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Environmental assessment of trout farming in France by life cycle assessment: using bootstrapped principal component analysis to better define system classification

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ABSTRACT

Trout farming is the main fish production system in France. This article describes a system to classify trout farms based on environmental impacts calculated by life cycle assessment and technical and economic indicators. Since the number of surveyed farms was too small for a robust assessment, we combined principal component analysis (PCA) with a non-parametric bootstrap technique. French trout farms were surveyed to collect technical and economic indicators. The representativeness of the survey was verified by comparing it to a national inventory. Life cycle assessment was used to estimate environmental impacts of farms and the contribution of each production stage to impacts. PCA was used to evaluate both technical-economic and environmental indicators of the trout farms, which were separated into three groups based on the size of fish produced (pan-size, large and mixed-size, and very large). Non-parametric bootstrap was used to compare the groups and to test the significance of PCA results. Results validated the fish-farm classification system based on the size of fish produced and indicated that farm operations and fish feeding contributed the most to environmental impacts. The PCA method distinguished three groups via their technical indicators, with non-significant differences among the groups in environmental impacts. However, environmental indicators showed strong links with technical and economic indicators. In conclusion, bootstrapped PCA offers the ability to assess groups of trout production system when the sample size is too small and provides more conservative results by considering uncertainty. Future studies should focus on providing reliable data to reduce uncertainty.

1. Introduction

Trout farming is the main aquaculture production system in France. It is primarily based on farming rainbow trout (*Oncorhynchus mykiss*) in flow-through systems, in which inlet water is diverted from a river, passed once through the rearing tanks and then returned to the river. All nutrients are provided by exogenous formulated feed containing fish meal, fish oil and plant-based ingredients. Production is carried out in small (10 t/year) to large farms (900 t/year). The farms have different production objectives responding to different markets. For example, some farms produce pan-sized trout or large trout for filets; other farms produce fish for restocking rivers or ponds for angling. These different production strategies imply different practices (e.g., feed type, feeding management, oxygen supply, rearing densities, and water treatment). The trout farms in France are spread widely throughout the country, but their number is small (around 600) comparing to livestock systems. Since trout farming uses water of good quality, farm practices and the quality of water at their outlets are watched closely.

Despite the rapid growth of fish farming throughout the world (mean increase of fish production volume of 12%/year in the last ten years) (FAO, 2012), trout production decreased in France from 47 000 t in 1997 to 37 000 t in 2007 (Agreste, 2011). This production suffers from economic competition from other aquatic products and the application of water-quality regulations (e.g., European Union Water Framework Directive), which can cause farmers to abandon fish production. The decrease in the number of farms and the corresponding decline in production led the French aquaculture producer organization (CIPA) to assess the sustainability of French

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trout farming. To do so, different approaches were applied: development of indicators of economic, social and environmental sustainability; environmental assessment of farms based on biological and chemical-physical measurements (Aubin et al., 2011); and life cycle assessment (LCA). This paper focuses on the definition of a trout-farm classification system using LCA indicators and certain technical and economic indicators.

LCA is a holistic method designed to estimate potential impacts associated with a product or service based on the resources consumed and pollutants emitted into the environment at all stages of its life cycle, from raw material extraction to its end-of-life (Guinée et al., 2002). It is an internationally accepted method described in ISO standards (ISO 14040 (2006), ISO 14044 (2006)). LCA has been adapted to fish farming (Papatryphon et al., 2004b) and applied in several studies to estimate environmental impacts of aquaculture in different contexts (Aubin, 2013; Cao et al., 2013; Henriksson et al., 2012). Salmonid production has been studied in particular, since it is common in Europe and North America. Moreover, it is a simple and well-controlled rearing system which fits with the industrial ecology rationale of LCA. Some studies about salmon production have investigated different rearing and feeding practices (Ayer and Tyedmers, 2009; Pelletier and Tyedmers, 2007; Pelletier et al., 2009). Other studies have investigated trout production (Aubin et al., 2009; Gronroos et al., 2006; Papatryphon et al., 2004b; Samuel-Fitwi et al., 2013). All of these studies helped to understand the contribution of system components to environmental impacts and showed the overwhelming influence of feed composition and management. Nevertheless, these studies were based on small numbers of farms.

To better understand the influence of rearing practices in trout farming, Papatryphon et al. (2004b) classified production systems into three classes according to the size of fish produced (pan-size, large trout, and very large trout). They observed high variability in the impact categories (relative variation ranged from 41% in biotic resource use to 87% in energy demand). Moreover, variability in impacts was associated with different production techniques; for example, variation in eutrophication was related mainly to differing feed efficiency among farms. However, the small number of farms investigated ($n = 8$) did not allow broader conclusions. As mentioned by Henriksson et al. (2012), the number of farms investigated often raises the question about the representativeness of aquaculture systems in LCA. As a consequence, environmental assessment of fish farms is relatively weak, making extrapolation of their potential environmental impacts delicate. To better characterize heterogeneous populations, especially in agricultural and aquacultural production, building classification systems is a common practice (Lazard et al., 2010). These classification systems are often based on surveys and statistical analysis, such as Principal Component Analysis (PCA).

PCA reduces the dimensionality of an observed dataset with many correlated variables by transforming them into a new set of variables, named principal components (PCs), which retain as much as possible the variation of the observed dataset (Jolliffe, 2005). It is used to extract the most important information from the dataset to get an overview of it in a small number of dimensions (e.g., two or three) described by their eigenvalues (measures of variation in samples explained by the PCs), loadings (coordinates of original variables in the PCs) and scores (coordinates of individuals in the PCs). PCA is commonly used to represent the variability in observed samples. However, a small sample size ($n < 30$) may not allow conclusions to be extrapolated to the entire population when the standard error of the mean is large (Berthouex and Brown, 2002). Hence, the consideration of uncertainty in the results due to small sample size is an important subject in statistical analysis. Indeed, this type of uncertainty can be expressed with a confidence interval (CI) or standard error (Luo et al., 2013; Melia et al., 2012).

Bootstrap sampling is a numerical method used to quantify uncertainty due to random sampling errors without assumptions about a variable's distribution (Efron, 1979). A bootstrapped sample is created by randomly sampling from an observed sample repeatedly. Bootstrap sampling can be applied, for example, to estimate the accuracy and stability of PCA results by providing a CI for eigenvalues and loadings (Babamoradi et al., 2013; Daudin et al., 1988; Timmerman et al., 2007). However, there are two shortcomings when using bootstrap-based PCA. First, the coordinates of component loadings and scores are arbitrary (Jackson, 1995; Jolliffe, 2005; Mehlman et al., 1995), which may overestimate the CI of loadings (reflection). Second, PCs may have a similar eigenvalues in a bootstrapped sample, which may change the order of PCs compared to the observed sample (re-ordering) (Timmerman et al., 2007). To address these problems, reflection and re-ordering corrections are performed on each bootstrapped sample (more details in Peres-Neto et al. (2003) and Babamoradi et al. (2013)).

In this study, we decided to bypass the problem of the small sample size of trout farms by using non-parametric bootstrap. This method has the advantage of being more robust than parametric bootstrap when the distribution of observed data fails a normality test. Therefore, to better understand the characteristics of French trout farms, this study used PCA to validate a classification system of French trout farms based on their types of commercial products. This system classifies trout farms based on their estimated environmental impacts and production techniques. The accuracy of PCA results (CI) is evaluated with the bootstrap method.

2. Materials and methods

2.1. Sample survey and national inventory

A sample of 24 trout farms throughout France was selected based on the size of fish produced, hydrogeological characteristics of the environment, and farmer agreements. The farms were surveyed from 2007 to 2011, recording data such as farm production (types and quantities of products), farm inputs (types, quantities and origins, especially of energy sources, feed, juveniles, and water), infrastructure and equipment, and water quality (Aubin et al., 2011). Annual trout production of the farms varied from 20 to 667 t. Farms were divided into three groups according to the size of fish produced, as performed by Papatryphon et al. (2004b): G1, pan-size trout (250–400 g); G2, large and mixed-size trout (e.g., different sizes from 200 to 3000 g); and G3, very large trout (>2000 g). The number of farms per group was 5, 9 and 10, respectively. To check the representativeness of the trout farm sample in the survey, we compared it to a classification of trout farms (defined by the amount of feed consumed) available in a 2007 inventory of French trout farms (Agreste, 2009).

2.2. Life cycle assessment

LCA was conducted according to the four steps and general requirements of the methodology proposed by ILCD (European Commission, 2010). The methodology was adapted to characteristics of fish farming. The goal and scope of this study is the environmental assessment of trout farming in France at the farm scale in order to adapt improvement strategies as a function of farm type. The boundary of the production system mainly contains farm operations, feed production (including ingredient production and transportation), production of juveniles, infrastructure construction, equipment manufacturing, and production of medicines and other inputs, such as liquid oxygen and energy carriers (Fig. 1). Despite the existence of thousands of processes in LCA of trout production, these processes are the most important contributors to overall impacts, according to the literature (Aubin, 2013).