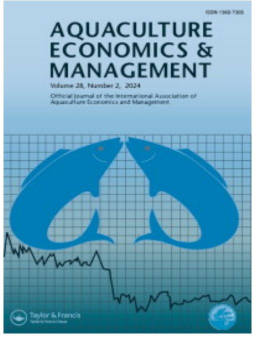

Aquaculture Economics & Management

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/uaqm20

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AQUACULTURE ECONOMICS & MANAGEMENT
2024, VOL. 28, NO. 2, 208–237
https://doi.org/10.1080/13657305.2024.2314511

Nutrient policies and the performance of aquaculture in developed countries – a literature review

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ABSTRACT
Eutrophication is a serious problem in many parts of the world, and aquaculture production can contribute to the problem as well as be part of its solution. Nutrient polices in developed countries are often command-and-control policies that may have contributed to the slow growth of the sector. We perform a literature review to investigate how current nutrient polices affect the sector and if economic incentive policies have greater potential to support sector growth. Although the literature is limited in many aspects, the results indicate that this may be the case. Given that the ability to measure, monitor and control has improved over time, possibilities for using economic incentive policies have increased. For example, subsidies that are results-based, i.e., based on the amount of emissions that are reduced, could be used. It is also possible for aquaculture production to benefit from being included in emissions trading systems, where these are available.

KEYWORDS
Aquaculture; command-and-control; economic incentive; eutrophication; nutrient policies

Introduction

Since the early 1970s, global aquaculture production, farming of aquatic organisms, has grown at an annual rate of 8 percent (Garlock et al., 2020). However, the growth rates in Europe and North America have been much slower than in other parts of the world. Canada and Norway have been exceptions but the United States and most of Europe, have not been part of the global growth trend (Garlock et al., 2020). As a result, aquaculture production in developed countries is

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Supplemental data for this article can be accessed online at https://doi.org/10.1080/13657305.2024.2314511
This article has been corrected with minor changes. These changes do not impact the academic content of the article.

small compared to developing countries. In 2020, about 58 percent of the production (in quantity) took place in China and 88 percent in Asia (FAO, 2022). In contrast, Europe, contributed only 2.7 percent to the global production of aquatic animals and algae in 2020 (FAO, 2022). The main reason for the lack of growth has been attributed to restrictive regulatory structures (Abate et al., 2016; Anderson et al., 2019; Garlock et al., 2020; Guillen et al., 2019; Naylor et al., 2021, 2023). More specifically, strict environmental regulations, a high bureaucracy burden and widespread use of command-and-control instruments are the key constraining elements (Guillen et al., 2019; Rubino, 2023).

While there are some private incentives to reduce environmental impact as e.g. mortality and escapees are costly (Pincinato et al., 2021a,b), environmental regulation is generally necessary to address negative externalities associated with aquaculture. These externalities include water pollution from emissions of nutrients, genetic contamination of wild populations from escaped farmed fish, habitat degradation from converting nature areas into aquaculture farms, spreading of disease and overfishing of wild stocks to provide feed. At the same time, aquaculture can have positive effects on the environment such as enhanced water quality through filtering of nutrients, reduced reliance of more greenhouse gas-intensive animal proteins and less pressure on wild fish stocks (Asche et al., 2022). Water pollution from nutrient emissions has been problematic in many parts of the world, especially in water bodies that are eutrophic. For example, both the Baltic Sea in Northern Europe and the Chesapeake Bay in the US suffer from severe problems with eutrophication (EPA (Environmental Protection Agency),), 2021; HELCOM, 2018). Additionally, local emissions of nutrients from fish aquaculture can be problematic (Eriksson et al., 2019; Jensen et al., 2023). Although feeds and feeding techniques have improved in the last twenty years and emissions per unit of fish produced has decreased (Asche et al., 2009; Kause et al., 2022), there are still many water bodies that are sensitive to further emissions of nutrients (Iho et al., 2015). In many parts of the world, the potential growth of aquaculture production is thus closely linked to policies that aim to regulate nutrient emissions.

Aquaculture can be defined as intensive or extensive depending on the extent to which feed is used in the production. Intensive aquaculture, e.g., salmon farming, uses feed whereas extensive aquaculture, e.g., mussel farming, relies on naturally occurring feed in their surroundings. Intensive aquaculture, depending on technique, can cause emissions of nutrients. Traditional technologies, such as open-cage fish aquaculture, typically result in larger emissions compared to newer closed or semi-closed land-based fish aquaculture (Eriksson et al., 2019). On the other hand, extensive aquaculture has a more limited impact and often extracts unwanted nutrients from the water. Thus, there may be negative or positive externalities from the production, depending on type of aquaculture and the status of surrounding waters.

Economic policy instruments can be used to regulate the negative externalities from intensive aquaculture and support the positive externalities from extensive aquaculture. However, it is desirable that the policy instruments are cost-effective in the sense that the marginal abatement cost is the same for all emitters. This ensures that the cost of reducing the emissions does not become unnecessarily high, thereby avoiding harm to the growth of the sector. Economic-incentive policies, such as emission charges, emission abatement subsidies and emissions trading systems have the potential to be cost-effective in the right circumstances whereas command-and-control instruments of various types (e.g., standards on inputs, emissions, or technology) usually are not. In theory, introducing economic-incentive policies in a sector will improve its economic performance, but in practice, there may be many reasons why such policies are not implemented. They may, for example, be information intensive, unreliable, costly, or hard to enforce. Regulating nutrient emissions in watersheds is complex since it is hard to track and trace pollution sources.

The aim of this study is to review the economic literature on nutrient policies for aquaculture in developed countries. Previous reviews about aquaculture policies have focused on discussing externalities of aquaculture in general (Anderson et al., 2019; Asche et al., 2022; Naylor et al., 2021) and policies that can be used to correct these externalities (Asche et al., 2022) as well as economic evaluations of the policies in use (Anderson et al., 2019). We believe that part of the explanation of the slow growth of aquaculture in many parts of the developed world could be related to how policies for limiting eutrophication have been implemented. This is an issue that has only received limited attention so far.

We perform a systematic literature review where focus is on policies that aim at reducing nutrient emissions from intensive aquaculture as well as encouraging nutrient uptake from extensive aquaculture. We investigate which policies are analyzed and proposed, what is documented about their economic effects, and what limitations have been encountered when applying them. Possible knowledge gaps in the literature are also documented.

The rest of the paper is organized as follows. The next section describes how we perform the systematic review. Delimitations and screening methods are described in detail. We then present the results from the literature review by accounting for different types of policy instruments analyzed in the literature. Finally, the paper ends with a concluding discussion highlighting possible challenges with implementing cost-effective abatement policies.

Methods

We perform a literature review of the economic literature on nutrient policies for aquaculture. The evaluated policies can be either policies that have been implemented in practice or policies that are evaluated based on modeling studies. As traditional literature reviews are susceptible to different types of biases, there has been a move toward systematic reviews in the scientific literature in recent years. Systematic reviews are planned and documented in detail to maximize the transparency and reliability during the review process (Haddaway et al., 2015). In practise this means that the final report of a systematic review should explain which limits were applied to the choice of subjects, which search terms and databases were used in the article search, which studies were eliminated in the screening and the reasons why these were not considered usable.

Below, we present the process of finding relevant studies, discussing how search terms were selected and the databases used. We also describe the screening process and explain why studies were or were not considered relevant for our selected sample.

Searching for studies

The aim of the literature search is to find studies focusing on how policies aimed at reducing nutrient emissions or promoting nutrient uptake from aquaculture affect the economic performance of the aquaculture sector. When constructing the search string, we focused on four groups of terms: nutrient-related, policy-related, sector-related and economic. Nutrient-related search terms included the terms *nutrient*, *nitrogen*, *phosphorus*, *eutrophication*, and *nitrate*. Since we were interested in all possible policy instruments, we opted for the terms *policy* and *regulation* although especially the latter is expected to increase the number of records due to its double meaning. Sector-related terms were *aquacult**, *mussel**, *seaweed**, *alga** and *oyster**. Economic terms were *market**, *cost**, *revenue**, *income**, *profit** and *economic*. The search terms *producti**" and *measure** were tested but omitted because of their common use in texts concerning natural science provided an unmanageable number of records. In all searches, non-high-income economies were excluded. Non-high-income economies were defined as economies having a Gross National Income lower than $12,696 per capita according to the World Bank (World Bank, 2022).

Abstracts, titles and key words were searched using a search string. Thus, the search was performed using the following Boolean string (excluding the search terms for omitted countries):

TITLE-ABS-KEY(nutrient* OR nitrogen OR phosphorus OR eutrophication OR nitrate) AND TITLE-ABS-KEY(polic* OR regulat*) AND TITLE-ABS-

KEY(aquacult* OR mussel* OR seaweed* OR alga* OR oyster*) AND TITLE-ABS-KEY(market* OR cost* OR revenue* OR income* OR profit* OR economic)

The search string was used in Elsevier's SCOPUS database (https://www.elsevier.com/solutions/scopus) and Clarivate Analytics' Web of Science Core Collection (https://www.webofscience.com/wos/woscc/basic-search). The search resulted in 512 records in Scopus and 453 records in Web of Science. To evaluate the relevance of this initial search string, we used information from two previous review studies on aquaculture: Fong See et al. (2021) and Anderson et al. (2019). See Appendix B for details. After the evaluation, the Boolean string was modified slightly in order to find more relevant results:

TITLE-ABS-KEY(effluent* OR nutrient* OR nitrogen OR phosphorus OR eutrophication OR nitrate) AND TITLE-ABS-KEY(polic* OR regulat*) AND TITLE-ABS-KEY(aquacult* OR "*fish farm*" OR "*fish pond" OR mussel* OR seaweed* OR alga* OR oyster*) AND TITLE-ABS-KEY(market* OR cost* OR revenue* OR income* OR profit* OR economic)

The full search string, including the search terms for omitting non-high income countries, is presented in Appendix A. Searches in publication databases, with the updated search string, were performed on May 30, 2022, using university library subscriptions (at Lund University and the Swedish University of Agricultural Sciences). The search included all available years and document types but was restricted to texts in English. We found 574 records in Scopus and 460 records in Web of Science, which is a total of 1034 records. Of these, 748 were unique search records and 286 were duplicates.

In order to find more texts and grey literature, the modified search string was used in Google Scholar (https://scholar.google.com) in incognito mode. Due to the 32-world limit for a Google search, excluding all non-high-income countries was not feasible. To fit the search string within the search word limit, the words "alga* and oyster* were also excluded. The search was performed on October 31, 2022, and the titles and abstracts of the first 250 records were evaluated. Only 14 of the studies were also found in Web of Science or Scopus, thus we had 236 unique search records from the Google search at this stage. In total, we had 984 records.

Screening the studies

The studies were first screened by reading titles and abstracts using the following exclusion criteria (number of excluded records in parentheses):

1. All studies not including economics (661).
2. All studies not concerned with aquaculture (87).

3. All studies not concerned with policy instruments related to nutrients (100).
4. All studies concerning developing countries (72).

The exclusion criteria were applied in descending order. If an article was not excluded after the first criteria (including economics), the next criterion was investigated, and so forth. Around half of the studies were not concerned with economics but rather focused on biological or technical effects. Some studies were not related to aquaculture or nutrient-related policies. Finally, despite excluding non-high-income countries in the search string when using Web of Science and Scopus, some studies analyzed aquaculture in developing countries. These were excluded in the final exclusion criterion. If it was unclear if the paper fulfilled the selection criteria, it was selected for further analysis. Two researchers screened the records independently, and results were compared. A list of 64 records was agreed upon and the full studies were downloaded, except in five cases where the full versions of the studies were not found.

A more detailed investigation of the full texts of the records was made to confirm the relevance of the 59 potentially relevant studies found in the first screening. Two researchers independently read the texts, and results were compared, resulting in the exclusion of 21 studies that did not meet the selection criteria during the full-text screening. The most common reason for excluding studies at this stage was a lack of analysis of policies aimed at reducing nutrient leakage or supporting nutrient uptake. This meant that 38 studies passed the selection process at this stage. It should be mentioned that we interpreted the policy criterion quite liberally. Few studies evaluated policies aimed at regulating nutrients from, or supporting uptake of nutrients with, aquaculture. It appears as if the literature, so far, has focused on how nutrient leakage can be reduced technically but there has been little interest in how the government can support nutrient reduction or uptake with policy. Hence, we chose to select studies that discuss policy solutions even if these are not evaluated in detail.

When reading full texts, we noted relevant additional literature that was not captured by the search string. The reasons for this were e.g., that the words *policy* or *regulation* were not mentioned in the title, abstract or keywords. Instead, more general words like *measures* or *tools* were used, or more specialized words like *nutrient credits*. In some cases, the type of aquaculture was described at a specialized level such as *cage farming* or *trout in flow-through systems* and was thus not captured by our search string. The additional literature provided ten more records, bringing the total number of studies to 48 at this final stage. The search process is illustrated in Figure 1.

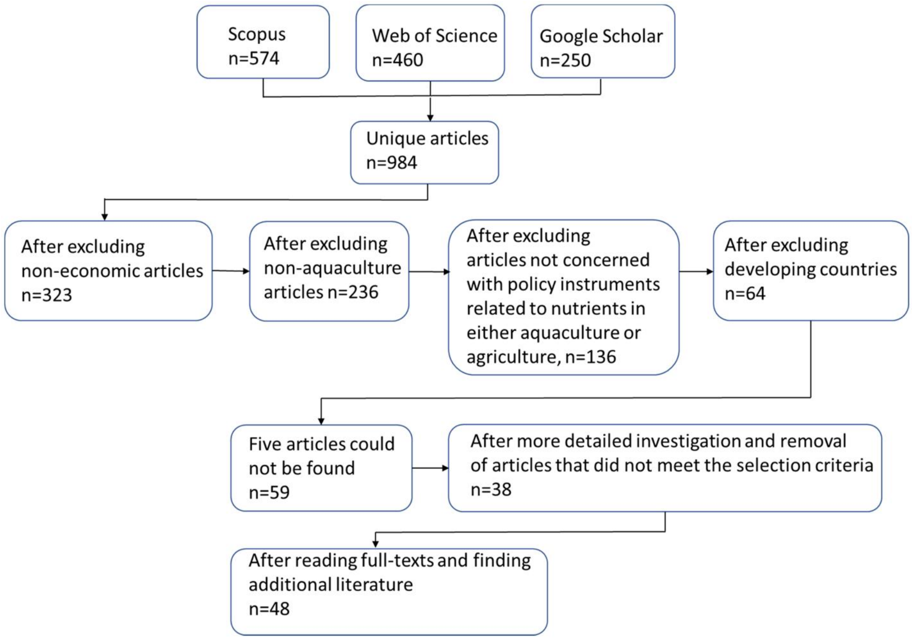

Figure 1. The search process illustrated in a flow diagram.

Basic characteristics of selected studies

Below we summarize basic characteristics of the selected studies, investigating methods used as well as species and countries/areas analyzed to get an overview of the type of studies that have been conducted. Table 1 shows that simulation modeling is the most common method used in the selected studies followed by literature review. We can also see that finfish and mussels/oysters are the most common species analyzed. In general, studies focusing on mussels/oysters and seaweed analyze how these species can contribute to better water quality through nutrient uptake, while studies focusing on other species discuss nutrient leakage from aquaculture production. Most of the selected studies focus on nutrient uptake rather than nutrient leakage. Finally, Table 1 shows that the geographical scope of the selected studies is relatively large, although studies analyzing aquaculture in the US are the most common in our selection.

We will now review the selected studies in more detail and summarize the results on how policy can be used for either reducing nutrient leakage from aquaculture or for promoting nutrient uptake with aquaculture. In the analysis, we group the studies based on the policy instrument that is studied and discuss the efficiency of the policy instrument. To the best of our knowledge, the approach to group the studies based on the economic policy instruments is novel within the aquaculture literature and gives an

Table 1. Basic characteristics of selected studies.

Method	Species	Country/Area
Simulation model 23	Mussels/oysters 21	US 15
Literature review 10	Finfish 19	World 11
Survey 11	Aquaculture in general 5	Denmark 8
Field study 3	Seaweeds 4	Sweden 4
Case study 2	Shrimps/prawns 2	Europe 3
Regression analysis 1		Baltic Sea 2
		Chile 2
		Australia 1
		Portugal 1
		Norway 1

Note: The number of studies does not add up to 48 in each column since one study could use more than one method, study more than one class of species or cover multiple countries. Thus, "Method" includes two studies that use a simulation model in combination with a field study. "Species" includes two studies that study mussels/oysters in combination with finfish.

added value for the understanding of how specific policy instruments can or have been used within the aquaculture sector.

Results

In this section, we discuss the findings in the selected literature. Most of the literature focuses on either command-and-control policies or economic-incentive policies as tools to promote nutrient reduction or uptake from aquaculture. There is also a complementary strand of literature focusing on spatial management, i.e. how to decide where to locate aquaculture facilities. All but one of the selected papers deal with command-and-control policies, economic-incentive policies or spatial management. Stanley (2000) instead investigates voluntary approaches to reduce nutrient emissions from intensive aquaculture. As only one paper analyses voluntary approaches as a policy measure, we have chosen not to include this policy type in the presentation of the results. Hence, below we will present the results from studies focusing on command-and-control policies, economic-incentive policies and spatial management.

Command-and-control policies

Command-and-control policies are based on some form of regulation or standards and are commonly used. In comparison to policies based on economic incentives, command-and-control policies do not promote emission abatement at the lowest possible cost and are, hence, normally not cost-effective. On the other hand, command-and-control policies are relatively easy to implement.

From our literature search, it is clear that the number of studies discussing the effects of using command-and-control policies for regulating nutrients from aquaculture is limited, and they are also relatively old with10 out of 13 identified studies being more than 10 years old. All 13 studies analyzing command-and-control policies focus on intensive aquaculture, which is not surprising since this branch of the sector mainly contributes to eutrophication. In this context, the study by Abate et al. (2016) is interesting as it shows that strict environmental regulations are negatively correlated with growth of intensive aquaculture in a country, but not with growth of extensive aquaculture. The literature on command-and-control policies focus on three types of standards: standards on inputs, emissions and technology. We discuss these and their effects on aquaculture according to the literature below.

Input standards

Rather than setting standards for emissions, it is possible to set standards on inputs used in the production process. In some cases, it is more difficult or costly to measure emissions than the inputs that are causing them. Farm-specific feed quotas, limiting the amount of feed used, are a common way to control emissions from intensive aquaculture. However, feed quotas are normally not cost-effective as the control authority cannot know the abatement costs of each emitter. Although there are no incentives for farmers to decrease emissions below the feed quota, economic incentives exist for fish farmers to use feed more efficiently if it leads to increased profits. Thus, a feed quota system may give incentives to the development of more efficient feeding systems, allowing for higher production levels with lower losses of feed and emissions per unit produced. More efficient feeding techniques have been developed for many types of fish in the last 50 years and the amount of feed used per kilo fish produced has decreased (Asche et al., 2009).

We have found four studies discussing feed quotas: Nielsen (2012), Nielsen et al. (2014), Nielsen et al. (2016) and Jacobsen et al. (2016). All but Nielsen et al. (2016) compare using feed quotas in Danish aquaculture with a trading system to regulate nitrogen emissions. Assuming that the emission level is held constant, the results show that production and profits of rainbow trout are substantially lower when using feed quotas rather than the emissions trading system. Also, production costs are higher when using feed quotas. Hence, the feed quota was not a cost-effective policy. Nielsen (2012) and Nielsen et al. (2016) also show that the Danish feed quota system prevented aquaculture producers from making use of economies of scale and investing in technology that would reduce nutrient emissions per kilo of fish produced. When farms investing in recirculation technology and water purifications systems were allowed to expand their production above their feed quotas, the size of farms increased, the production cost per kilo of fish decreased and the total emissions decreased (Nielsen et al., 2016). Among all identified studies investigating command-and-control policies, Nielsen (2012), Nielsen et al. (2014) and Jacobsen et al. (2016) are the only that compare command-and-control policies to economic-incentive policies.

Emission standards

Emission standards can be established for each emission source and then be monitored for compliance. Standards could e.g., limit the level of emissions of nutrients per year and facility for firms with licenses to produce. Traditionally, emission standards are considered most effective for point sources of pollution and are typically accompanied by penalties for non-compliance. The use of emission standards has the potential to reach environmental goals but will normally not be cost-effective since abatement costs are not known by the regulator (Tietenberg & Lewis, 2012). They also require measuring and monitoring of the emissions, which could be more difficult than merely reporting the amount of feed used.

The use of emission standards is, just like feed quotas, mainly relevant for intensive rather than extensive aquaculture. However, the economic effects of using emission standards are rarely discussed in the aquaculture literature that we have found, and we have not found any study that discusses differences in economic performance when using emission standards and alternative polices. We have found three studies that analyze emission standards: Kouka and Engle (1996) who discuss which technology out of three possible is the most cost-effective if standards are imposed on catfish farms in the US, MacMillan et al. (2003) who evaluate the costs of implementing different farm-specific practices used to comply to emission standards on trout farms, and Brennan (2002), who discuss a proposal of emission standards for prawn farms in Australia. Emission standards were also briefly touched upon in a workshop discussion summary by O'Bryen and Lee (2003).

Both Kouka and Engle (1996) and MacMillan et al. (2003) suggest that adapting to emission standards may not be very costly for aquaculture if the right technology or practice is chosen. Kouka and Engle (1996) argue that the most cost-effective method for catfish farms is to cultivate rice with water from fish ponds, since additional costs for pumping water to the rice fields would be offset by increased revenues from selling rice. MacMillan et al. (2003) show that facility-specific phosphorous pollution limits for rainbow trout farms in Idaho, US, can be reached by using facility-specific best management practices (BMPs) plans with only small cost increases. The cost for adopting to an emission standard depends, however, on the limit set by the standard, and a stricter limit will result in higher costs.

Brennan (2002) points out that emission standards do not provide incentives, trough e.g., technological improvements, to reduce emissions below the limit set in the standard, and that it is not always suitable to use the same standard for all facilities. If abatement costs are different between farms, it would be ineffective to apply the same per hectare emission standard for all farms. It may also be more difficult for farmers entering the sector to adapt to emission standards than it is for existing aquaculture farms, since it requires that emissions are estimated prior to production. Brennan (2002) further shows that it is inefficient to only regulate aquaculture when there are other polluters in the same area. Australian prawn farms had considerably higher abatement costs than sugar cane farms operating in the same area. Since there were no limitations on emissions from sugar cane farms in Australia in 2002, regulating prawn farms by emission standards while leaving the sugar cane farms unregulated would result in large efficiency losses. The participants at the workshop that O'Bryen and Lee (2003) summarize also point out that leaving non-point sources of emissions such as agriculture unregulated while using emission standards for aquaculture will not be optimal for the environment or the economy.

Technology-based standards

Technology-based standards, such as requiring aquaculture facilities to adopt certain practices or invest in certain equipment, are often included in permits. Two common standards are requirements to use the best conventional pollutant control technology (BCT) or the best available technology economically achievable (BAT). These standards are often based on specific technologies. Although producers often can choose any technology that lowers emissions to an acceptable level, in practice, they tend to choose technologies cited in the standard to avoid the risk of breaking the law. Technology-based standards are relatively easy to monitor, and the abatement costs are more certain for the producer. The disadvantage is that it is more uncertain if emission limits will be reached as compared to when emission standards are used. In practice, it is often found that producers focus too narrowly on specific technologies rather than on lowering emissions when technology-based standards are used. Technological development will stagnate, and abatement not covered by the specified technologies is not undertaken (Tietenberg & Lewis, 2012).

The literature on technology-based standards in aquaculture is focusing on the situation in the United States where the Effluent Limitation Guidelines (ELG) program bases its rulemaking on such standards. We have found six studies analyzing how technology-based standards in the US affect production costs: Engle and Valderrama (2003), Wui and Engle

(2004), Engle et al. (2005), Engle (2007), Engle and Wossink (2009), and Engle et al. (2019).

One important result is that costs of implementing technology-based standards depend on farm size, i.e., small farms tend to have higher costs per unit produced than large farms due to lack of economies of scale. This result was observed when using settling basins, i.e., basins that retain sludge and remove suspended solids from water supplies, in catfish production (Engle & Valderrama, 2003) and for trout in flow-through systems (Engle et al., 2005). Further, it is shown that farm size affects technology choice for emission treatment for Hybrid Striped Bass farming in pond production systems (Wui & Engle, 2004). Imposing technology-based standards would raise barriers to entry in the industry and increase the required scale for farms to be profitable (Engle et al., 2005). Other farm-related factors shown to affect the cost of implementing technology-based standards are location and topography of the farms (Engle & Valderrama, 2003).

The literature highlights some technologies as costly. Engle and Valderrama (2003) show that settling basins are generally not an economically feasible technology for catfish production due to high costs. Converting ponds into basins, constructing settling basins, and constructing wetlands are also found to be costlier options for Hybrid Striped Bass farming in pond production systems in Wui and Engle (2004). However, these technologies reduce emissions to a greater extent than the more profitable options (no annual draining of pond water, not flushing pond water). Thus, if the most efficient technology options are regarded as too costly technological standards risk not meeting environmental targets.

Engle and Wossink (2009) discuss how implementing new treatment technologies in aquaculture could increase costs. Generally, investing in new technology requires capital. If loans must be taken, the financial risk increases, and interest charges will increase. There is also a risk that new technology will reduce the production capacity, e.g., if fishponds are replaced by settling ponds, which would reduce revenue. For example, if emissions treatment is coupled with requirements of sampling and analysis of emission concentrations, variable costs may also increase. Engle et al. (2019) find that the costs of regulations for emissions and their monitoring comprise 62 percent of the regulatory cost burden for US salmonid farms. The same study highlights that US regulations prescribing specific practices have shown little flexibility to adjust to local conditions (Engle et al., 2019). Costs included costs of testing water samples, delivery of samples to laboratories, services of engineers, environmental consultants and attorneys. Most costs were fixed, which affected the scale of production.

Table 2. Effects of command-and-control policies according to the literature.

	Production	Profits	Costs	Tech. dev.	Target
Input standards (vs. emission trading system)	negative	negative	positive	negative	likely
Emission standards (vs. no specific policy)	unclear	unclear	positive	negative	likely
Technology-based standards (vs. no specific policy)	unclear	unclear	positive	negative	unlikely

Note: Techn. dev. referes to how technological development of the sector is affected, and Target refers to if the environmental target is likely to be reached.

Summary

We summarize the results from the literature on command-and-control policies in Table 2. Here we see that standards on inputs, emissions, and technology may affect production, profits, costs, technological development, and the environmental target in different ways. Most studies have not compared the command-and-control policy analyzed to alterative policy choices. The exception is input standards that have been compared to emission trading systems. Common for all command-and-control policies discussed in the selected studies is that they tend to have a positive effect on costs, i.e., costs increase, and have a negative effect on technological development. Moreover, the environmental target is likely to be reached with input and emission standards but not with technology-based standards. Effects on production and profits are unclear, i.e., there are no studies measuring the effects of using emission standards or technology-based standards. Input standards, on the other hand, are shown to have a negative effect on production and profits of firms. Additional information on the command-and-control policy studies can be found in Table B2 in Appendix B.

Policies based on economic incentives

Now, we turn to policies that can be characterized as economic incentives polices. The intention of these policies is to affect demand and supply on the market by including environmental considerations when decisions are made. We have found 20 studies investigating economic-incentives policies. Before reporting the results of these, we briefly summarize results from studies that discuss economic-incentive policies in more general terms. Some studies discuss the need to internalize environmental costs without going into detail about the policies needed to do so (Chopin, 2010; Chopin et al., 2001). Other studies discuss the cost-effectiveness of using extensive aquaculture for nutrient reduction but do not analyze in detail the policies resulting in the most cost-effective solutions (Filippelli et al., 2020; Flood, 2019; Kotta et al., 2020; Merrill et al., 2021).

If extensive aquaculture proves to be more cost-effective than other abatement measures, it may be justified to incorporate aquaculture into subsidy schemes or emissions trading schemes that aim to control nutrients. Merrill et al. (2021) compare extensive aquaculture with wastewater treatment, while Filippelli et al. (2020) assess it against 14 different agricultural measures. Both studies find that extensive aquaculture is cheaper in most settings, although Flood (2019) report it as one of the more expensive options. The cost effectiveness of using extensive aquaculture for nutrient extraction depends on geographic area, species and methods used. This is demonstrated by Kotta et al. (2020) who estimate cost of farming and harvesting of blue mussels in the Baltic Sea at three different sites. Costs depend on the type of farm and the salinity and nutrient levels at the sites. Several studies also highlight the potential long-term cost advantage of extensive aquaculture, since nutrient abatement can be achieved faster compared to other measures (Filippelli et al., 2022; Gren et al., 2018; Kotta et al., 2020; Merrill et al., 2021).

The 20 studies that investigate economic-incentive policies in more detail focus on three types of policies: emission charges, subsidies and emissions trading systems. We discuss these and their effects on aquaculture performance according to the literature below.

Emission charges

Using an emission charge, which is a fee levied on each unit of emission, theoretically results in a cost-effective allocation of emissions, since each producer will regulate the emissions as long as the marginal abatement cost is lower than the emission fee per unit. This implies that all farmers/emitters will have the same marginal abatement cost (equal to the fee). An emission charge encourage the adoption of more cost-effective means to control emissions and promotes technological progress (Tietenberg & Lewis, 2012). A disadvantage is that emission charges must be adjusted through trial-and-error to achieve the desired emissions level, creating uncertainty for investors. The underlying assumption for emission charges is that the environmental damage does not depend on where the emissions are done, which does not hold in our case. In the case of nutrient leakage from intensive aquaculture, using ambient charges, i.e., charges that are unique for each emitter and equal to the value of the damage on different water bodies caused by each emitter, could be more efficient. Nevertheless, monitoring and control could be difficult when using ambient charges.

The literature discussing emission charges for aquaculture is very limited and sometimes superficial. We have found three studies that discuss the issue, all dating back to the 1990s: Folke et al. (1994), Kouka and Engle (1996) and Sylvia et al. (1996). The study providing the most detailed results is Folke et al. (1994) who show that salmon farming in Sweden would not be economically sustainable if a uniform emission tax was introduced. A gradual introduction of a tax is believed to shift production from the monoculture used at the time to eco-efficient technologies such as integrated seaweeds- mussel- and salmon culture (Folke et al., 1994). Sylvia et al. (1996) argue that tax revenues could be used for subsidizing efforts to reduce emissions from aquaculture. It is difficult to draw any conclusions from Kouka and Engle (1996) since it is unclear if the assumed tax level can reach the emission goal. However, they find that a tax would reduce net returns per hectare on catfish farms.

Since ambient charges may have high transaction costs, uniform charges or even charges on inputs could serve as alternatives. Charges on inputs are seldom discussed in the literature, although Brennan (2002) briefly mentions taxes on feed or postlarvae. A feed tax would reduce the use of feed and subsequently reduce nutrient leakage, while taxes on postlarvae would reduce the stocking rate, also contributing to reduced nutrient leakage (Brennan, 2002).

Subsidies

Governments can use subsidies to internalize externalities caused by nutrients. They can be of different kinds, e.g., funds can be made available for environmental improvement, tax exemptions can be imposed or loans with reduced interest rates can be offered. The funds available for aquaculture within the European Maritime, Fisheries and Aquaculture Fund (EMFAF) for aquaculture producers in the European Union is one example. However, not all subsidies are cost-effective. Cost-effective subsidies are given to producers that reduce eutrophication the most per monetary unit spent. In general, it is more cost-effective to give payments for results than practices.

Although subsidies are widely used to promote aquaculture in the EU and elsewhere, our literature search has not found any studies discussing the economic effectiveness of using subsidies to mitigate nutrient emissions from intensive aquaculture. There is some discussion about the ineffectiveness of subsidies being available for agriculture but not for intensive aquaculture (i.e., Cammies et al., 2021; Engle, 2007). Cammies et al. (2021) discuss the conditions for aquaponics, i.e., a system with recirculating aquaculture and plants, and point out that, today, aquaponics in the European Union must compete with horticultural facilities that are entitled to subsidies. The eligibility criteria, requiring production sites to cover at least five hectares for Common Agricultural Policy subsidies, pose challenges to many aquaponic facilities, which often fall below this size threshold.

We have found seven studies discussing subsidies for extensive aquaculture aimed at compensating for nutrient extraction. Van der Schatte Olivier et al. (2020) estimate the global value of nutrients removed by cultivated shellfish (primarily clams, mussels and oysters) at a potential $1.2 billion per year. The authors argue that this sum indicates the scale of global payments that could be paid for nutrient extraction by shellfish. However, two studies (Lindahl & Kollberg, 2009; Rose et al., 2014) conclude that relying solely on subsidies from existing payment schemes may not suffice to make shellfish aquaculture profitable unless the end products can be used elsewhere, such as in human food or animal feed (Lindahl & Kollberg, 2009; Rose et al., 2014). On the other hand, Hasselström and Gröndahl (2021) point out that payments should not be given to already profitable enterprises. Based on the EU agri-environmental aid program, Lindahl and Kollberg (2009) find that if mussel farmers receive the same payment rate as farmers growing catch crops (eleven euros per kilo of nitrogen retained in 2006) roughly 25 percent of the income of an average mussel farm would be covered. Examining seaweed on the Swedish west coast, Hasselström et al. (2020) conclude that subsidies for nutrient extraction are not likely to be a tipping point for the industry as the seaweed industry has the potential to become profitable also without subsidies. By modeling the economic effects of giving subsidies, in the form of loans with low interest rates, to extensive aquaculture, Weber et al. (2018) find that oyster production in Maryland, US, and nutrient extraction would increase with subsidies, but nutrient trading schemes could potentially have even larger effects. However, the results depend on the price of credits and the level of the interest rates and are thus difficult to interpret.

Van den Burg et al. (2022) interview experts in different countries, mainly European, about suitable ways to subsidize nutrient extraction by mussels, oyster and seaweed. Several types of subsidies are discussed: e.g., subsidies for nitrogen and phosphorus uptake, subsidies to farmers for using seaweed to feed animals and subsidies to seaweed farmers. According to the experts, subsidies for nutrient extraction are perceived as relatively affordable and politically feasible. They also argue that subsidies can be used temporarily when new markets emerge.

In addition to subsidizing nutrient reductions or uptake, providing subsidies for research and development can be justified if innovations exhibit characteristics of public goods. One example may be that the development of feed for intensive aquaculture can benefit producers who did not contribute to the costs of developing the feed. Although individual aquacultural firms have incentives to innovate to lower costs, they do not take the benefits of other aquaculture firms into consideration. Asche et al. (1999) discuss how research and development in feed for Norwegian salmon aquaculture contributed to reducing emissions from feed waste and enhancing the sector's productivity during the 1980s and 1990s. While there was some public funding of mainly basic research, the bulk of the financing came from feed manufacturers. The reason for this was that the

Norwegian feed manufacturers where large enough to undertake large investments, employ expertise and take the economic risks involved in developing new types of feed (Asche et al., 1999). Under different circumstances, there may be a case for more publicly funded research about feed for aquaculture.

Emissions trading systems

The idea of emissions trading systems is that the overall level of emissions is restricted and quotas, or credits are traded between firms. The allocation of production will be optimal as low-cost emitters will expand or enter the market, and high-cost emitters will contract or leave. Efficient emissions trading systems should include all emitters in relevant water bodies, e.g., rivers, lakes, estuaries, or catchments. Excluding aquaculture from an emissions trading system would be inefficient, as low-cost abatement should be undertaken before high-cost abatement. Nutrient trading systems can be difficult to establish if it is costly to measure the emissions of nutrients.

We have found 12 studies that discuss nutrient trading systems incorporating aquaculture production. Both intensive aquaculture (rainbow trout) and extensive aquaculture (mussels, oysters and seaweed) are discussed in connection with nutrient trading systems. If extensive aquaculture is a cost-effective measure, it can be included as an abatement measure in a nutrient trading system. Producers, such as wastewater plants, can then buy emission credits from extensive aquaculture.

All studies focusing on intensive aquaculture find positive economic effects of nitrogen emissions trading. Nielsen (2012) models the effects of replacing feed quotas with nitrogen emission trading for producers of rainbow trout in tanks or raceways in Denmark. It is found that both production and profits increase with a trading system, also when trade is only allowed within catchments. Nielsen et al. (2014) also analyze a trading system and develop the model in Nielsen (2012) where 50 new technologically more advanced fish farms with recirculation and water purification systems are included. Again, the introduction of a trading system is associated with increased production and profits, along with a reduction in the number of fish farms and an increase in average farm size. Jacobsen et al. (2016) identify gains of a common trading system of nitrogen emissions for agriculture crop and intensive aquaculture production in Denmark. Common regulations for both sectors are found to increase aquaculture production by 88 percent and Danish GDP by euro 32 million, equivalent to 2.2 percent of the initial GDP contribution of the two sectors.

Next, we turn to studies investigating extensive aquaculture. Production of extensive aquaculture species could increase if polices that pay producers for extracting nutrients are used. However, such payments will only be made available if nutrient extraction from extensive aquaculture is cheaper than alternative options. First, there are three studies from northern Europe where the inclusion of mussel farming in emissions trading systems is shown to decrease total nutrient abatement costs (Filippelli et al., 2022; Gren et al., 2018; Lindahl et al., 2005). Filippelli et al. (2022) model a trading system in the largest catchment in Limfjorden and show that abatement costs decrease by 12 percent when mussel farmers can sell emission credits to agricultural farmers. Modeling the inclusion of mussel farming in a potential nutrient trading system in the Baltic Sea, Gren et al. (2018) show that abatement costs decrease by 11 percent. Lindahl et al. (2005) show that mussel farming is cheaper than sewage treatment for one of two investigated sewage plants on the Swedish west coast.

In the US, there are several nutrient trading systems in place and some of them include possibilities for aquaculture producers to sell nutrient credits. Weber et al. (2018) and Parker and Bricker (2020) discuss the inclusion of oyster aquaculture in the emissions trading system in Maryland, US. Weber et al. (2018) find that the nutrient trading system increases aquaculture production - the higher the price of nutrient credits, the larger is the effect on production. Similarly, Parker and Bricker (2020) suggest that the range of potential payments for oyster nitrogen removal is very wide and it is unclear from the study results what effects the inclusion of oyster farming in the nutrient credit trading program would have on the production of oysters in Maryland.

Several studies highlight potential challenges associated with emission trading systems including extensive aquaculture. Challenges include low acceptance among stakeholders, difficulties to measure the effects of nutrient removal, uncertainty regarding removal rates at different sites at different times, and uncertainty about the details of the trading system when aquaculture is included (Ferreira & Bricker, 2016; Filippelli et al., 2022; Gren et al., 2018; Hasselström & Gröndahl, 2021; Kim et al., 2015; Van den Burg et al., 2022; Weber et al., 2018). Conceptually, it can be challenging to allow one sector to "pollute" when another sector is compensating for the pollution (Van den Burg et al., 2022). Filippelli et al. (2022) argue that farmers tend to prefer to implement measures on their own land and are generally skeptical about entering into market-based mechanisms.

Summary

We summarize the results from the literature on economic-incentive policies in Table 3. Here, we see that emission charges, subsidies and emission trading systems may affect production, profits, costs, technological development and the environmental target in different ways. The table also shows if the studies analyzed have compared effects of economic-incentive policies

Table 3. Effects of economic incentive policies according to the literature.

	Production	Profits	Costs	Tech. Dev.	Target
Emission charges (vs. no specific policy)	negative	unclear	positive	positive	unclear
Subsidies (vs. no specific (6 studies) and emissions trading system (1 study)	positive	positive	unclear	unclear	unclear
Emissions trading systems (vs. Input standards (3 studies) and no specific (9 studies)	positive	positive	negative	positive	likely

Note: Techn. Dev. refers to how technological development of the sector is affected, and Target refers to if the environmental target is likely to be reached.

to alternative policy choices. As can be seen in the table, most studies have not done this type of comparison but exceptions exists for subsidies and emission trading systems.

The literature on emission charges shows that this policy choice tends to have a negative impact on production, but positive effects on costs, i.e., costs increase, and technological development. Effects of emission charges on profits and the possibility of reaching the environmental target are more unclear. Subsidies have unclear effects on costs, technological development, and the possibility of reaching the environmental target, while the effects on production and profits are positive. Lastly, emissions trading systems tend to have positive effects on production, profits and technological development, while effects on costs are negative. If implementing an emissions trading system, it is also likely to reach the environmental target set. Additional information on the economic-incentive policy studies can be found in Table B3 in the Appendix B.

Spatial management

Since nutrient emissions or nutrient uptake from aquaculture facilities depend on how much space is allocated to aquaculture in aquatic environments, spatial management is closely related to nutrient management (Asche et al., 2022). In total, we found 10 studies that discuss spatial management in relation to aquaculture. Many studies from our search mention that spatial planning can be used to provide information to managers (Buschmann et al., 2008; Ferreira et al., 2014; Rose et al., 2014; Silva et al., 2011) and potential aquaculture investors (Brennan, 2002; Kotta et al., 2020), as well as to help solving user conflicts between different interest such as commercial fishing, recreational use, and coastal homeowners use (Dinesen et al., 2011; Rose et al., 2014). Spatial information about water quality will be one important factor in the planning process, and appropriate planning can reduce transaction costs and lower entry costs for aquaculture producers (Brennan, 2002). Regarding user conflicts, Dinesen et al.

(2011) show in a model that the introduction of new mussel farms in Denmark decreases catches and profits of mussel fishers to some extent.

Several studies present models that can be used by managers when planning for areas that may be suitable for aquaculture production (Ferreira et al., 2007; 2009; 2014; Henderson et al., 2001; Rose et al., 2014; Silva et al., 2011; Weber et al., 2018). Some studies suggest that modeling at different scales can be used (Ferreira et al., 2014; Rose et al., 2014; Silva et al., 2011). Silva et al. (2011) is one example where first one model is used to exclude areas that are legally or socially unsuitable for extensive aquaculture; then another model is used to find areas that are suitable from an ecological perspective, and finally, a model that estimates, production, profits, and environmental effects at the farm level is used. Similarly, Rose et al. (2014) argue that online mapping tools are available in several states in the US and can be used to find areas that are suitable for extensive aquaculture expansion that do not impact significantly on other uses. These tools can then be combined with farm-scale models that find the most productive areas for extensive aquaculture (Rose et al., 2014). Ferreira et al. (2014) conclude that their modeling framework can make an important contribution in assessing the feasibility of aquaculture and can be used in spatial planning. They show that when finfish is combined with mussels in an offshore area, nutrient leakage from finfish aquaculture is reduced while inshore clam production is negatively affected.

Discussion

We find that the literature evaluating aquaculture policies aiming to minimize nutrient loads is limited. This supports the general picture given in Andersen et al. (2019), who describe economic research on aquaculture as limited and argue that economists have been largely absent from evaluating or designing policies that affect aquaculture. Despite seafood production from aquaculture now being as large as the production of seafood from wild captures (measured in live weight equivalents) (FAO, 2022), economists have been giving much more attention to wild fisheries than to aquaculture (Anderson et al., 2019). There is no reason why economist should stay away from analyzing this sector considering its increasing importance, the many externalities associated with it and the possibility to make use of policies based on economic incentives that could increase benefits to society.

Our review shows that significantly more attention has been given to emissions trading systems than any other policy, and the number of studies on this topic has increased recently. The second most investigated policy is subsidies, but it is only discussed in the context of extensive aquaculture and not in connection with intensive aquaculture. Most studies investigating command-and-control policies are more than ten years old and predominantly focus on costs of implementing the policies. We also find that some of the literature identified with our search string only superficially discusses policies. This is the case, for example, in the literature discussing the cost-effectiveness of using mussels for nutrient remediation. Policies are mentioned, but more in general terms, see e.g. Kotta et al. (2020) and Filippelli et al. (2020).

Despite the research gaps described above, we believe that we can draw some interesting conclusions from our literature review. First, our review suggests that command-and-control policies tend to be an expensive way to reach the environmental target. For example, studies show that input standards are expensive compared to other policies, with negative effects on production and profits (Nielsen, 2012; Nielsen et al., 2016). Further, technological standards raise fixed costs, making it more difficult for small firms to survive and for potential entrants to join the sector (Engle et al., 2005; Engle & Valderrama, 2003). Technological standards also risk discouraging the use of new technology (Tietenberg & Lewis, 2012), which may affect costs and abatement potential in the long run (Afewerki et al., 2023; Føre et al., 2022). Emission standards tend to increase costs as well, but the cost increases may be more limited (Kouka & Engle, 1996; MacMillan et al., 2003), possibly due to the fact that it is a more flexible measure. A basic problem with the command-and-control policies is that they do not provide economic incentives for nutrient abatement or uptake and will not give cost-effective nutrient abatement.

From a theoretical point of view, economic-incentives policies appear to be a better choice than command-and-control policies in many cases. They can provide flexibility to producers and have the potential to be cost-effective in the right circumstances. The literature shows that economic-incentives policies, such as emissions trading systems, could improve the economic performance of the sector (Jacobsen et al., 2016; Nielsen, 2012; Nielsen et al., 2014), as well as decrease total abatement costs for limiting eutrophication (Filippelli et al., 2022; Gren et al., 2018). Spatial management is an important complement to command-and control and/or economic-incentives policies that can give aquaculture producers possibilities to expand in suitable areas (Ferreira et al., 2014; Rose et al., 2014).

The cost-effectiveness of economic-incentive policies often depends on the possibility to pay for results (e.g., subsidies to extensive aquaculture for nutrient uptake) or to adjust the policy to each emitter (e.g., ambient charges). It is somewhat unclear how well this will work in practice as economic-incentive policies are seldom used, and many studies are based on modeling. A reoccurring problem with many of the policies that could provide more cost-effective nutrient abatement (e.g., emission standards, taxes, results-based subsidies, and emission trading) is that they require measuring of nutrient emissions or nutrient uptake. Accurately measuring emissions (uptake) and damages (benefits) may be both difficult and costly. For example, damages and costs for reducing nutrient leaching differ in different areas as retention rates, i.e., the share of nutrients that are retained by natural processes before reaching water bodies, are highly location specific. Often, you need information on nutrient emissions/uptake from every aquaculture facility, which may be costly and unpractical to collect even in cases when measuring methods are well-known.

Another potential problem that should be considered is that the financial risk for the producer could be high if payments are dependent on nutrient reductions/uptake. When producers get paid for the value of nutrient reduction/uptake, there is a risk that producers do not get any payment despite great effort to achieve results. For example, external factors that producers cannot influence, such as the weather or ocean currents, may affect performance. If the risk of nonpayment is high, it may be difficult to get producers to participate in economic-incentives policies. In emissions-trading systems, buyers of credits may be unwilling to buy from sellers that may not be able to deliver. Weber et al. (2018) argue that buyers may require a risk premium when buying credits from unregulated entities. Unless there are legal sanctions for aquaculture producers that fail to produce and remove shellfish or seaweed, there is an added risk to buyers that will lower credit prices.

A possible solution to these problems can be found in the agricultural literature where modeling nutrient emissions has been put forward as an alternative to measuring. Payment is then based on modeled results associated with certain actions in certain locations, which both makes individual measuring unnecessary and removes the payment uncertainty. In agriculture, there is enough knowledge and data on impacts of nutrient reduction measures today to be able to model outcomes with precision (Bartkowski et al., 2021). It is possible to take spatial variability into account, for example through using GIS software (Sidemo-Holm et al., 2018; Talberth et al., 2015). Modeling is already used for proxying some forms of air pollution and nitrogen reduction effects for wetlands in Denmark (Brady et al., 2022). When modeling is an option to measuring nutrient emissions at every producer, emission-based policies become more attractive.

Modeling could also be a way to obtain information on nutrient emissions from intensive aquaculture. It would probably be easier to estimate emissions from aquaculture production than from agricultural production, considering that aquaculture is most often considered as a point-source for emissions while agriculture is a non-point source. Several models that estimate water quality and emissions from aquaculture already exist. For example, there is the MOM-system (Modeling – Ongrowing Fish – Monitoring) developed in Norway for intensive aquaculture in open net-pens (Andersson et al., 2016).

For extensive aquaculture, the challenge is not how to measure nutrient emissions but rather nutrient uptake. According to our review, this measurement problem appears to be less severe than that for intensive aquaculture. Several studies indicate that it is relatively easy to measure nutrient uptake (Rose et al., 2014; Van den Burg et al., 2022; Weber et al., 2018). Rose et al e.g., (2014) suggest that nitrogen uptake from mussels and oysters can be easily estimated by measuring the length of the shells. A model that can be used to assess and value nutrient uptake from potential extensive aquaculture farms has been developed by Ferreira et al. (2007) and is used in Ferreira et al. (2009) to estimate potential production, economic performance, and water quality impacts of aquaculture production in five areas in the European Union. Since costs of software and data have been sharply reduced recently, applying such modeling frameworks should not be too expensive (Ferreira et al., 2014). Similarly, Weber et al. (2018) argue that, nutrient credits for oyster tissue can be generated by modeling relatively easily.

Another important conclusion from our review is that cost-efficient environmental policies require that aquaculture is not treated separately from other sources of emissions or providers of emissions uptake (Brennan, 2002). Using uniform emission standards may not be cost effective when there are differences in abatement costs between aquaculture farms and other emission sources. Performance-based payments for reductions in emissions, paid to a producer, aquaculturist or other, can provide the least-cost measures. Emissions trading systems should include all emission sources in an aquatic environment to allow trades between low-cost emitters and high-cost emitters. If quotas/subsidies are auctioned off, it should not matter who decreases emissions (non-point sources or point sources, agriculture or aquaculture).

As mentioned above, the literature analyzed has certain limitations. This means that there are several interesting possibilities for future research. A drawback with many of the studies analyzed is that they do not compare different policies when evaluating effects. Exception are for example, Nielsen (2012) and Nielsen et al. (2014), who compare input standards to emissions trading systems. It would be interesting to see more of these types of studies in the future looking at other policies and other countries than Denmark. Furthermore, we have not found any study that evaluates implemented nutrient policies with data. It is an important task for future research to perform empirical analysis of current and future policies for aquaculture. To be able to do so, data collection before and after policy implementation would be helpful. Finally, we believe that bio-economic modeling could be expanded and improved to estimate the effects on aquaculture of implementing different policies. One interesting approach would be to compare performance-based subsidies with results-based subsidies for extensive aquaculture.

The focus of our literature review is on nutrient control and aquaculture. Although nutrient emissions or uptake are important externalities related to aquaculture there are many other externalities (positive and negative) that require policy actions. Spreading of disease, noise pollution from aquaculture facilities, local pollution underneath open cages, fish escaping from cages and chemical pollution are some examples. In this context it may be useful with policies that aim to correct for several different externalities. e.g., a tax on nutrient damages may also affect emissions of greenhouse gases if production decreases when the tax is implemented. But there is also a risk that policies that aim at correcting one externality unintentionally affect other externalities negatively. Thus, interactions between environmental externalities should be carefully taken into consideration when designing policy.

Conclusions

We have reviewed the literature evaluating aquaculture policies that aim to minimize nutrient loads to understand how these policies can affect the growth and production of aquaculture. The review is intended to give an overview of different policies and describe possibilities and challenges in implementing more cost-effective policies. Policies used today in many parts of the developed world may have contributed to the slow growth of the sector. The review shows that common command-and-control policies seldom are the most cost-effective way to reach the environmental targets and that they may have a negative effect on the growth of the aquaculture sector. Economic-incentive policies such as emissions trading systems are more cost-effective than command-and-control policies. However, these are seldom used in practice due to implementation problems. It is important to further investigate how to implement more cost-effective policies for nutrient control in aquaculture. In particular, it is important to investigate if modeling can be used to estimate nutrient leakage and damage on aquatic environments, as this is expected to ease implementation of policies such as ambient charges, subsidies and emissions trading systems.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This work was supported by FORMAS, the Swedish Research Council of sustainable development, under Grant 2020-03136.

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