicitation using the IDEA protocol. *Methods. Ecol. Evol.,* 9:169-180. https://doi.org/10.1111/2041-210X.12857

Hillestad, B., Johannessen, S., Melingen, G.O., & Moghadam, H.K. 2021. Identification of a new infectious pancreatic necrosis virus (IPNV) variant in Atlantic Salmon (*Salmo salar* L.) that can cause high mortality even in genetically resistant fish. *Front. Genet.,* 12:635185. https://doi.org/10.3389/fgene.2021.635185

Hoban, S., Bruford, M.W., Funk, W.C., Galbusera, P., Griffith, M.P. *et al.* 2021. Global Commitments to Conserving and Monitoring Genetic Diversity Are Now Necessary and Feasible. *BioScience,* 71(9): 964-976. https://doi.org/10.1093/biosci/biab054

Hotaling, S., Kelley, J.L., & Frandsen, P.B. 2021. Toward a genome sequence for every animal: Where are we now? *PNAS*, 118(52):e2109019118. https://doi.org/10.1073/pnas.2109019118

Houston, R.D., Haley, C.S., Hamilton, A., Guy, D.R., Mota-Velasco, J.C., Gheyas, A.A. *et al.* 2009. The susceptibility of Atlantic salmon fry to freshwater infectious pancreatic necrosis is largely explained by a major QTL. *Heredity.,* 105:318-327.

Hutchings, J.A. & Kuparinen, A. 2020. Implications of fisheries-induced evolution for population recovery: Refocusing the science and refining its communication. *Fish. Fish.,* 21(2):453-464. https://doi.org/10.1111/faf.12424

IBOL. 2022. International Barcode of Life: Illuminate Biodiversity. https://ibol.org/

ICES. 2018. Interim Report of the Working Group on the Application of Genetics in Fisheries and Aquaculture (WGAGFA), 15–17 May 2018, Brest, France. *ICES CM* ASG:03. 39 pp.

Keep.eu. 2022. LABELFISH. https://keep.eu/projects/5412/LABELFISH-EN/

Kerr, L.A., Hintzen, N.T., Cadrin, S.X., Clausen, L.W., Dickey-Collas, M., Goethel, D. R., Hatfield, M.C., Kritzer, J.P., Nash, R.D. 2017. Lessons learned from practical approaches to reconcile mismatches between biological population structure and stock units of marine fish. *ICES J. Mar. Sci.*, 74:1708-1722.

Kleiber, P., & Maunder, M.N. 2008. Inherent bias in using aggregate CPUE to characterize abundance of fish species assemblages. *Fisheries Research* 93:140–145.

Kristensen, M.L., Olsen, E.M., Moland, E., Knutsen, H., Grønkjær, P., Koed, A., Källo, K. & Aarestrup, K. 2021. Disparate movement behavior and feeding ecology in sympatric ecotypes of Atlantic cod. *Ecol. Evol.*, 11(16):11477-11490.

Kuwae, M., Tamai, H., Doi, H., Sakata,M., Minamoto, T., Suzuki, Y. 2020. Sedimentary DNA tracks decadal-centennial changes in fish abundance. *Commun. Biol.,* 3(1):1-12.

Leitwein, M., Duranton, M., Rougemont, Q., Gagnaire, P. A., & Bernatchez, L. 2020. Using haplotype information for conservation genomics. *Trends Ecol. Evol.*, 35(3):245-258. https://doi.org/10.1016/j.tree.2019.10.012

Lorenzen, K., Beveridge, M.C. & Mangel, M. 2012. Cultured fish: integrative biology and management of domestication and interactions with wild fish. *Biol. Rev*., 87:639–660.

Mair, G.C. & Lucente D. 2020. What are “Farmed Types” in Aquaculture and why do they Matter? *FAO Aquaculture Newsletter,* 61:40-42. http://www.fao.org/3/ca8302en/CA8302EN.pdf

Mayne, B., Espinoza, T., Roberts, D., Butler, G.L. *et al.* 2021. Nonlethal age estimation of three threatened fish species using DNA methylation: Australian lungfish, Murray cod and Mary River cod. *Mol. Ecol. Resour*., 21(7): 2324-2332. https://doi.org/10.1111/1755-0998.13440

Milner, G.B., Teel, D.J., Utier, F.M., & Winans G.A. 1985. A Genetic Method of Stock Identification in Mixed Populations of Pacific Salmon, *Oncorhynchus* spp. *Mar. Fish. Rev.*, 47:1-8.

Miya M., Gotoh R.O. & Sado T. 2020. MiFish metabarcoding: a high-throughput approach for simultaneous detection of multiple fish species from environmental DNA and other samples. *Fish. Sci.,* 86:939-970. https://doi.org/10.1007/s12562-020-01461-x

Myhr, A.I., Kristin Rosendal, G. & Olesen, I. 2012. New developments in biotechnology and IPR in aquaculture: are they sustainable? *Aquaculture*. ISBN 978-953-307-974-5.

Nature. 2022. Japan embraces CRISPR-edited fish. *Nat. Biotechnol.,* 40:10. https://doi.org/10.1038/s41587-021-01197-8.

Normile, D. 2018. CRISPR bombshell: Chinese researcher claims to have created gene-edited twins. Science Insider. https://www.science.org/content/article/crispr-bombshell-chinese-researcher-claims-have-created-gene-edited-twins

Nep, S., & O'Doherty, K. 2013 Understanding Public Calls for Labeling of Genetically Modified Foods: Analysis of a Public Deliberation on Genetically Modified Salmon. *Soc. Nat. Resour.,* 26(5):506-521. https://doi.org/10.1080/08941920.2012.716904

Nielsen, E.E., Cariani, A., Aoidh, E.M., Maes, G.E., Milano, I. *et al.* 2012. Gene-associated markers provide tools for tackling illegal fishing and false eco- certification. *Nat. Commun.,* https://doi.org/10.1038/ncomms1845.

NOAA. 2020. NOAA ‘Omics Strategy’. Strategic Application of Transformational Tools for the National Oceanic and Atmospheric Administration U.S. Department of Commerce. p. 8. https://sciencecouncil.noaa.gov/Portals/0/2020%20Omics%20Strategy.pdf?ver=2020-09-17-150026- 760

Olesen, I., Rosendal, K., Rye, M., & Bentsen, H.B. 2009. Who Shall Own the Genes of Farmed Fish? Global privatization and its impact., Edited by Hagen I J, Halvorsen T J,: chapter 6. Who shall own the genes of farmed fish?; *Nova Science Publ.* ISBN: 978-1-604-56785-4, p. 103-113.

Olesen, I., Myhr, A.I., & Rosendal K.G. 2011. Sustainable Aquaculture: Are We Getting There? Ethical Perspectives on Salmon Farming. *J. Agric. Environ. Ethics.*, 24(4). https://doi.org/10.1007/s10806-0109269-z

Olesen, I., Bentsen, H.B., Phillips, M. and Ponzoni, R.W. 2015. Can the Global Adoption of Genetically Improved Farmed Fish Increase beyond 10%, and How? *J. Mar. Sci. Eng.,* 3:240-266. https://doi.org/10.3390/jmse3020240

Ovenden, J., Berry, O., Welch, D.J., Buckworth, R.C. & Dichmont, C.M. 2015. Ocean’s eleven: a critical evaluation of the role of population, evolutionary and molecular genetics in the management of wild fisheries. *Fish. Fish.,* 16, 125–159. https://doi.org/10.1111/faf.12052

Ovenden, J., Hoyle, S., Peel, D., & Broderick, D. 2002. Gene-tagging for fisheries sustainability. *Today's Life Science*. 14(5):50-52.

Oye, K.A., Esvelt, K. Appleton, E. Catteruccia, F., Church, G. Kuiken, T., Lightfoot, S.B., McNamara, J., Smidler, A., & Collins, J.P. 2014. "Regulating gene drives." *Science.* https://doi.org/10.1126/science.1254287.

Pearson, S.M. 2013. Encyclopedia of Biodiversity (Second Edition). https://www.sciencedirect.com/topics/earth- and-planetary-sciences/effective-population-size

Perry, W.B., Lindsay, E., Payne, C.J., Brodie, C. & Kazlauskaite, R., 2020. The role of the gut microbiome in sustainable teleost aquaculture. *Proc. R. Soc*. B., 287(1926):20200184. https://doi.org/10.1098/rspb.2020.0184

Petrou, E.L. Fuentes-Pardo, A.P., Rogers, L.A., Orobko, M., *et al.* 2021. Functional genetic diversity in an exploited marine species and its relevance to fisheries management. *Proc. R. Soc*. B., 288:20202398. https://doi.org/10.1098/rspb.2020.2398

Pikitch, E.K. 2018. A tool for finding rare marine species. *Science*, 360(6394):1180-1183. https://doi.org/10.1126/science.aao3787

Pinsky, M.L., Palumbi, S.R. 2014. Meta-analysis reveals lower genetic diversity in overfished populations. *Mol. Ecol.*, 23(1):29–39.

Pinsky, M.L. 2021. Genomic stability through time despite decades of exploitation in cod on both sides of the Atlantic. *PNAS*, 118:15. https://doi.org/10.1073/pnas.2025453118

Prince, A.E.R., Berkman, B.E. 2018. Reconceptualizing harms and benefits in the genomic age. *Per. Med.*, 15(5):419-428. https://doi.org/10.2217/pme-2018-0022

Pullin, R.S.V., D.M. Bartley, & J. Kooiman (eds). 1999. Towards Policies for Conservation and Sustainable Use of Aquatic Genetic Resources. *ICLARM Conference Proceedings*, 59. Manila.

Redford, K.H., Brooks, T.M., Macfarlane, N.B.W. & Adams, J.S. (eds.) 2019. Genetic frontiers for conservation: An assessment of synthetic biology and biodiversity conservation. Technical assessment. Gland, Switzerland:166pp. https://portals.iucn.org/library/efiles/documents/2019-012-En.pdf

Rees, H.C., Maddison, B.C., Middleditch, D.J., Patmore, J.R.M. & Gough, K.C. 2014. The detection of aquatic animal species using environmental DNA – a review of eDNA as a survey tool in ecology. *J. Appl. Ecol.*, 51:1450–1459.

Reid, N.M., Proestou, D.A. Clark, B.W. Warren, W.C. Colbourne, J.K. Shaw, J.R. Karchner, S.I. Crawford, D.L. Oleksiak, M.F. Hahn, M.E. Nacci, D.& Whitehead. A. 2016. The genomic landscape of rapid repeated evolutionary adaptation to toxic pollution in wild fish. *Science*, 354(6317):1305-1308.

Rodríguez - Ezpeleta, N., Díaz - Arce, N., Walter III, J. F., Richardson, D. E., Rooker, J. R., Nøttestad, L. *et al.* 2019. Determining natal origin for improved management of Atlantic bluefin tuna. *Front. Ecol. Environ.*, 17:439-444. https://doi.org/10.1002/fee.2090

Rodríguez-Ezpeleta, N., Zinger, L., Kinziger, A., Bik, H.M., Bonin, A., Coissac, E., Emerson, B.C., Lopes, C.M., Pelletier, T.A., Taberlet, P. & Narum, S. 2021. Biodiversity monitoring using environmental DNA. *Mol. Ecol. Resour.*, 5:1405-1409.

Rosendal, G.K., Olesen, I., & Walløe Tvedt, M. 2014. Balancing ABS and IPR governance in the aquaculture sector. In Sebastian Oberthür and G. Kristin Rosendal (Editors.). *Global Governance of Genetic Resources*. Routledge, pp. 196-212.

Rourke, M.L., Fowler, A.M., Hughes, J.M., Broadhurst, M.K., DiBattista, J.D., Fielder, S., Wilkes Walburn, J., Furlan, E.M. 2021. Environmental DNA (eDNA) as a tool for assessing fish biomass: a review of approaches and future considerations for resource surveys. *Environ. DNA*, 4:9–33.

Russo, T., G. Maiello, L. Talarico, C. Baillie, G. Colosimo, L. D'Andrea, F. Di Maio, F. Fiorentino, S. Franceschini, G. Garofalo, D. Scannella, S. Cataudella, & Mariani, S. 2021. All is fish that comes to the net: metabarcoding for rapid fisheries catch assessment. *Ecol. Appl.*, 31(2):e02273. https://doi.org/10.1002/eap.2273

Salter, I. Joensen, M., Kristiansen, R., Steingrund, P., & Vestergaard, P. 2019. Environmental DNA concentrations are correlated with regional biomass of Atlantic cod in oceanic waters. *Commun. Biol.*, 2:461. https://doi.org/10.1038/s42003-019-0696-8

SeaTraces. 2022. Tracking seafood's journey. https://www.seatraces.eu/

Secretariat of the Convention on Biological Diversity. 2011. Nagoya Protocol on Access to Genetic Resources and the Fair and Equitable Sharing of Benefits Arising from their Utilization to the Convention on Biological Diversity: text and annex. Montreal, Canada. ISBN: 92-9225-306-9.

Segelbacher, G., Bosse, M., Burger, P. *et al.* 2022. New developments in the field of genomic technologies and their relevance to conservation management. *Conserv. Genet.,* 23:217–242. https://doi.org/10.1007/s10592-021-01415-5

Shelton A.O., Ramón-Laca, A., Wells, A., Clemons, J., Chu, D., *et al.* 2022. Environmental DNA provides quantitative estimates of Pacific hake abundance and distribution in the open ocean. *Proc. R. Soc. B.,* 289:20212613. https://doi.org/10.1098/rspb.2021.2613

Smalley, E. 2018. As CRISPR–Cas adoption soars, summit calls for genome editing oversight. *Nat. Biotechnol.,* 36, 485. https://doi.org/10.1038/nbt0618-485

Spear, M.J., Embke, H.S., Krysan, P.J., Vander Zanden, M.J. 2020. Application of eDNA as a tool for assessing fish population abundance, *Environ. DNA*, 3(1) 83-91. https://doi.org/10.1002/edn3.94

Tave, D. 1995. Selective breeding programmes for medium-sized fish farms. *FAO Fisheries Technical Paper* 352: 122 p.

Teletchea, F. 2021. Fish domestication in aquaculture: 10 unanswered questions. *Anim. Front.,*11:3, 87–91. https://doi.org/10.1093/af/vfab012

Therkildsen, N.O. Wilder, A.P., Conover, D.O., Munch, S.B., Baumann, H., Palumbi, S.R. 2019. Contrasting genomic shifts underlie parallel phenotypic evolution in response to fishing. *Science*, 365(6452): 487–490.

Tibbetts, S.M., Wall, C.L., Barbosa-Solomieuc, V., Bryenton, M.D., Plouffe, D.A., Buchanand, J.T., & Lall, S.P. 2013. Effects of combined 'all-fish' growth hormone transgenics and triploidy on growth and nutrient utilization of Atlantic salmon (*Salmo salar* L.) fed a practical grower diet of known composition. *Aquaculture,* 406(7):141-152.

Van Eenennaam, A.L. & Muir, W.M. 2011. Transgenic salmon: A final leap to the grocery shelf? *Nat. Biotechnol*., 29(8):706710.

Van Eenennaam, A.L., De Figueiredo Silva, F., Trott, J.F., Zilberman, D. 2021. Genetic Engineering of Livestock: The Opportunity Cost of Regulatory Delay. *Annu. Rev. Anim. Biosci*., 9:453-478.

van Zinnicq Bergmann, M.P.M., Postaire, B.D., Gastrich, K., Heithaus, M.R., Hoopes, L.A., Lyons, K., Papastamatiou, Y.P., Schneider, E.V.C., Strickland, B.A., Talwar, B.S., Chapman, D.D., & Bakker, J. 2021. Elucidating shark diets with DNA metabarcoding from cloacal swabs. *Mol. Ecol. Resour.,* 21(4):1056-1067. https://doi.org/10.1111/1755-0998.13315

Wargelius, A., Leininger, S., Skaftnesmo, K.O., Kleppe, L., Andersson, E., Taranger, G.L., Schulz, R.W. and Edvardsen, R.B. 2016. Dnd knockout ablates germ cells and demonstrates germ cell independent sex differentiation in Atlantic salmon. *Sci. Rep.*, *6*(1):1-8.

Weldon, L., O'Leary, C., Steer, M., Newton, L., Macdonald, H. & Sargeant, S. 2020. A comparison of European eel *Anguilla anguilla* eDNA concentrations to fyke net catches in five Irish lakes. *Environ. DNA,* 2(4):587-600. https://doi.org/10.1002/edn3.91

World Intellectual Property Organization. 2019. *Patent Landscape Report: Marine Genetic Resources*. https://tind.wipo.int/record/29088

Yang, Z., Yu, Y., Tay, Y.X. & Yue, G.H., 2022. Genome editing and its applications in genetic improvement in aquaculture. *Rev. Aquac.*, 14(1):178-191.

Yates, M.C., Fraser, D.J., & Derry, A.M. 2019. Meta-analysis supports further refinement of eDNA for monitoring aquatic species-specific abundance in nature. *Environ. DNA*, 1(1):5–13. https://doi.org/10.1002/edn3.7

Yorisue, T., Iguchi, A., Yasuda, N., Yoshioka, Y., Sato, T., Fujita, Y. 2020. Evaluating the effect of overharvesting on genetic diversity and genetic population structure of the coconut crab. *Sci. Rep.*, 10:1–9. https://doi.org/10.1038/s41598-020-66712-4

Annex 1

Letter of inquiry sent to prospective experts in genetic technologies, aquaculture and fisheries

The process of contacting and interviewing experts started November 2018 and continued through June 2019. Revised draft was sent to experts for additional input on 2022. The original letter of inquiry is below.

Dear Colleague,

In light of your experience in fisheries, aquaculture, conservation and/or genetics, FAO is seeking your assistance in examining how current and expected advances in genetic technologies in the next decade might require shifts in policy and practice in fisheries and aquaculture.

Genetic technologies are becoming more powerful and have great potential to improve the sustainable use and conservation of the world's aquatic resources:

- Traditional selective breeding can improve desirable traits by around 10% per generation;
- Genomic selection, i.e. selection based on specific genes or DNA sequences, is even more powerful and becoming more used;
- Useful genes and harmful genes and how they are regulated are being discovered and characterized;
- Digital Sequence Information and synthetic biology allow the reproduction of genes and simple organisms from a 'soup' of amino acid building blocks;
- Gene editing techniques allow for the expression of desirable genes or the silencing of harmful genes;
- Gene transfer technologies, e.g. production of transgenics or GMOs, is common in crops, but consumer resistance has prevented its application in aquaculture;
- Genetic markers are able to distinguish
  - fish stocks and help identify components of mixed-stock fisheries more accurately;
  - pedigrees very accurately and determine genetic relatedness in groups of individuals, e.g. identify full siblings, parents, offspring, and cousins;
  - farmed aquatic species from their wild relatives;
- Useful DNA can be extracted from extremely small quantities of tissue, e.g. fin clips, preserved material, e.g. museum specimens, and even from fossils for analyses;
- Environmental DNA (eDNA) techniques can determine whether a species is present in a water body simply by sampling the water; more sophisticated techniques are being developed to quantify the abundance of the species in the water body;
- Genetic analysis of gut contents is being used to determine trophic relationships and even as an assessment of biodiversity;

Clearly there is great scope for wider application of these technologies and FAO needs to be able to advise member countries on the opportunities, risks and benefits. We hope to produce a framework that summarizes the key areas for FAO Members to consider when assessing the impacts that genetic technologies could have on fisheries and aquaculture (Framework).

We (Kim Friedman, Graham Mair, Devin Bartley, and Yogi Carolsfeld) would like to have a ~30 minute interview with you (skype, WhatsApp, phone etc.) to get opinions on the following.

1. What are the top 3 key areas that are likely to be impacted by advances in genetic technologies? Please consider the following general areas in your response:
   a. Governance
   b. Effort of fishers – **Fishery people only**
   c. Genetic improvement and domestication – **Aquaculture people only**
   d. Stock structure and stock assessment
   e. Biodiversity impacts and interaction
   f. Trade, marketing traceability including consumer and socio-cultural perspectives.

2. For the 3 key areas that you identified above
    a. What do you think the impacts will be and
    b. What do you think is needed to deal with the impact and how can we go about addressing those needs?

We are conducting about 30 interviews and will be using the structured expert elicitation using the IDEA protocol (V. Hemming *et al.* 2017. Methods in Ecology and Evolution DOI: 10.1111/2041-210X.12857) which involves:

i. All interviews will be summarized by FAO and a copy of the complete set of interviews will be returned to each interviewee for their opportunity to see the full set of responses; taking that overview into account, each will have the opportunity to adapt their responses if they wish. The complete set of responses returned to each individual interviewee will not include any information on the source of each interview, i.e. they will be anonymous;
ii. All final interviews will be returned to FAO;
iii. FAO will then collate and summarize all interviews and comments to document commonly recognized information across all responses;
iv. This information will be put into a manuscript for publication, recognizing as authors all participants who make a contribution to the writing of the subsequent manuscript.

Would you be interested in participating in the interview? If yes, please respond with your preferred method of communication (skype, WhatsApp, Zoom etc.) and we will be in touch with you to arrange an interview. Please also rate yourself on your knowledge of genetics: 1 = no knowledge; 2 = some knowledge; 3 = expert knowledge. We will keep all responses confidential and only include your name where we have written permission to do so, e.g. as an author or in Acknowledgement section.

Apologies for the long email and we will be pleased to provide more information on this process.

Regards,

The team.

P.S. Some examples of the myriad of ways that advances in genetic technologies could impact fisheries and aquaculture:

- Traditional selective breeding can improve desirable traits by around 10% per generation;
- Genomic selection, i.e. selection based on specific genes or DNA sequences, is even more powerful and becoming more used;
- Useful genes and harmful genes and how they are regulated are being discovered and characterized;
- Digital Sequence Information and synthetic biology allow the reproduction of genes and simple organisms from a ‘soup’ of amino acid building blocks;
- Gene editing techniques allow for the expression of desirable genes or the silencing of harmful genes;
- Gene transfer technologies, e.g. production of transgenics or GMOs, is common in crops, but consumer resistance has hampered its application in aquaculture;
- Genetic markers are able to distinguish
    - fishery stocks and help identify components of mixed-stock fisheries more accurately;
    - pedigrees very accurately and determine genetic relatedness in groups of individuals, e.g. identify full siblings, parents, offspring, and cousins;
    - farmed aquatic species from their wild relatives;
- Useful DNA can be extracted from extremely small quantities of tissue, e.g. fin clips, preserved material, e.g. museum specimens, and even from fossils for analyses;

- Environmental DNA (eDNA) techniques can determine whether a species is present in a water body simply by sampling the water; more sophisticated techniques are being developed to quantify the abundance of the species in the water body;
- Genetic analysis of gut contents is being used to determine trophic relationships and even as an assessment of biodiversity;
- Genetic analyses are permitting an overview of parasite, viral, and/or bacterial load in fisheries and aquaculture products.

ISBN 978-92-5-136716-2 ISSN 2070-6065

9 789251 367162

CC1236EN/1/08.22