DNA-analysis to monitor Fisheries and Aquaculture: Too costly?

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DNA-analysis to monitor fisheries and aquaculture: Too costly?

Jann Th. Martinsohn[1] | Paul Raymond[2] | Trey Knott[3] | Kevin A. Glover[4,5] | Einar Eg Nielsen[6] | Lars Bonde Eriksen[7] | Rob Ogden[8] | John Casey[1] | Jordi Guillen[1]

[1]European Commission, Joint Research Centre (JRC), Ispra, Italy

[2]Office of Law Enforcement (Retired), National Marine Fisheries Service, National Oceanic and Atmospheric Administration, Washington, District of Columbia

[3]Forensic Laboratory, Northwest Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration, Charleston, South Carolina

[4]Institute of Marine Research, Bergen, Norway

[5]Institute of Biology, University of Bergen, Bergen, Norway

[5]Section for Population Ecology and Genetics, National Institute of Aquatic Resources, Technical University of Denmark, Silkeborg, Denmark

[6]Ministry of Foreign Affairs of Denmark, Danish Fisheries Agency, HR, kommunikation og jura, Copenhagen, Denmark

[7]Edinburgh Royal (Dick) School of Veterinary Studies and the Roslin Institute, University of Edinburgh, Easter Bush Campus, Edinburgh, UK

Correspondence
Jann Th. Martinsohn, European Commission, Joint Research Centre (JRC), Directorate D – Sustainable Resources, Unit D2 – Water and Marine Resources, Ispra, Italy
Email: jann.martinsohn@ec.europa.eu

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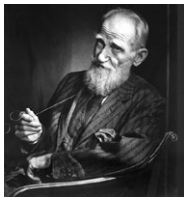
Abstract

Evidence from DNA-analysis is commonplace in human criminal investigations, and while it is increasingly being used in wildlife crime, to date, its application to control and enforcement activities in fisheries and aquaculture has only been sporadic. Contemporary DNA-analysis tools are capable of addressing a broad range of compliance issues, species identification, mislabelling of fish products, determining the origin of catches and the farm of origin of aquaculture escapees. Such applications have the potential to ensure traceability along the fish product supply chain and to combat consumer fraud and Illegal, Unreported and Unregulated fishing. Nevertheless, DNA-analysis is not yet used routinely in investigations into compliance with fisheries and aquaculture legislation. One potential reason for this is that DNA-analysis techniques may have been regarded as too expensive. However, costs have plummeted over the past decade prompting us to objectively assess whether the costs associated with routine use of DNA-analysis techniques for fisheries and aquaculture control and enforcement activities do constitute an impediment. Based on a number of recent fisheries and aquaculture compliance investigations that incorporated DNA-analysis, our results indicate that the use of genetic analysis was justified and worthwhile in all cases examined. We therefore conclude that the costs associated with DNA-analysis do not represent a barrier to the routine adoption of DNA-analysis techniques in fisheries and aquaculture compliance investigations. Thus, control and enforcement agencies should be encouraged to use such techniques routinely.

KEYWORDS
control, costs, enforcement, genetics, genomics, marine resource management



Ghoti papers

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Etymology of Ghoti

George Bernard Shaw (1856–1950), polymath, playwright, Nobel prize winner, and the most prolific letter writer in history, was an advocate of English spelling reform. He was reportedly fond of pointing out its absurdities by proving that "fish" could be spelt "ghoti." That is: "gh" as in "rough," "o" as in "women" and "ti" as in palatial.

1 | INTRODUCTION

DNA-analysis can answer a number of questions relevant to control and enforcement and supply chain traceability in the fisheries and aquaculture sectors (Figure 1): "which species does a fish product contain?", "from where did a fish originate?" (Ogden, 2008; Rasmussen & Morrissey, 2009), "was it captured legally?" (Glover et al., 2012a) and even the farm of origin of aquaculture escapees can be identified (Glover, 2010). Yet, while DNA-analysis has undergone phenomenal methodological advances in the past decade it remains under-utilized for fisheries and aquaculture management (Bernatchez et al., 2017).

This is regrettable since there clearly is a need to strengthen fisheries control and enforcement schemes to combat Illegal, Unregulated and Unreported (IUU) fishing, which is a major impediment to achieving sustainable and profitable exploitation of fish stocks. An estimate of the global value of IUU fishing is between 10 and 23 billion USD annually (Agnew et al., 2009), representing approximately one-fifth of the first sale value of the global capture fishery landings (FAO, 2011). For the USA, it was estimated that illegal and unreported catches represented 20%–32% by weight of wild-caught seafood imports, with a value of 1.3 to 2.1 billion USD in 2011 (Pramod, Nakamura, Pitcher, & Delagran, 2014). These numbers, together with widespread fraud along the supply chain (e.g., Miller, Jessel, & Marini, 2011), highlight the need for effective schemes to ensure the traceability of fish and fish products from source to plate. While current traceability schemes are predominantly based on labelling and certification, the routine use of DNA-analysis techniques for species authentication and origin assignment would arguably provide an additional and powerful independent control tool.

A number of reasons why genetics methods are still not routinely used for fisheries and aquaculture management in general have been extensively discussed elsewhere (e.g., Bernatchez et al., 2017; Ovenden, Berry, Welch, Buckworth, & Dichmont, 2015; Waples, Punt, & Cope, 2008). While it is generally known that DNA sequencing costs have continuously declined over the past decade (Wetterstrand, 2014), and that the enormous progress in DNA-analysis has led to a paradigm shift from "genetics" to "genomics" (Zhang, Chiodini, Badr, & Zhang, 2011), a sound reflection on inherent costs and resulting benefits has been neglected, despite being crucial information to policy makers and stakeholders. We are convinced that the lack of objective information on costs and benefits of DNA-analysis for fisheries/aquaculture control and enforcement is a major impediment to its routine application.

Here, we investigate whether the routine use of DNA-analysis in fisheries and aquaculture control and enforcement is likely to be justifiable from a cost perspective by studies relating to the following relevant issues (see also Figure 1):

1. Species identification;
2. Geographic origin assignment;
3. Identification of farmed escapees.

An overview of the importance of each issue for control and enforcement is given below.

2 | SPECIES IDENTIFICATION

DNA-analysis for species identification can be employed at each stage of the market chain: at the point of landing, it is mainly used to detect IUU fishing, while at the retail or import stages, DNA-analysis is mainly used to detect product fraud (e.g., mislabelled filleted or processed fish of an embargoed product or species). These issues may be related and causative.

With the increase in international trade of fish products (Asche, Bellemare, Roheim, Smith, & Tveteras, 2015; Gephart & Pace, 2015),

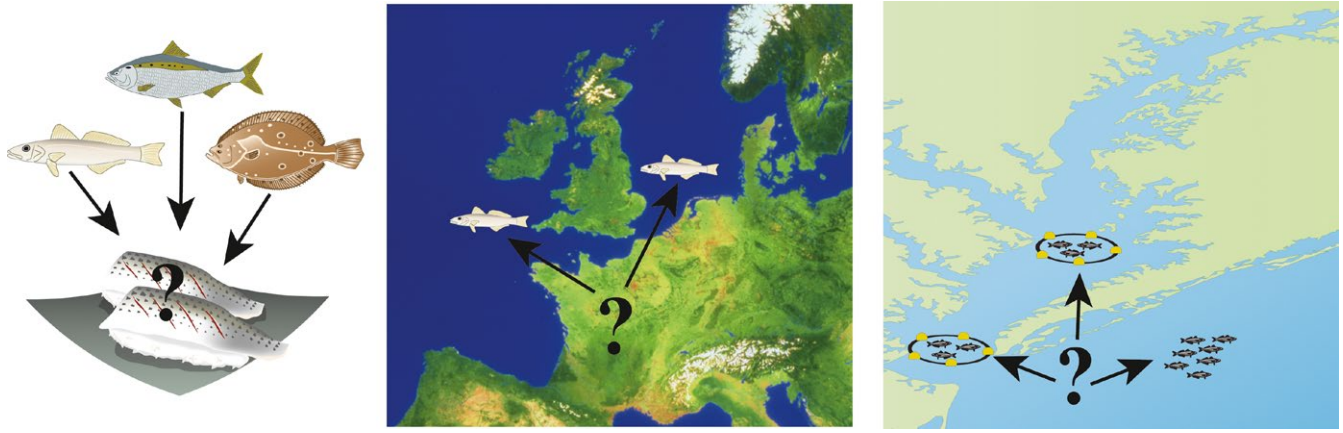

FIGURE 1 Three essential questions, relevant for fisheries control and enforcement and traceability along the supply chain are "What species?" (left) "Where captured from?" (middle) "Wild or cultured," including "Where did it escape from?" (right). The genetic distinction between wild and farmed fish, which overlaps with challenge depicted on the right, will become more relevant in the near future, due to the steep rise in aquaculture activity worldwide and the interaction between cultured and wild conspecifics. See text for details. Fish symbols courtesy of the Integration and Application Network, University of Maryland Center for Environmental Science. European Map: © European Union, 2010

their traceability has become particularly challenging. The value of fish products depends on several factors, with species and origin being the most important (Asche & Guillen, 2012; Asche & Sebulonsen, 1998; Wessells, 2002). Thus, significant differences in value provide an incentive to mislabel fish products.

Fish product mislabelling has been recognized as significant worldwide (Miller et al., 2011 and references therein), and often occurs at the import or retail market stages (Jacquet & Pauly, 2008; Miller et al., 2011) where high-value species may be substituted with species of lower value (Hsieh, Woodward, & Blanco, 2007; Jacquet & Pauly, 2008). Illegal over-quota catches and catches of protected species may also be mislabelled and sold (Miller et al., 2011; Wong & Hanner, 2008). DNA-analysis for species identification can be successfully applied to a diverse range of even highly processed products (Martinsohn et al., 2011; Rasmussen & Morrissey, 2009) and open-access genetic reference databases for species identification are available (Zanzi & Martinsohn, 2017). DNA barcoding for species identification of seafood product composition is increasingly being established (Nicolè et al., 2012), and new DNA markers are continually being developed (Paracchini et al., 2017).

3 | ORIGIN ASSIGNMENT

A classic example of a control issue in marine fisheries occurs when catches from a particular area are suspected to have been taken elsewhere. In such cases, control agencies will wish to confirm or refute the alleged origin of the fish or fish products. The power of DNA-analysis for origin assignment has been clearly demonstrated for a wide variety of marine fish, such as the European hake (*Merluccius merluccius*, Merlucciidae), Atlantic cod (*Gadus morhua*, Gadidae), Atlantic herring (*Clupea harengus*, Clupeidae) and common sole (*Solea solea*, Soleidae) via the project FishPopTrace (Nielsen et al., 2012). In principle, DNA-analysis could be used in any region of the world provided the management is based on a spatial component and the stocks (populations) can be distinguished genetically.

4 | FARMED ESCAPEES (IDENTIFYING THE FARM OF ORIGIN)

A major concern arising as a result of marine aquaculture is the escape of farmed individuals (Glover et al., 2017), which may give rise to a range of ecological (Arechavala-Lopez, Sanchez-Jerez, Bayle-Sempere, Uglem, & Mladineo, 2013; Johansen et al., 2012; Madhun et al., 2015) and genetic (Glover et al., 2012b, 2013; Karlsson, Diserud, Fiske, & Hindar, 2016) interactions with wild conspecifics.

Atlantic salmon (*Salmo salar*, Salmonidae) serves as the leading example of our knowledge of farm escapees and the management of escape events. In terms of production weight, aquaculture of Atlantic salmon is 1,000 times that of wild capture fisheries (FAO, 2018) and in Norway alone, the annual average reported a number of escapees from aquaculture facilities was 440,000 salmon over the period 1993–2005 (Thorstad et al., 2008). This is an impressive number considering that the number of wild salmon that returned to the Norwegian coast in 2005 was estimated to be only 700,000 (Hansen, Fiske, Holm, Jensen, & Sægrov, 2006). In Chile, from 1993 to 1996, the number of Atlantic salmon farm escapees was estimated to be 1.5 million fish (Thorstad et al., 2008). Interbreeding with escaped domesticated salmon over several decades has started to erode wild population genetic structure in Norway (Glover et al., 2012b; Skaala, Wennevik, & Glover, 2006).

Aquaculture species are subject to selection for economically important traits. Consequently, interbreeding results in changes to the genetic makeup of wild populations (Glover et al., 2017), and the offspring of farmed escapees display reduced survival in the wild (Bekkevold, Hansen, & Nielsen, 2006; FAO, 2016; Fleming et al., 2000; McGinnity et al., 1997, 2003; Skaala et al., 2012). Farmed escapees represent a significant threat to the genetic integrity and the evolutionary capacity of wild populations (Ferguson et al., 2007; Glover et al., 2017; Hindar, Ryman, & Utter, 1991; Naylor et al., 2005). Hence, regulation is needed to mitigate the potential impact of farm escapees, together with measures to support implementation by the aquaculture industry.

Two challenges inherent to farmed escapees need to be tackled; differentiating farmed escapees from wild fish, and identifying the farm of origin of escapees. The former can be addressed by studying morphological characteristics of "suspect" individuals (Lund & Hansen, 1991) or through DNA-analysis (Bylemans et al., 2016; Karlsson, Moen, Lien, Glover, & Hindar, 2011). For the latter, authorities might need to establish which farm has lost the escapees. In Norway, genetic assignment methods are now routinely and successfully used to identify the farm of origin for salmon escapees (Glover, 2010; Glover, Skilbrei, & Skaala, 2008), rainbow trout (*Oncorhynchus mykiss*) (Glover, 2008) and Atlantic cod (Glover, Dahle, & Jorstad, 2011; Glover et al., 2010) as evidence for enforcement (Glover, 2010).

5 | ASSESSING THE COSTS OF DNA-ANALYSIS IN FISHERIES AND AQUACULTURE: THE APPROACH

To undertake a full assessment of all costs and benefits for DNA-analysis to be routinely used in fisheries and aquaculture compliance, an investigation would need to involve a Cost–Benefit Analysis (CBA). A CBA is not limited to monetary values, and ideally, environmental and societal costs and benefits also need to be quantified and taken into account.

However, due to the absence of relevant data and information, for example value of illegal and mislabelled catches, losses in tax revenue and the associated environmental costs, we have not attempted a comprehensive CBA. We therefore performed a semi-quantitative analysis to objectively assess the costs of DNA-based technologies to support fisheries control and enforcement and to

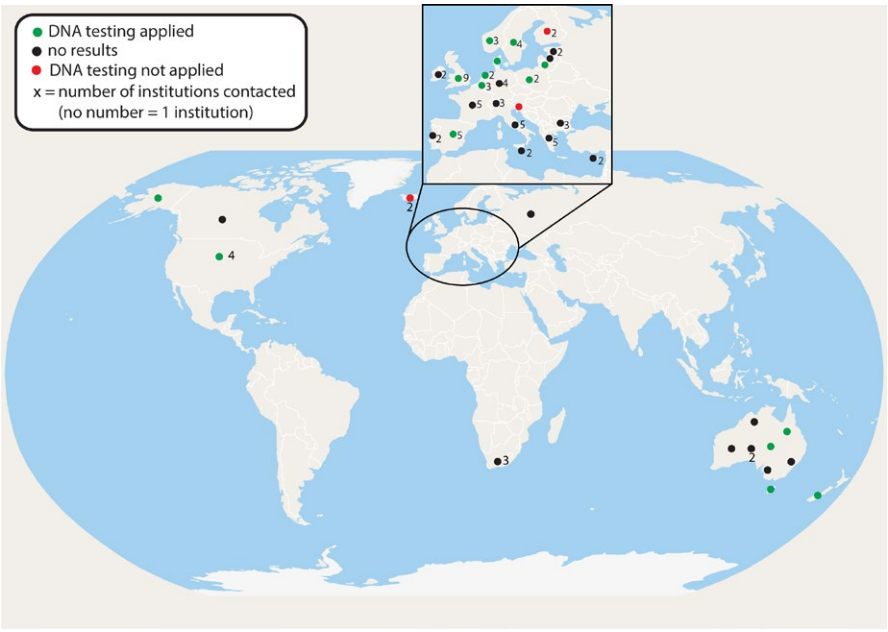

FIGURE 2 Institutions contacted with a questionnaire to gather information on the use of genetics in the context of control and enforcement. Dots indicate institutions to which the questionnaires has been submitted. Black dots indicate that no results have been obtained, red dots indicate that no DNA-technology is applied for fishery control and enforcement or fish product identification, green points indicate that DNA-testing is used for fishery control and enforcement or the identification of fish products in the respective country (however in some cases, the questionnaire has not been returned with more specific information on frequency of use, costs *etc.*), numbers indicate the number of institutions contacted

express such costs relative to any monetary penalties imposed as a result of infringements detected using such technologies.

In 2011, an electronic questionnaire was sent to 94 institutions in 30 countries (see Figure 2). The questionnaire posed the following questions:

1. In how many cases genetic analysis was used in a fisheries inspection context?
2. How many of these cases obtained positive evidence of fraud?
3. What was the estimated total value of illegal catches found?
4. What was the total value of the fines applied?
5. What were the total operational costs?
6. Other estimated costs that were initially required to use these tools (fixed costs), such as training courses for inspectors?

The institutions were selected based largely on prior knowledge of, or references to authorities or institutions which have used or have to potential to use DNA-analysis for fisheries and aquaculture compliance investigations. Based on the responses, 57 suitable cases were identified as having sufficient data and information to be included in our analysis.

The data received were screened to extract information on both the total operational costs (sampling and processing) of the DNA-analysis and the estimated value of the illegally caught fish and/or the value of any fines imposed. For the present study, the costs taken in consideration are exclusively those emerging in the context of the control and enforcement operation, under the condition that DNA-analytical capacity (knowledge, premises and equipment) already exists.

For species identification and geographic origin assignment, where possible, the total operational costs of the DNA-analysis (including administrative costs) were compared to the value of fish illegally caught or traded and/or any fines imposed.

6 | COSTS OF DNA-ANALYSIS FOR SPECIES IDENTIFICATION

Our species identification case-studies have been classified into two groups, a major case of mislabelled imports of catfish (Pangasiidae) into the USA, and other cases.

6.1 | Mislabelled imports of catfish into the USA

Following complaints from the Association of Catfish Farmers of America about the massive import of cheap catfish, in 2003 the USA imposed an anti-dumping tariff on catfish imports (Duc, 2010). A number of companies attempted to circumvent the tariff and continued to import catfish under other species names (e.g., grouper (Serranidae), sole (Soleidae)). The value of grouper is four times that of frozen catfish (Jacquet & Pauly, 2008), and some companies mislabelled and sold catfish as grouper.

The Office of Law Enforcement and Marine Forensics Laboratory of the US National Oceanic and Atmospheric Administration (NOAA) supported nine cases with DNA-analysis to test whether suspicious catfish products were correctly labelled. Altogether, 1,505 samples were analysed at a total cost of 61,780 USD. In four of the nine cases, evidence of mislabelling was found and the fraud was judged to be sufficient enough to impose jail sentences. Total fines (based partially on the taxes evaded) in these four cases amounted to 1,648,000 USD. Thus, total fines exceeded the analytical costs by 27 times. In these cases, all analytical and administrative costs and revenues incurred were considered.

6.2 | Other cases where DNA-analysis has been used for species identification in the US

Information from NOAA was provided for 43 additional cases. These cases were related to illegal catches or imports of marine mammals and endangered species and illegal fishing practices (e.g., illegal gears, lack of Turtle Excluder Devices). The 43 cases involved the analysis of 593 samples, with a cost of 24,343 USD. Evidence for infringements were found in 33 of the 43 cases. Fines were imposed in 18 cases, accounting for 1,794,872 USD, which is 74 times the analytical costs.

7 | COSTS OF DNA-ANALYSIS FOR ORIGIN ASSIGNMENT

We are aware of only two well-documented cases where DNA-analysis was used to clarify the dubious origin of wild captured fish for compliance purposes. In both cases, at the request of the Danish inspection authorities, the analyses were carried out by the National Institute of Aquatic Resources of the Danish Technical University (DTU aqua), an academic institution.

In the first case, in 2003, a fisher declared 7,759 kg of Atlantic cod (*Gadus morhua*, Gadidae) as being harvested from the eastern Baltic Sea. Inspectors observed that the fish resembled North Sea cod in appearance and size and were associated with a large by-catch of pollack (*Pollachius pollachius*, Gadidae) which is unusual for the Baltic Sea. DNA-analysis showed that the provenance probability of the cod allegedly from the eastern Baltic was one in 6 million and 1 in a 1,000 that the fish originated from the western Baltic. The case was judged in court in 2005 and the verdict, substantially influenced by the DNA evidence was delivered in early January 2006. The 7,759 kg of confiscated cod were worth 25,131 USD and a fine of 9,218 USD was imposed. The costs for the genetic analysis accounted for 1,799 USD (663 for Academic staff, 973 for laboratory working time and 162 for operations). Hence, the estimated value of the detected IUU catch was 14 times higher than the analytical costs, and the fines were five times higher than the analytical costs.

The second case took place in 2006, when two fishing vessels landed 922 tonnes of sprat from the Baltic Sea at a port in the north-western part of Jutland. The vessels were only allowed to harvest 400 tonnes each from the Baltic Sea, and the vessel owners invented a trip in the logbooks claiming the fish in excess was caught in the North Sea. Genetic testing showed that it was highly unlikely that the catch originated (partly) from the North Sea. Confronted with this evidence, combined with satellite tracking records, the fishers accepted a fine and the confiscation of the catch without going to court. Fines accounted for 24,055 USD and the confiscated catch accounted for 41,238 USD. The costs for the DNA-analysis were not available in this case, but the data from the cod case given above, strongly indicate that they were substantially lower than the fines.

8 | COSTS OF DNA-ANALYSIS TO IDENTIFY THE FARM OF ORIGIN OF AQUACULTURE ESCAPEES

The Norwegian Institute of Marine Research (IMR) developed a DNA-based analytical testing procedure to obtain information on the potential source of recaptured farm-escaped fish (Glover, 2010; Glover et al., 2008). From 2006 to 2015, at the request of the Norwegian Directorate of Fisheries (NDF), this procedure was applied in 19 cases of unreported escape events, 16 of which concerned Atlantic salmon, one rainbow trout and two Atlantic cod. A detailed account of the first nine cases is available in Glover (2010).

In the rainbow trout case, and one of the two Atlantic cod escapes, a non-ambiguous genetic signal confirming their farm of origin was obtained. However, there was no subsequent legal investigation, so no further assessment was possible. For the remaining 17 cases (16 involving salmon and 1 involving cod), DNA-analysis was used as part of a legal investigation on the probable origin of escapees. Of the 17 cases, two have so far resulted in prosecutions and ended with fines of ~40,642 USD and ~121,925 USD for the companies found in breach of the regulations. For 13 of the remaining 15 cases, the analyses have revealed the most likely farm of origin for the escapees, but legal action is pending. In summary, for the first four cases (2006–2010), 161 escapees and 34 cages (50 individuals per cage) were sampled, accounting for a total of 1,861 samples and an analytical cost of 121,015 USD. For these four cases, the total benefits for the administration (fines of 162,567 USD) were 1.3 times higher than the analytical costs. Importantly, an added value is created through the origin assignment inherent to analysis. This information helps farmers, also those not fined, to improve the quality of management, approaches and routines to reduce escapes.

9 | THE ANALYSIS IN SUMMARY

The results covering the four different control and enforcement issues are summarized in Table 1.

TABLE 1 Data compiled for the comparison of costs relative to monetary penalties imposed

Case	Samples	Cost (USD)	Evidence	Fines (USD)	IUU/fraud value (USD)
Trade mislabellingcatfish	1,505	61,780	4 out of 9	1,648,000	n.a.
Other species identification	593	24,343	33 out of 43	1,794,872	n.a.
Origin assignment	n.a.	1,799	1 out of 1	9,218	25,131
Farm escapees	1,861	121,015	3 out of 4	162,567	n.r.

Note. n.a. for not available, and n.r. for not relevant.

TABLE 2 Approximate costs associated with laboratory set-up in a monitoring and forensic context

Purpose	Activity	Application	Cost (1,000 USD)	Comment
Monitoring	Lab equipment (capital cost)	Species ID	50	Use of real-time PCR assays
		Origin ID	50	
	Running costs (p/a)	Species ID	55	Service, depreciation (20%) & consumables
		Origin ID	55	
	Research	Species ID	15	Standard markers employed
		Origin ID	500	Marker discovery & ref. data
	Validation	Species ID	5	Up to two markers
		Origin ID	20	Up to 25 markers
	Per sample service	Species ID	0.05	Assuming multiple samples processed simultaneously
		Origin ID	0.1	
Forensics	Lab equipment (capital cost)	Species ID	200	DNA sequencer
		Origin ID	50	Use of real-time PCR assays
	Running costs (p/a)	Species ID	90	Service, depreciation (20%) & consumables
		Origin ID	60	
	Research	Species ID	15	Standard markers employed
		Origin ID	500	Marker discovery & ref. data
	Validation	Species ID	5	Up to two markers
		Origin ID	20	Up to 25 markers
	Per sample service	Species ID	0.5	Single sample cost, economies of scale possible
		Origin ID	1	

Notes. Approximate costs associated with laboratory set-up, assay production and testing services for the genetic identification of fish and fish products. Monitoring costs assume that the testing laboratory is an accredited testing facility, not academic research lab. Difference in equipment costs between monitoring and forensic applications reflect the use of DNA sequencing for species ID in forensic casework. Running costs are for equipment maintenance, depreciation over 5 years and consumables only, not staff or facility costs. This is a simplified comparison—multiple options exist for testing with multiple possible cost models.

The results show that the costs of DNA-analysis were less than the value of the confiscated catch or the fines imposed in all analysed cases.

An accurate estimate of costs associated with DNA-analysis is essential for agencies to take an informed decision on whether such analyses should become routine in investigating fisheries and

aquaculture compliance. Depending on the importance attributed to fisheries control and enforcement, countries or authorities might be prepared to dedicate DNA-analytical laboratories exclusively for such purposes. It is necessary to estimate budgetary needs for the creation and running of such a facility and ideally the expected benefits should also be quantified. Estimates should include set-up costs, acquisition of analytical instruments, access to reference data.

While, to assess whether costs might be prohibitive in the short-term, frequently a simple price-per-sample estimate is the preferred option, in the absence of an established testing service it is necessary to consider a wider set of cost issues. This includes the distinction between research, validation and service costs, the anticipated laboratory sample throughput (economies of scale) and the ultimate use of the resulting data, for example for monitoring purposes or to produce forensic evidence (Ogden, 2010). Each of these aspects has a significant effect on DNA-testing costs. Table 2 summarizes costs to sustain a laboratory dedicated to DNA-analysis for fisheries control and enforcement on a routine basis. Laboratory equipment (capital costs) refers to the costs required to purchase the equipment to run the DNA-analysis; while running costs refers to costs related to labour and depreciation of the equipment on an annual basis.

The production of DNA assays for diagnostic testing can be divided into three principle phases: (i) fundamental research, including the development of DNA markers and production of reference data; (ii) validation, which involves a study of assay robustness, accuracy and reproducibility; and (iii) the provision of a routine testing service for the validated assays. For species identification, all three phases are often completed and a service available, enabling a price-per-sample estimate. For origin assignment, undertaken on a species-specific basis, the analyst is either limited to testing a few species within certain geographic areas, or faces some additional costs for development of new assays.

Assay development and production costs may be met by the laboratory, under a commercial service model, or by the fish and food industry, driven by the need for self-regulation. In either situation, the service is only likely to be worthwhile with respect to accruing costs when a high throughput of samples is guaranteed. Where assay production is funded from non-commercial sources, the subsequent costs of maintaining a commercial testing service may be prohibitive. Therefore, for applications to identify major commercial species it is likely that genetic testing could be routinely provided by non-government diagnostic testing laboratories; testing for other species is likely to require government subsidy from research all the way through to service provision.

The third consideration affecting costs is how the data are intended to be used. Monitoring applications, in which many samples are routinely tested by industry, third-party certifiers or regulators, will cost significantly less than a forensic analysis and reporting of individual samples for a criminal prosecution. Although the basic assay employed will often be identical, the level of control, documentation and reporting in forensic casework means that the difference in cost is often up to a factor of ten. This has implications for the DNA-testing strategy that enforcement agencies employ, suggesting a model of routine testing backed-up by occasional forensic re-analysis of any samples suggesting an infringement (Figure 3).

Such a model is more complex than a simple price-per-sample estimate, as end-users need to consider various analytical options and their associated costs (Table 2). However, with an increasing application frequency, it is likely that DNA-testing costs will decrease.

Routine DNA-analysis will likely increase the number of infractions detected, but the ratio of infractions found per control instance will decrease compared to the situation where only suspect samples are analysed.

10 | CONCLUSIONS AND RECOMMENDATIONS

The main advantage of DNA-based analytical techniques for fisheries/aquaculture control and enforcement, as well as traceability along

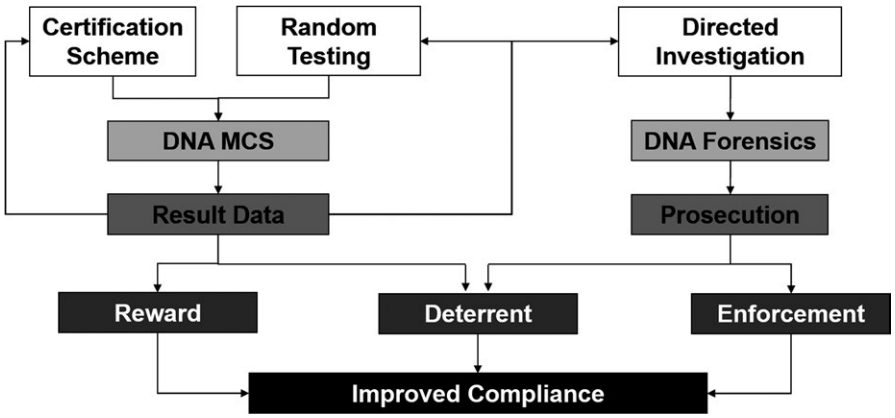

FIGURE 3 Flow diagram depicting the impact of genetic identification methods on monitoring (DNA MCS; MCS stands for the technical term Monitoring, Control and Surveillance) and enforcement (DNA Forensics) to improve compliance with fishing regulations. Forensic investigations are up to ten times more expensive than routine tests carried out for monitoring purposes, implying that the DNA-testing strategy of enforcement agencies will foresee routine testing, backed-up by occasional forensic re-analysis of samples initially found to indicate illegality. Adapted from Martinsohn and Ogden (2009)

the supply chain, is that they can provide independent and robust information on the species and its origin. Genetic tools have proven to be a powerful instrument to ensure traceability and to fight against consumer fraud and IUU fishing. Two recent studies also convincingly demonstrate the applicability of DNA-analysis for the management and control of Northeast Arctic and Norwegian coastal cod fisheries (Dahle, Johansen, Westgaard, Aglen, & Glover, 2018; Johansen et al., 2018), with Dahle et al. hinting at the cost efficiency by estimating the DNA-analytical costs (€150,000) at 0.02% of the landing value of the fishery during the analytical period (€730 million).

So the question remains why, in contrary to the field of human forensics (Kayser & de Knijff, 2011), and also wildlife forensics (Ogden, Dawnay, & McEwing, 2009), DNA-analysis remains under-utilized to support investigations in the context of fisheries control and enforcement. This has been addressed recently and a number of bottlenecks have been identified (Bernatchez et al., 2017; Martinsohn et al., 2011; Ovenden et al., 2015), amongst them insufficient knowledge on the costs and benefits of using DNA-analysis for fisheries control and enforcement. The latter point is the driver of this study: By analysing the costs inherent to the application of DNA-analysis, and trying to estimate the benefits arising through their use, we attempted to assess the value of using DNA-based analysis for fisheries control and enforcement in an objective manner. This should support policy makers and other stakeholders in the decision as to whether to pursue the integration of DNA-analysis on a routine basis in fisheries/aquaculture control and enforcement schemes at each stage along the supply chain.

In all cases examined in this study, analytical costs (including administrative costs) were lower than the value of confiscated catches, illegal imports and associated fines. Therefore, our results indicate that DNA-analysis not only constitutes a valuable element in fisheries control and enforcement schemes, but is also justifiable from a cost perspective.

Since IUU fishing is a global phenomenon having great ecological as well as socioeconomic impact, and world aquaculture is on the rise, we believe that the results from this study indicate that the introduction of DNA-analysis for fisheries and aquaculture control and enforcement warrants serious consideration in regions. Such an idea is in line with discussions held during the third Global Fisheries Enforcement Workshop (The International MCS Network, 2011).

The use of DNA-technology for fisheries control and enforcement potentially has a strong deterrent effect, particularly if forensic standards are applied. Moreover, in many cases, defendants, if guilty and confronted with forensic genetic evidence, tend to admit guilt, which can considerably shorten court procedures and has a substantial cost-saving effect (R. Withler, pers. comm.). It is worth noting that the deterrent effect can be further enhanced when combined with carefully adjusted fines: The routine application of genetic analysis in combination with higher fines in accordance with environmental and societal costs would mutually enhance their deterrence effect in a fisheries control and enforcement context (Sumaila, Alder, & Keith, 2006). It should furthermore be considered, as already applied in some countries, that fines can also constitute an important source of revenue for funding of fisheries management and enforcement activities (Supernault et al., 2010).

Importantly, the use of DNA-analysis in a fisheries/aquaculture control and enforcement context relies on the availability of reference data and baselines, such as those provided for species identification by FishTrace (Zanzi & Martinsohn, 2017), the Fish Barcode of Life Initiative (FISH-BOL; www.fishbol.org) and for genetic population structure of marine fish by FishPopTrace (https://fishpoptrace.jrc.ec.europa.eu). Furthermore, the marked reduction in costs for DNA-analysis means that the establishment of robust genetic reference baseline data is much more feasible than in the past and hence provides the opportunity to integrate genetic and genomic approaches into fisheries and aquaculture monitoring. This is illustrated by a rough comparison of the costs inherent to genetic marker development between the projects FishPopTrace (undertaken from 2008 to 2011) and the FP7 Project AquaTrace (https://aquatrace.eu) (undertaken from 2012 to 2016). In both the projects, Single Nucleotide Polymorphism markers (SNPs) have been developed for control, enforcement and traceability purposes. The costs for SNP discovery and characterization per 1,000 samples were about 250 Euros for FishPopTrace while they were about 50 Euros in AquaTrace, that is a fivefold drop in costs occurred during those 4 years, a trend which is continuing. As the genetic reference baseline information created by such fundamental research projects is valuable in a general fisheries management and conservation context, that is beyond control, enforcement or traceability, it constitutes a significant added value for our society (Hemmer-Hansen et al., 2014; Martinsohn, 2013).

The Danish AgriFish Agency together with the academic institution DTU Aqua have successfully carried out a test project which explored the feasibility for fishery inspectors to undertake sampling for DNA-analysis. In doing so, they produced a simple guide on the use of DNA for fisheries control and developed a small control toolbox and pre-formatted report delivery note, which enables fishery inspectors to carry out tissue sampling in situ with little extra equipment, or effort (Lars Bonde Eriksen, pers. comm.).

Although control and enforcement for fisheries/aquaculture is costly, the absence of such activities can be even more costly in socioeconomic and environmental terms that can arise through unaccounted for illegal and unreported fishing and the uncontrolled release of farmed fish (OECD, 2005).

While since 2008, the Norwegian authorities have routinely utilized DNA-analysis to trace the farm of origin, of Atlantic salmon aquaculture escapees (Glover, 2010), globally there remains a need to increase awareness and capacity-building (Martinsohn, 2011). In this context, it is interesting to note that the Control Regulation (EC) 1224/2009 for the Common Fisheries Policy (CFP) of the European Union refers in Article 13 to genetic analysis, suggesting pilot studies to assess whether the use of such technologies would lead to an improved compliance with rules of the CFP in a cost-effective way (European Council, 2009). To our knowledge, only one such study had been launched by the UK Department for Environment, Food and Rural Affairs (DEFRA; FAO 118; https://fishpoptrace.jrc.ec.europa.eu/fpt-legacy). We hope that more similar studies will be launched and that the results from

such studies, combined with better knowledge about inherent costs and resulting benefits, can produce a positive spill over so that the use of DNA-analysis for fisheries control becomes more routine.

Meanwhile, we believe that there are a sufficient number of examples which provide robust evidence for the power of DNA-analysis in a fisheries control and enforcement context. Taken together with our observations, we advocate that DNA-based analytical approaches provide efficient and affordable tools, which have the potential to support compliance in the fisheries and aquaculture sectors thereby justifying their integration in control and enforcement on a routine basis.

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ORCID

Jann Th Martinsohn https://orcid.org/0000-0003-3407-5839
Jordi Guillen https://orcid.org/0000-0003-3705-2253

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