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REVIEW

REVIEWS IN Aquaculture

A guide to assess the use of gene editing in aquaculture

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Abstract

Aquaculture creates 'aquatic foods' such as fish, shellfish, and seaweeds that are critical for food security. Gene editing using CRISPR-Cas9 has the potential to transform aquaculture by improving animal welfare, nutritional attributes, and farming efficiency, with benefits for environmental sustainability. However, gene editing also poses risks of harm via side effects on other important traits or genetic introgression into wild populations. Public acceptance of gene edited aquatic species will rapidly erode if risk mitigation is ineffective or not applied. Here, we review the benefits and risks for gene editing in aquaculture. A general framework for risk–benefit analysis of gene editing in aquaculture is proposed, incorporating nine key considerations: genetic impacts, ecological impacts, disease risk mitigation, nature of edit, supply chain environmental footprint, animal welfare, human nutrition, ethical business implications and impacts on local communities. When applied on a case-by-case basis, the framework will help identify how gene editing of a farmed species can most enhance production and nutritional benefits while minimising harms to animal welfare, the environment, and society.

KEYWORDS
animal welfare, CRISPR-Cas9, ethics, public acceptance, risk–benefit, sustainability

1 | NEED FOR ASSESSMENT OF GENE EDITING APPLICATIONS

Gene editing using CRISPR-Cas9[1] is being rapidly adopted by researchers to disrupt and test the function of genes and other elements of the genome.[2–4] The DNA code can now be targeted and edited with high precision in virtually any species. Many beneficial applications are forecast for food production, including improved resiliency and animal welfare,[5] higher product quality and nutritional value,[6] and environmental benefits,[7] which all translate to greater food security and safety. However, there is uncertainty surrounding public acceptance,[8–20] sustainability,[21–24] and regulation[25] of this technology. Many governments, researchers, and food producers are cautious about being associated with the development of 'edited' food.

Aquatic foods are important for global food security,[26] human health and nutrition,[27] providing income and livelihood for many communities. Aquatic animal production results in lower greenhouse emissions than other forms of protein production, and can utilise low-trophic species, such as algae and shellfish, that require little human input and create very few emissions.[28] Aquaculture practices that secure animal welfare and minimise environmental impact are key to the sustainability of food production, and therefore global food security. Aquaculture produces hundreds of aquatic species (latest statistics compiled by FAO include 494 individual species in addition to hybrids and groups identified at higher taxonomic levels[29–31]), and most are at low levels of domestication compared to land animals and plants, selectively bred for millennia.[32] Gene editing is expected to play a major role in fulfilling aquaculture's potential,[4] and the first two edited fish strains have already been commercialised in Japan[33] (see https://www.seafoodsource.com/news/supply-trade/japan-s-government-taking-positive-stance-on-gene-editing-fish) However, there is still controversy regarding the broad application of gene editing in aquaculture.

Here, we review the key potential benefits and harms that should be considered and propose a framework that could be applied worldwide to evaluate the application of gene editing in aquaculture, based on systematic evaluation of the benefits and risk of harms ('risks' herein) associated with specific edits. Assessment of the merits of gene editing applications should provoke mitigation and management of risks, maximising public acceptance. If implemented as a transparent process coordinated by a national body to evaluate the merit of gene editing applications, this assessment would likely influence the direction of research towards applications that are more acceptable and beneficial to the public and of less risk to the environment and the industry.

2 | METHOD FOR FORMULATION OF THE ASSESSMENT FRAMEWORK AND REVIEW

The implementation of gene editing in aquaculture (and other farmed species) is in its infancy. Literature on the relevance of potential risks and benefits will only exist once a risk assessment, such as proposed in this review, has already been carried out. Accordingly, this paper is part 'opinion' (thinking about future consequences) and part 'review' (where references to the topics covered did exist).

The literature review process involved a search in Web of Science in 2023 for publications including [gene editing OR CRISPR OR genome editing] AND [aquaculture OR fish OR shellfish OR algae] as well as more specific literature searches on specific topics.

The assessment format was informed by general frameworks used for workplace risk assessments, available decision support tools developed for assessing and managing risks associated with genetically modified aquatic organisms[34–36] and for the application of animal biotechnology in general.[37] In addition to risk assessment and mitigation, we include in our framework a parallel methodology for assessing and weighing potential benefits from the implementation of the technology.

3 | TECHNICAL, SOCIAL, LEGAL, AND COMMERCIAL CHALLENGES WITH GENE EDITING

Implementing gene editing into farming systems is a long, complex process. First, it is necessary to identify target gene(s) whose modification could result in positive effects on the trait of interest.[2,4,5] For instance, quantitative trait loci of large effect can sometimes be identified and finely mapped using genome-wide association analysis, and the contrast in the expression of genes mapping to these regions might indicate causative genes likely affecting the trait (e.g.,[38]). Next, selection of the type of mutation necessary to achieve the desired effect is required (DNA sequence insertion or deletion, gene activation, repression or duplication, amino acid change, etc.). Currently, it is relatively straightforward to knock out a gene, but this could have large implications for individual welfare and species biology.

The introduction of the desired edit can result in off-target effects[39] or uncontrolled epistatic gene interactions,[40] and therefore a thorough evaluation of the impact of the edit is required (e.g., animal welfare, food safety, environmental consequences, etc.) before implementing it to make animals for consumption.[41]

Finally, if the edit is to be introduced into production stock, then we need to consider: (i) at which level of the breeding chain should it be implemented (breeding nucleus, multiplier, or farm level), (ii) how to efficiently perform the editing at that level (e.g., delivery mechanism, in embryos or germ cells, elimination or reduction of mosaicism), and (iii) how to make gene editing compatible with breeding program management (e.g., limiting loss of genetic variability and inbreeding, ability to reverse edits for traits such as sterility).

As well as being technically challenging to produce and implement, there are significant social, legal, and commercialisation challenges with gene editing and genetic modification. A genetically modified organism is typically defined as one containing a gene that has been transferred from another species. In contrast, gene editing normally involves modification of specific targeted DNA bases and does not involve the introduction of whole genes from other species. Livestock was first genetically engineered in 1985,[42] but few genetically engineered animals have been commercialised for food production[43]; AquAdvantage Atlantic salmon is the first notable example.[44] The approval process and laws governing production and sale of genetically modified animals for food is complex and restrictive. By default, gene-edited animals are considered as genetically modified organisms by many jurisdictions, such as the European Union. However, legislation has been passed in some countries that open the possibility of producing gene-edited food.[45] For instance, the United Kingdom parliament's *Genetic Technology (Precision Breeding) Act 2023*[46] allows gene editing to produce food, providing that the end crop is no different to a variety that could have been naturally produced and that adverse effects are prevented or minimised, and more permissive legislation exists in other countries such as Japan and Brazil.[45]

Applying CRISPR-Cas9 technology to aquaculture sectors could be a blessing or a curse, depending on the nature of the edits, the motivation, and the risk of harm resulting from creation of, or exposure to, the edited species. Profitable production will be a driving motivation, but stakeholders must thoroughly assess risks and benefits beyond economics alone. The decisions we make about gene editing are of great importance and could affect all parts of the aquaculture value chain, the aquatic ecosystem, and our city, rural and indigenous communities (Figure 1).

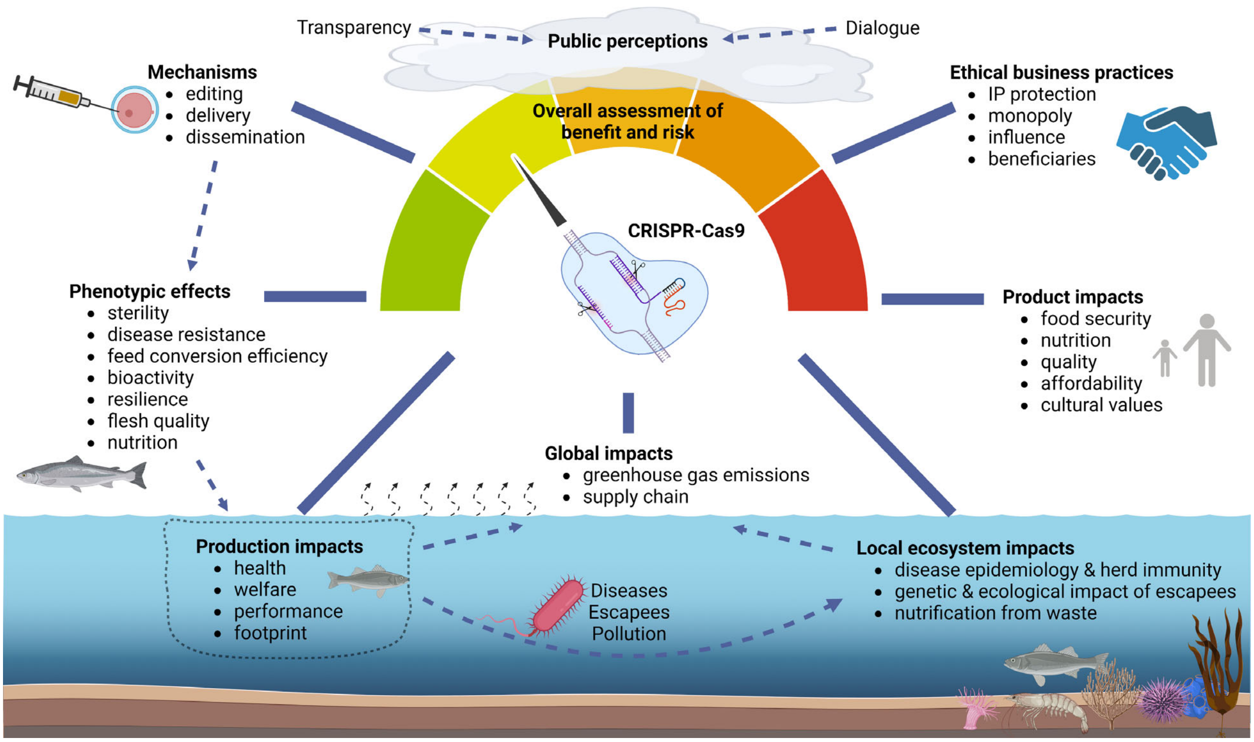

FIGURE 1 Gene editing applications will have a consequential web of potential benefits and harms with associated risks affecting all levels of aquaculture value chains, aquatic ecosystems, and society. The same principles apply to the aquaculture of all aquatic organisms. Large solid lines indicate the main areas requiring careful consideration and assessment: mechanisms for creating and disseminating gene-edited food; phenotypic effects on the animal under production; positive or negative impacts (on production, local ecosystems, global effects, and food products), and ethical business practices. Public perceptions will be influenced by having good transparency and continuous dialogue about the risks and the benefits assessed for each gene editing application. Created with BioRender.com.

4 | CONSIDERATION OF GENE EDITING APPLICATIONS

In our opinion, more careful consideration of the broad harms, risks, and benefits for the aquaculture value chain, aquatic environment, and society should be given to potential gene editing applications, and gene editing should be used to find solutions for major challenges rather than to seek incremental improvements in commercial traits. For instance, selective breeding is highly effective for many traits, for example, improvement of ~12% per generation in growth rate (when the entire focus of improvement is on this single trait).[47] Therefore, gene editing should instead focus on introducing de novo variation to generate a 'leap' change in a trait that is crucial for sustainability or animal welfare.

Gene editing synergises perfectly with selective breeding, since it may effectively allow the removal of a trait from the breeding objective (e.g., if edited animals are highly or fully resistant to a disease), enabling the breeding program to give greater weight to other traits in the selection index.

4.1 | Animal health and welfare

Aquaculture around the world is greatly expanding[48] and bacterial, viral, and parasitic disease outbreaks are challenging to prevent and control, representing a constant problem.[49] Diseases can wound, weaken, and kill infected individuals, with obvious deleterious effects on animal welfare. When they exist, prevention and treatment methods are not completely effective,[50] often pose welfare concerns (e.g., involving crowding, pumping, and bathing) and may have broader negative impacts on the surrounding ecosystems (e.g., antibiotic treatment, which can also result in antimicrobial resistance[51]). If it were possible to use gene editing to make farmed animals highly or completely resistant to particular diseases, this would present a strong moral argument for implementing this technology.

A caveat to this strategy is that disease agents could evolve resistance/avoidance more quickly for edits at one or a few genes than for selective breeding, which usually results in changes across many loci in the genome. For instance, the infectious pancreatic necrosis virus in Atlantic salmon mutates rapidly and creates new variants of different virulence.[52–55] Indications are that Atlantic salmon that were fixed using selective breeding for a major trait locus giving high resistance to the disease[56,57] are not as resistant to some variants of the virus.[58–60] The continuation of selective breeding for such traits might act as a backup and make it more challenging for the disease agent to overcome host resistance.

Resistance to infectious pancreatic necrosis in Atlantic salmon is a special case where a single gene has a very large effect on resistance.[57] But in most instances, disease resistance is influenced by the additive effects of many genes of small effect on the trait. There might be little value in using gene editing to mimic quantitative trait loci (i.e., creating multiple gene edits, each having a small effect on the trait). But if the function of these genes is well understood it could be possible to devise de novo editing strategies for some of these genes in a way that achieves much larger effects on quantitative traits like disease resistance.

4.2 | Food chain implications

Fish and shellfish are highly nutritious foods with many positive health benefits and there is potential to use gene editing to make these animals an even healthier choice for consumers (e.g., higher omega-3 fatty acid levels), more desirable (improved texture, colour, and flavour) and to help meet food security and supply challenges. Disease outbreaks among aquatic stock can sometimes have devastating local effects on the livelihood and supply of nutrition to rural communities in developing countries.[61] There could also be potential to use gene editing to create disease-resistant strains or 'tailored' lines of products with desirable properties (e.g., greater tolerance for production in high or low salinity environments). Changes made to key biological pathways affecting these traits via gene editing could have large effects. For example, inter-muscular bones and spines in carp can be removed with gene editing techniques.[62] The carps (e.g., grass carp, common carp, rohu carp) are the most widely farmed fish throughout Asia (∼25 million tons per year[63]) and are a key source of dietary protein. Making carp more palatable and easier to eat could promote consumption and improve the nutrition of hundreds of millions of people, but it will be important to evaluate the overall benefits and pitfalls of using gene editing to achieve this.

4.3 | Impact on nature

One main consideration of gene editing in aquaculture is a positive or negative impact on wild species and ecosystems. Changes that improve the optimisation of resource use in aquaculture (e.g., improvements to feed conversion efficiency or survival) can have positive environmental consequences (reduced use of resources, greenhouse gas emission, and wastes) for example, for catfish farming in Africa.[64] In plant crops gene editing to improve protein recovery is predicted to reduce global warming impact, terrestrial acidification, land use, and ecosystem damage (e.g., use to upgrade potato cultivars[7]).

Disease in some natural aquatic populations is thought to be driven to a large extent by propagation and transmission from farms (e.g., Atlantic salmon[65]). Connected to the previous section, gene editing for disease resistance will potentially reduce the number and rate of reproduction of pathogens, in turn reducing propagation and transmission from aquaculture farms to natural populations (i.e., having a 'herd effect') and improving the health of farmed and wild populations.

One of the main challenges for many aquaculture species is the existence of wild counterparts and their co-habitation in the same environment. The main risk of harm to nature of gene editing is likely to be due to genetic introgression, whereby escaped gene-edited individuals breed with wild conspecifics or congenerics, producing wild offspring that carry edited genes. Introgression is already occurring to some extent through the genetic interaction of farmed with wild Atlantic salmon.[66] Introgression could lead to ecological and evolutionary impacts, depending on the fitness value of the edited gene.[67] Edits that increase fitness in the wild could conceivably spread to fixation in the wild population and have significant ecological effects. Edits that do not affect the fitness of farm-wild hybrids may persist as an ecologically benign 'corruption' of the wild gene pool. Finally, if the edits are deleterious in the wild, wild individuals that breed with escapees, or with farm-wild hybrids, will produce offspring with reduced fitness, causing the edited genes to be lost through natural selection. This may be viewed as a desirable outcome if introgression events are rare, although frequent introgressions of this type might threaten the persistence of affected wild populations.[67] For instance, genetic modifications of the growth hormone gene might give fish a reproductive advantage if released to the wild due to their larger size and earlier maturation, while the offspring of such fish could have lower fitness in the wild, and modelling of the release of such fish has predicted that this could lead to reduced wild population sizes.[68]

These concerns apply especially to certain aquaculture practices that are prone to escape events. Escapes can occur for example when net pens or sea-cages are damaged,[69] when ponds overflow during heavy rain or flooding, or when fertile stock spawn and their offspring enter the surrounding environment.[70,71] Escapees from aquaculture may go undetected, and most are not able to be recaptured,[72] increasing the opportunity for genetic introgression. Moreover, many cultured species have prodigious dispersal capabilities in the wild, with individuals travelling hundreds of kilometres as planktonic larvae, juveniles, or adults,[73] meaning that an escape event can have regional rather than local consequences within a single generation. While mandated technical standards and engineering advances can reduce escapes,[35,69] complete avoidance is unlikely. However, for genetic impacts to take effect, escapees need to successfully breed with their wild counterparts and produce viable offspring. This opens the door for a range of mitigation measures that can work even after an escape event, including gene editing for sterility, for which there is proof-of-concept work complete in Atlantic salmon in Norway[74–76] that is likely to achieve broad public support.[77] One could also imagine future innovations that use gene editing to introduce traits that reduce the survivorship or competitiveness of escapees once they enter the natural environment (e.g., a trait that is activated in the absence of a particular feed ingredient). Such innovations could minimise possibilities for ecological and genetic impacts and improve the sustainability of aquaculture.

4.4 | Implementation and dissemination

The implementation and spread of gene editing will in most instances be facilitated by the biological characteristics of aquatic species, such as external fertilisation and high fecundity, as well as by the structure of aquaculture breeding programmes that have relatively few or no multiplication layers. But without an effective means and plan for implementation potential benefits to society will not be fully realised. For major improvements to welfare, nutritional value, or sustainability to become prevalent across the industry, a plan for large-scale implementation will be required.

In instances where existing breeding companies and multipliers service several customers and countries with different policies and/or laws concerning the import and production of gene-edited stock, there will probably be a need to create edited individuals as an 'alternative product' to existing selected individuals. Options for establishing new gene edited product lines will need to be carefully explored and evaluated to find the best fit for the circumstances of each company. Options could include splitting the breeding nucleus and continuing the selective breeding program for both edited and non-edited individuals. Alternatively, a single breeding nucleus could be maintained, and edits made to some individuals at the multiplier level. Complicating factors will be: the efficiency of editing and whether further breeding is required to make fully homozygous edited individuals; how many different traits will be targeted and whether separate lines of edited individuals should be created for each trait; whether sterility is also needed and whether sterile individuals should be created through gene editing; the ability to 'reverse sterility' to breed individuals that are made sterile using gene editing; the size of the effect of the edit(s) on the trait and whether one or several edits are required for each trait; and options for the use of surrogate broodstock with edited germ cells or other 'high-throughput delivery systems'.

How gene edits are deployed through time and space, and in tandem with other practices (such as special feeds, environmental controls, and biosecurity), also needs consideration. For example, efforts to mitigate the impact of escapees, disease transmission to wild populations, or counter-evolution of disease agents may vary in their effectiveness, depending on where the gene-edited individuals are used. Eco-evolutionary modelling could help predict how to best implement gene editing to achieve the largest possible benefits.[78]

5 | PUBLIC ACCEPTANCE

Public acceptance is a key determinant for the successful application of gene editing in aquaculture, and all stakeholders will benefit from gene editing applications being viewed positively by consumers. To build the public's acceptance of gene editing, or to give the opportunity to reject implementation of the method based on facts, good scientific communication and dissemination of research results are necessary. Public engagement, enabling expression of opinions, reflections, and concerns, should occur. Producers and regulators will need to provide rationale and allay fears about how and why gene editing is applied and demonstrate that the benefits substantially outweigh any risk of harm to society, animal welfare, or the environment. Such evaluations need to be made publicly available before gene-edited animals make it into production systems. Scientists, industry, and regulators need to work closely with indigenous communities to ensure possible changes do not affect the cultural significance of species and their place in the environment. We contend that sound judgement must be applied when deciding which applications to pursue.

In the case of Atlantic salmon (which is one of the most valuable global aquaculture commodities), three main moral principles have been suggested as important by stakeholders: welfare, integrity, and iconic status,[79] with protection of the environment and wild salmon being key sustainability issues.[21–24] From reports of surveys conducted in Norway, most consumers consider gene editing applications with clear societal and sustainability benefits (e.g., promotion of fish health and reduction of environmental impact) as positive, while applications that focus on production traits or negatively affect animal welfare elicit negative responses.[77] Additionally, research has found that Indian and North American consumers are more inclined to prefer more natural production practices and these preferences have driven the adoption of practices like free-range chicken farming and organic branding.[80,81] It is therefore plausible that there will be higher public acceptance of gene editing if the changes made are closer to the extent and type of variation that is found in nature (e.g., gross changes by inserting new DNA sequences may be less accepted).

Selective breeding drives genetic improvement by selecting the best genetic variants in the population. These genetic variants arise as a result of natural mutations occurring at different genetic loci. Gene editing, like selective breeding, is a means of driving genetic improvement, however, in the case of gene editing, the mutation process is under control and is directed to affect the function of specific target genes. We think it is relevant and interesting to consider why genetic improvement by selective breeding is generally well accepted in the public (e.g.,[82]) and why in contrast there is more uncertainty and concern about the potential consequences of other forms of genetic improvement such as gene editing (e.g., user attitudes to GMO food in Norway[83,84]). The general acceptance of selective breeding could be due to various factors, including it being a well-established practice used to improve food production over hundreds of years, public familiarity with terrestrial animal and plant breeds, selection of naturally occurring genetic variants, and that it produces a slow and gradual change in traits. In contrast, changes caused by gene editing might be de novo changes of large effect made through one or a few gene editing steps with potential to cause rapid, more obvious effects on the targeted phenotype than selective breeding (although it is possible that editing may go largely unnoticed and could become the 'new normal' in the public's mind).

Some societies and groups of people seem to be more comfortable with the notion of genetic manipulation than others

(a)

Date last updated:	12/01/2023	
Updated by:	Nick Robinson	
Project name:	CrispResist	
Aim:	Provide Atlantic salmon with host resistance to sea lice	
Is the ultimate purpose to produce animals for aquaculture?	Yes	Note: If yes, continue with assessment. If the gene editing is for another purpose (e.g. research tool to test the function of genes or for producing a gene drive for pest control) another assessment procedure is needed.
Availability of alternative solutions?	No	Note: If highly effective alternative solutions are available, consider whether gene editing is appropriate
Strategy for rolling out gene editing	Introduce at multiplier level by injection of fish	Note: A detailed strategy for implementation is essential

(b)

TOPIC			BENEFIT ASSESSMENT			
ID	**Area of concern**	**Weight (1-10)**	**Notes on potential benefits**	**Probability of positive impact**	**Magnitude of benefit**	**Benefit rating**
3	Effect on disease risk for cultured and wild pops		Resistance in farmed salmon could act like a vaccine affecting the prevalence and transmission of infection to wild populations of salmon (herd effect).	High	High	Highly beneficial

(c)

RISK ASSESSMENT									OUTCOME
Notes on potential harms	**Probability of negative impact**	**Magnitude of harm**	**Initial risk rating**	**Risk mitigation or control (s)**	**Control owner (s) name and role**	**Residual probability of negative impact**	**Residual magnitude of harm**	**Residual risk rating**	**Net benefit score**
Parasite or pathogen evolves to overcome resistance, possibly becoming more virulent.	Medium	High	Severe	Design edit in such a way as it is difficult to counter, introduce multiple edits affecting the trait and deploy in time and space, and alongside other preventative methods, in ways that slow evolution of the parasite.		Very low	High	Moderate	2

FIGURE 2 Part of the pre-assessment (a) benefit assessment (b) and risk assessment (c) worksheet hypothetical case assessment spreadsheet (Supplementary Material 1), for a gene edit that boosts resistance of Atlantic salmon to parasitic sea lice. Parts (b) and (c) only show detail for key consideration 3 (effect on disease risk for cultured and wild populations) and the scoring of other key considerations can be found in the full spreadsheet in the Supplementary Materials. Benefit rating, initial risk rating, residual risk rating, and net benefit scores are values calculated by the spreadsheet. The worksheet accounts for the net benefit scores obtained for all key considerations and calculates an overall net benefit score for each case assessed (not shown).

(depending on socio-economic background, cultural environment, education, etc.).[85,86] Dialogue on the topic might not always change the public's perception of risk.[87] Even when little risk is apparent, moral standpoints about the use of genetic technologies might prevail.[88] The credibility and goodwill of communicators will have an important influence on public attitudes towards gene editing.[12,89] The way in which the change is pitched will also influence perceptions. Removing an unfavourable phenotype may win greater acceptance than improving productivity, for instance.

6 | RECOMMENDED ASSESSMENT FORMAT

As a way of processing the potential benefits and risks discussed above, we provide an assessment framework (Supplementary material 1, hypothetical example in Figure 2) for proposed gene editing applications within the field of aquaculture production. The user group making the assessment should consist of at least some members who do not have a vested interest in the project and involve representatives from industry (breeding companies and aquaculture

(a)

		Magnitude of benefit				
		Very high	High	Medium	Low	Very low
Probability of positive impact	Very low	Fairly beneficial	Low benefit	Low benefit	No benefit	No benefit
	Low	Highly beneficial	Fairly beneficial	Low benefit	No benefit	No benefit
	Medium	Highly beneficial	Fairly beneficial	Fairly beneficial	Low benefit	No benefit
	High	Highly beneficial	Highly beneficial	Fairly beneficial	Low benefit	No benefit
	Very high	Highly beneficial	Highly beneficial	Highly beneficial	Fairly beneficial	Low benefit

(b)

		Magnitude of harm				
		Very low	Low	Medium	High	Very high
Probability of negative impact	Very high	Moderate	Severe	Severe	Critical	Critical
	High	Sustainable	Moderate	Severe	Critical	Critical
	Medium	Sustainable	Moderate	Moderate	Severe	Critical
	Low	Sustainable	Sustainable	Moderate	Severe	Critical
	Very low	Sustainable	Sustainable	Sustainable	Moderate	Severe

FIGURE 3 Benefit (a) and risk (b) matrices used in the framework (Supplementary Material 1) to assess the risk-benefits associated with gene editing.

producers who might consider the purchase of gene editing stock), local communities (including indigenous people with ties to the species and aquatic environment), government, environmental non-government organisations, social scientists and geneticists familiar with the technology.

Before beginning the assessment, the user group is prompted to consider whether effective alternative solutions to the problem already exist, and if so, whether gene editing is appropriate. The user group is also prompted to consider strategies to ensure ease of dissemination and implementation (spread and frequency leading to spread and uptake of benefits). If the user group proceeds, they are invited to rate the benefits and risks of their application on specific areas of concern. We have listed 9 key considerations as a starting point:

1. Potential genetic impacts on wild populations.
2. Potential local ecological impacts.
3. Effect on disease risk for cultured and wild populations.
4. Disruptiveness of the edit (public perception).
5. Effect on supply chain environmental footprint.
6. Effect on welfare of animals.
7. Effect on human nutrition (amount and quality).
8. Ethical business practices (economic beneficiaries and transparency).
9. Effect on local community (sustainability, income, employment).

For each area of concern, the user should make notes to describe the rationale for the potential benefits and/or harms and use the pull-down boxes to rate the probability of impact and magnitude of benefit and/or harm. Risk mitigations, and their effects on the residual probability of negative impact and/or residual magnitude of harm, should also be documented in the final columns of the assessment framework. Further details describing how to use the assessment framework and the calculations that it performs are provided in the terms and calculations tab of the assessment framework (Supplementary Material 1). The potential for environmental harm or benefit is a part of considerations 1, 2, 3, and 5, and the user groups should be familiar with existing environmental risk assessment and management methodologies developed for genetically modified organisms.[34–36]

A hypothetical example case, a gene edit that boosts resistance of Atlantic salmon to parasitic salmon lice *Lepeophtheirus salmonis*, is filled into the excel spreadsheets contained in Supplementary Materials (pre-assessment visualised in Figure 2a and part of the main worksheet visualised in Figure 2b, c). The framework can be easily expanded and adapted to suit different circumstances. The supplementary model includes a description of the terms used and automatic ranking applied (according to the benefit and risk matrices shown in Figure 3) by the assessment framework. The end score that is calculated automatically by the assessment framework worksheet is the average overall risk–benefit ratio for the proposed application of gene editing. This is a relative value with a maximum of 3 (highly beneficial and sustainable risks) and a minimum of −3 (no benefit and critical risks).

7 | CONCLUSION

Public perceptions of aquaculture and gene editing technologies are divisive. Scientists, regulatory authorities, aquaculture producers and breeders need to be publicly accountable and transparent so that consumers are well informed regarding gene editing and the alternative viewpoints surrounding different claims.[90] Before embarking on projects involving gene editing, we need to consider whether the edits bring benefits to human health, animal welfare, food security, natural environments, and local communities, or if they will just increase profits. We should also question if inaction is morally acceptable when gene editing can provide a potential cure to otherwise intractable issues in aquaculture (being careful to weigh the risk of potential harm). Researchers and industry representatives involved in the assessment of gene editing applications should not have an economic interest in the application. Beneficent persuasion[91] by the scientific community might be warranted under some circumstances, but in general, scientists should mainly seek to make facts known.[92] Irresponsible actions of a few in the scientific community could tar the whole community and aquaculture in general.

Gene editing has the potential to provide solutions to some of the most intractable problems in aquaculture, but the aquaculture sector needs to consider deeply the various positive and negative consequences of using this new technology. Governments, researchers, indigenous communities, consumers, and industry should work together to assess the merits of gene editing on a case-by-case basis.

AUTHOR CONTRIBUTIONS

Nicholas A. Robinson: Conceptualization; writing – original draft; writing – review and editing; funding acquisition; investigation; methodology. **Tone-Kari Knutsdatter Østbye:** Investigation; writing – original draft; methodology; writing – review and editing. **Anne H. Kettunen:** Investigation; writing – original draft; methodology; writing – review and editing. **Andrew Coates:** Investigation; writing – original draft; methodology; writing – review and editing. **Luke T. Barrett:** Investigation; writing – original draft; methodology; writing – review and editing. **Diego Robledo:** Conceptualization; investigation; funding acquisition; writing – original draft; methodology; writing – review and editing. **Tim Dempster:** Conceptualization; investigation; funding acquisition; writing – original draft; methodology; writing – review and editing.

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DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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