Journal of Cleaner Production xxx (xxxx) xxx

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Multi-scale integrated evaluation of the sustainability of large-scale use of alternative feeds in salmon aquaculture

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ARTICLE INFO

Article history:
Received 7 April 2019
Received in revised form
6 September 2019
Accepted 6 November 2019
Available online xxx

Handling editor; Cecilia Maria Villas Bôas de Almeida

Keywords:
Salmon aquaculture
Alternative aquafeeds
Insects
MuSIASEM
Quantitative story-telling
Norway

ABSTRACT

The steady increase in production volume of salmon aquaculture has sharpened concerns about its sustainability. In particular the production of salmon feed is a reason for concern given its reliance on scarce natural resources, such as wild fish captures. Multi-scale integrated analysis is put forward as a tool to anticipate the environmental and socio-economic impacts of large-scale implementation of alternative salmon feeds, considering both plant and insect sources as potential replacements of fish meal and fish oil. The proposed accounting framework, based on relational analysis across hierarchical levels, describes the patterns of required inputs using biophysical and economic variables. It also considers the inputs used by external systems for the production of imported feed, thus providing a coherent assessment of the sustainability of the production system in terms of feasibility, viability, and desirability. The analytical tool-kit is illustrated in conceptual terms and then applied to the Norwegian salmon aquaculture, both in diagnostic (describing the actual situation) and anticipatory mode (examining feed scenarios). Results are used in an exercise of quantitative story-telling to check the quality of the narratives currently shaping policy discussions on aquaculture. Quantitative story-telling is a heuristic approach aimed at checking the robustness of knowledge claims in face of uncertainty. It is concluded that rearing insects in the salmon feed production chain enlarges the option space of feed sources by opening up the possibility of using locally-produced seaweed and organic waste, but also raises the level of uncertainty with regard to the possible insurgence of negative side effects.

1. Introduction

The combined increase in per capita fish consumption and human population over the last four decades has led to an increase in overall fish consumption by 2.8 times (FAO, 2018b; The World Bank, 2018). This increase was possible due to an impressive growth in the volume of aquacultural production, from 4.7 million tons in 1980 to 80 million in 2016 (FAO, 2018a). This growth is expected to continue in the future but at a lower rate. In Norway in particular, favorable environmental, technological and economic conditions have led to an impressive increase in salmon production by 1200 times over the last five decades (Hersoug, 2015), thereby making this country the first salmon producer and exporter in the world (FAO, 2018b). This upward trend is expected to continue, but at a reduced annual rate of about 3–5% (Olafsen et al., 2012).

Sooner or later exponential growth on a finite planet is expected to run into scaling problems (Bartlett, 2004; Steffen et al., 2015). Indeed, the environmental pressure generated by salmon aquaculture and the increase in price of fishmeal and fish oil are increasingly challenging the sustainability of this economic sector (Rana et al., 2009). This is a highly relevant issue for Norway because of the perceived relevance of salmon aquaculture in the country and the ambitions for further growth (DKNVS/NTVA, 2012).

One of the main concerns of the producers in the aquaculture industry in Norway (and other countries alike) is how to guarantee a robust feed supply. Diversifying feed supply alternatives is considered a desirable strategy to deal with the increasing problem of wild fish stock reductions and market price variations (Rana et al., 2009). Various solutions have been proposed, such as replacing the components of marine origin (meal and oil) with

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https://doi.org/10.1016/j.jclepro.2019.119210

Please cite this article as: Cadillo-Benalcazar, J.J et al., Multi-scale integrated evaluation of the sustainability of large-scale use of alternative feeds in salmon aquaculture, Journal of Cleaner Production, https://doi.org/10.1016/j.jclepro.2019.119210

products of plant origin and/or products of insect origin (Rumpold and Schlüter, 2013; Shepherd et al., 2017). However, as Sprague et al. (2016) have pointed out, by replacing the marine components of the salmon feed with terrestrial products, the content of omega-3 fatty acids—notably eicosapentaenoic acid [EPA; 20:5n-3] and docosahexaenoic acid [DHA; 22:6n-3]—in salmon may be reduced. This could have an important negative impact on the industry as salmon is recognized as a main source of omega-3 in the human diet in some countries (Dickhoff, 2010). Neither humans nor salmon can synthesize omega-3 fatty acids and therefore must obtain these through their diet. In the case of farmed salmon, omega-3 fatty acids are mainly derived from the fish oil used in feed.

Small-scale experiments with insect (Belghit et al., 2018; Gasco et al., 2018; Lock et al., 2016; Rumpold and Schlüter, 2013; St-Hilaire et al., 2007) and plant feed alternatives (Bell et al., 2004; Boissy et al., 2011; Gasco et al., 2018; Shepherd et al., 2017) in aquaculture have shown promising results. In addition, the EU recently approved the use of processed animal protein derived from farmed insects in aquaculture, provided conditions for rearing insects are met (Commission Regulation (EU) 2017/893 of May 24, 2017). One of these conditions concerns limitations on the substrate on which insects are fed.

However, alternative feed solutions may have unexpected side effects when implemented and scaled up to industrial production. In general, it is difficult to anticipate *what* can go wrong until it is too late and the technology has become entrenched. This is commonly known as the Collingridge dilemma (Collingridge, 1980). Thus, what is dearly needed is an overall analysis of the sustainability of the Norwegian salmon industry that is capable of anticipating the potential problems arising from the continuous increase in production volume and innovations in this sector.

This study is part of the AQUAFLY project, which explores the option of using insect feeds in salmon aquaculture, and contributes to a package of methods from ethics and environmental science, informed by theory from Science and Technology Studies, for integration into a STEM research project in a way that contributes to Responsible Research and Innovation (RRI). It aims to illustrate a novel approach to explore potential advantages and problems of changes in the salmon production process that may occur *outside* of the production system itself. The novel approach consists in the use of a semantically open accounting framework (MuSIASEM) to analyze narratives and support an informed stakeholder discussion through quantitative story-telling (QST).

The specific objective of the article is to illustrate the novel approach for the case of Norwegian salmon aquaculture performance through:

i. an evaluation of the current pressure of the Norwegian production system on the local environment and other (external) social-ecological systems (externalized pressure due to imported feeds and labour);
ii. an assessment of the potential changes in the environmental performance in response to changes in the salmon feed supply system.

The illustration of the methodology is based on the feed production alternatives studied in AQUAFLY. Of special interest to the project was the option of incorporating farmed insect ingredients in the salmon feed mix, using under-used marine resources not suitable for direct human consumption (kelp) as substrate for rearing the insects. Kelp is rich in omega-3 fatty acids and a readily available local resource in Norway.

The paper is structured as follows: section 2 presents the methodological approach and describes the alternative feed production systems considered, section 3 presents the results, and section 4 the discussion and conclusions.

2. Methodology

2.1. Quantitative story-telling

Quantitative Story-Telling (QST) is a novel approach to the use of quantitative information to inform policy. QST has the goal of checking the quality of the pre-analytical choice of narratives used to justify a given policy. According to Felt (2007) there are three types of narratives relevant in science for governance: (i) justification narratives – WHY we want to apply a policy; (ii) normative narratives – WHAT should be achieved with the policy; and (iii) explanation narratives – HOW to achieve the expected results. Most commonly, quantitative analysis is used in relation to explanation narratives to supply information about how to achieve a result. However, in this paper, the quantitative analysis is aimed at checking the validity of the justification narrative (the “why”): Why should Norway invest additional money and resources in increasing the actual level of salmon production?

QST has first been used in the EU-funded Horizon2020 project MAGIC (MAGIC, 2019) as an alternative to providing “scientific evidence” to inform sustainability policies. Applications have been provided in relation to agricultural development (Giampietro, 2018), desalination (Serrano-Tovar et al., 2019) and alternative energy sources (Renner and Giampietro, 2020). Rather than crunching numbers to identify an ostensibly optimal course of action or predict future states of the system, QST uses quantification to check the robustness of the story-telling associated with a given policy (Matthews et al., 2017; Saltelli and Giampietro, 2017, 2016).

In this particular study, QST is applied, in combination with multi-scale integrated analysis of societal and ecosystem metabolism (see next section), to prime a reflection on the future of salmon production in Norway. A core set of quantitative results is generated by considering relevant characteristics of the system simultaneously across different scales and dimensions of analysis, thus recognizing the existence of the legitimate and non-equivalent perceptions of performance of different relevant actors. QST starts from a first appraisal of the relevance of information referring to a general analysis of various aspects of the system. Then the various insights are used to prime a reflection on the existence of synergies and trade-offs among policy concerns.

2.2. Multi-scale integrated analysis of societal and ecosystem metabolism

Multi-scale integrated analysis of societal and ecosystem metabolism (MuSIASEM) is a relatively novel approach to explore the complex nature of the interactions between socio-economic systems and ecological systems with regard to sustainability (Giampietro et al., 2014, 2013, 2012). MuSIASEM adopts the concept of metabolism of social-ecological systems: the socioeconomic and ecological system are considered as two components of a larger complex (the social-ecological system) that interact across different hierarchical levels of organization (Giampietro et al., 2014). This interaction involves a network of exchanges of matter and energy that provides the required conditions for the social-ecological system to express and reproduce its functions. The expression of these exchanges over a given set of structural and functional elements is what is called ‘the metabolic pattern’ (Giampietro et al., 2012).

In MuSIASEM, the representation of the metabolic pattern of the social-ecological system relies on relational analysis (Louie, 2013, 2009; Rosen, 1985, 1958) and the flow-fund model of Georgescu-

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Roegen (1971). The first step of the approach involves the identification of the hierarchical structure of the social-ecological system in question (e.g., Norwegian salmon aquaculture) to describe the functional *relations* among its constituent metabolic elements. Following, the specific metabolic pattern of each one of the relevant elements is characterized using the concept of *processor*. The processors establish a relation among quantitative information referring to different hierarchical levels and different dimensions of analysis by consistently describing the profile of inputs and outputs associated with the expression of any given function or process in a common format (data array). Indeed, any metabolic element of the social-ecological system is considered an open system in itself with an expected 'behavior' linked to the overall metabolic pattern. This behavior is described in terms of: (i) consumption of a profile of inputs; (ii) expression of a profile of useful output; (iii) generation of unwanted products (emissions/waste) (González-López and Giampietro, 2017).

MuSIASEM is a semantically-open approach. In its pre-analytical framing, a series of decisions must be made consulting the stakeholders. First, it must be decided which boundaries and which metabolic elements are relevant for the definition of the hierarchical structure of functional relations. Second, formal categories (e.g., energy, water, labour requirements) must be selected for a meaningful characterization—using the concept of processors— of the metabolic system under study. Finally, in the last step, it must be decided how the quantitative information generated by the processors is organized into a coherent assessment. The latter step depends on the choice of logic and the purpose of the analysis. Thus, the rich information space produced by MuSIASEM may result in non-equivalent assessments (biophysical feasibility, economic viability, technical viability) tailored to the specific (research) questions or interests of specific stakeholders or storytellers. These pre-analytical choices will therefore determine the relevance of the resulting information for different story-tellers.

2.3. Tailoring MuSIASEM to aquaculture production systems

MuSIASEM has been applied to the societal energy metabolism and agricultural production, but to the best of our knowledge never to the sustainability of aquaculture. An integrated analysis of aquaculture must provide sufficient diversity of data so as to allow a characterizing of the performance of the investigated system according to the legitimate but diverging interests of the different social actors involved. For example, the information relevant for a Norwegian coastal community will be different from that needed by a general manager in the salmon producing industry or by the national environmental protection agency. In the same way, the data required by decision makers in salmon feed exporting countries will be different from that required by the feed importing countries. Hence the challenge here is how to handle the diversity of data referring to different levels of analysis (a specific aquaculture system, a specific community, the whole country, the global level) and different dimensions of analysis (monetary versus biophysical flows).

According to the steps mentioned above, Fig. 1 identifies the metabolic elements and the boundaries that will allow to establish the functional and structural relationships of the salmon aquaculture system in Norway. Note that the inputs used by this system are obtained either from the *technosphere* (controlled by humans) and/or from the *biosphere* (determined by and affecting the activity of ecosystems). Furthermore, required inputs are obtained either from within the chosen boundary of the system or from outside the system (imports). Inputs from outside imply *externalization* (or *outsourcing*) in terms of impacts on other (external) ecosystems (processes taking place in the biosphere outside the system borders) and other socio-economic systems (processes taking place in the technosphere outside the system borders). The same is true for the outputs produced. This distinction allows a study of the level of openness of the system and opens the discussion to the 'desirability' of exporting environmental problems.

Indeed, one important question in regard to the sustainability of Norwegian salmon aquaculture is how to relate information on salmon output (system size) and feed quality to required inputs from both local and external sources. The various pieces of information needed to define this relation are shown in Fig. 2 and include:

- The total quantity of salmon (to be) produced ($\sum$).

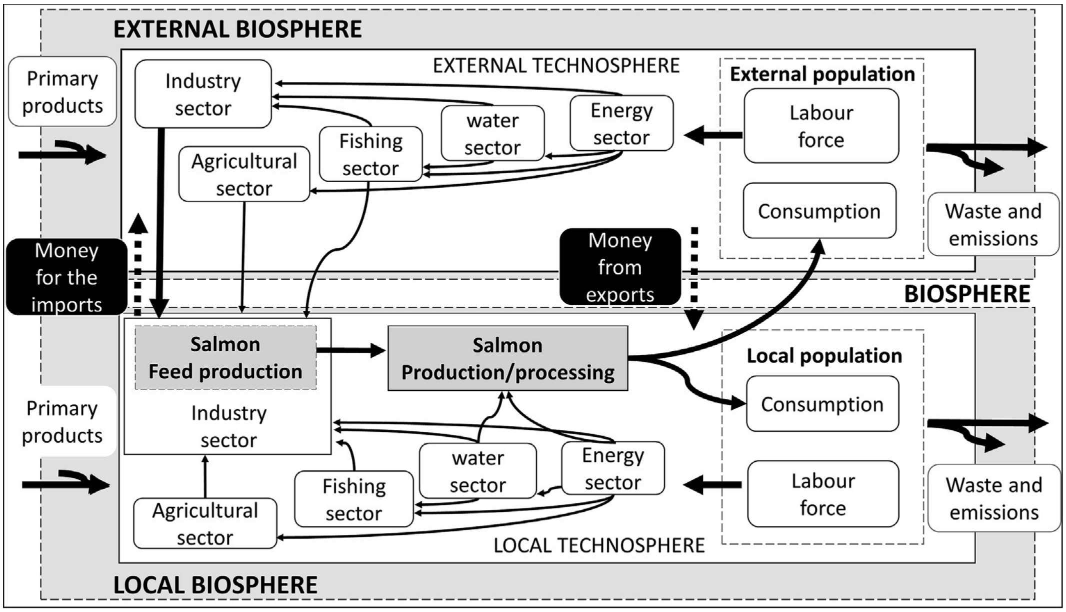

Fig. 1. Schematic overview of the relations among functional metabolic elements in salmon aquaculture systems.

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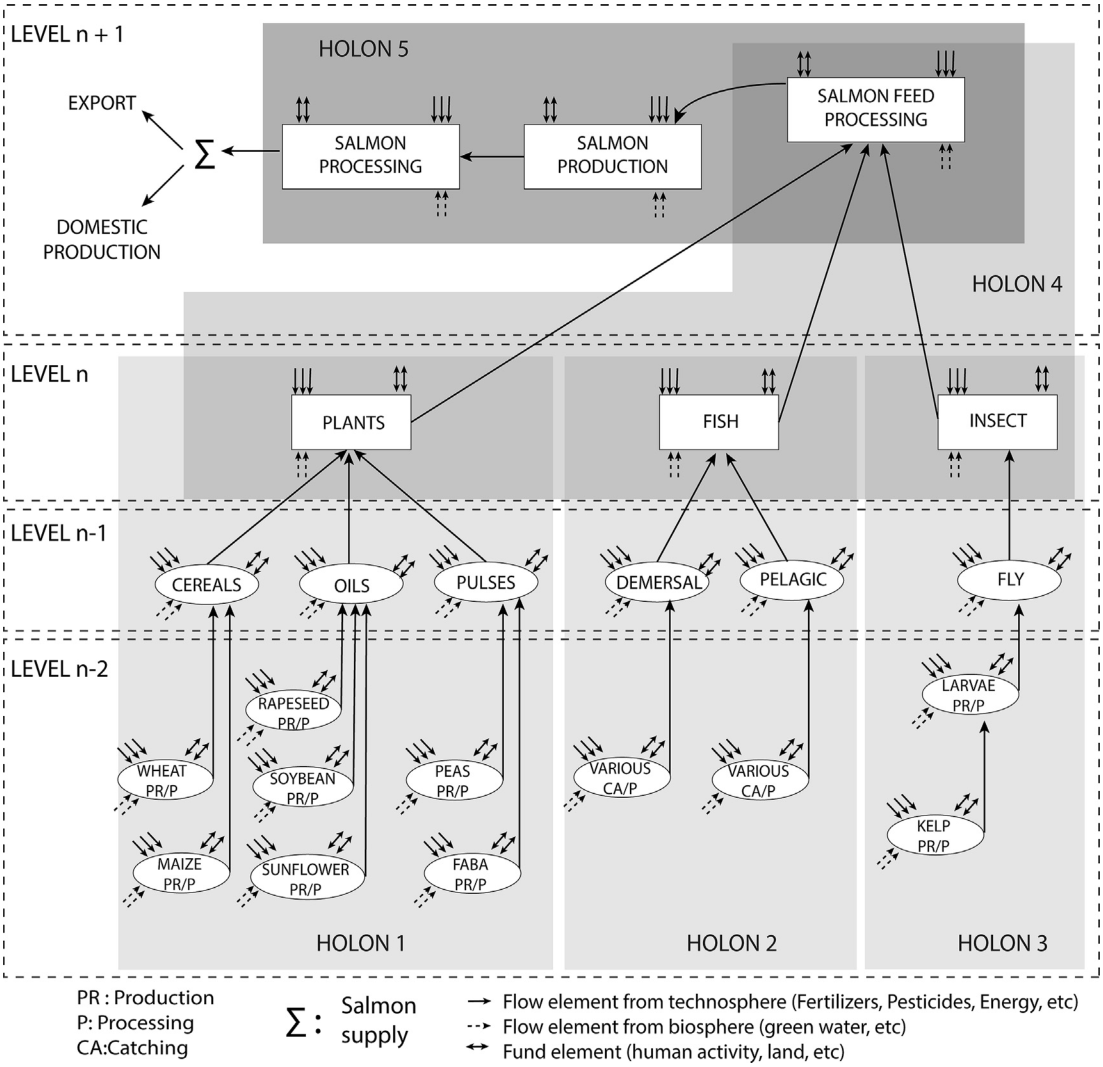

Fig. 2. Identification of five holons in the set of relations of the salmon aquaculture system: salmon production; salmon feed processing; plant ingredient production ('plant'), marine ingredient production ('fish'); insect ingredient production ('insect').

- The processors of salmon production, salmon processing and feed processing (referring to a higher level of analysis: level n+1). This information is generally readily available as it is routinely used in production management;
- The mix of products (plant-based feed, fish-based feed and insect-based feed) used to feed the salmon (and expected to meet salmon dietary requirements). This particular level of the hierarchy of relations is designed the level n of our analysis.
- The unitary processors for obtaining the various ingredients that make up the mix of products used for the production of the salmon feed (refers to the lowest hierarchy: level n-1 and level n-2)

Regarding the formalization of the characterization, MuSIASEM adopts from the theories of complexity and hierarchy (Ahl and Allen, 1996; Allen and Starr, 1982; Pattee, 1973; Salthe, 1985) the notion of *holon* (Koestler, 1978, 1968). The usefulness of this notion is to emphasize the epistemological problems inherent in the elusive relation between structural and functional elements in the representation of complex systems organized across different hierarchical levels (for more details see Giampietro, 2018; Giampietro et al., 2006). In our analysis five holons are distinguished: holons 1–3 represent the mapping of the characteristics of specific lower-level processes of production of feed inputs (Plants, Fish and Insect), holon 4 represents the functional and structural elements entailment to the production of the feed and holon 5 the elements related to the direct production of salmon.

In turn, the description of holons allows identifying the processors, which are the units that describe the metabolic elements of the system in terms of fund and flow. Where, funds are those that maintain their characteristics throughout the duration of the analytical representation. While, flows describe what the system does and change their identity over the duration of the analytical representation, namely, they enter but do not exit or vice versa (Georgescu-Roegen, 1971). In general terms, Fig. 3 shows the interaction of these elements with the processor. According to the characteristics of the salmon aquaculture system, any processor is considered within the technosphere. However, the interacting elements may be implied to the technosphere or the biosphere. In this analysis, fund elements are: land (ha), sea area (ha), labour (hours). While, flow elements are: fertilizers (t), blue water (m3), green water (m3), pesticides as active ingredient (t), energy (J) and money (euros).

Note that the relation between the profile of inputs/outputs and

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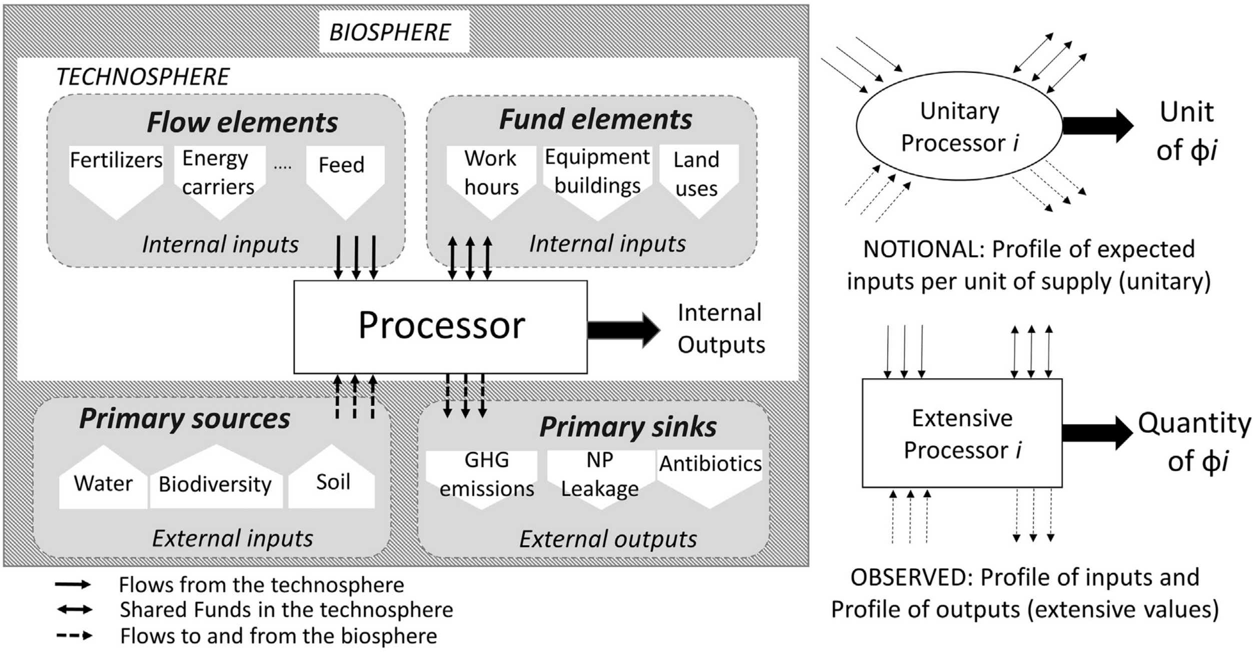

Fig. 3. The inputs and outputs of flows and funds described by processors.

the resulting output can be described either with intensive variables (unitary processor: expressed per unit of output) or (ii) extensive variables (extensive processor: expressed in absolute amounts) (Di Felice et al., 2019). This dual system of accounting is illustrated on the right side of Fig. 3.

Quantitative representations based on processors can be aggregated within and across hierarchical levels of analysis (Fig. 4). Within the same hierarchical level of analysis, the aggregation is based on a sequential pathway (material entailment). In other words, when a series of processors is operating in the same sequential pathway of a given production process, its overall characteristics can be represented as just one single processor (Fig. 4, upper graph) by summing the various homologous inputs in the corresponding data arrays (e.g., summing kg of nitrogen fertilizer to kg of nitrogen fertilizer, hours of labour to hours of labour, etc.). Across two different levels of analysis, the aggregation follows

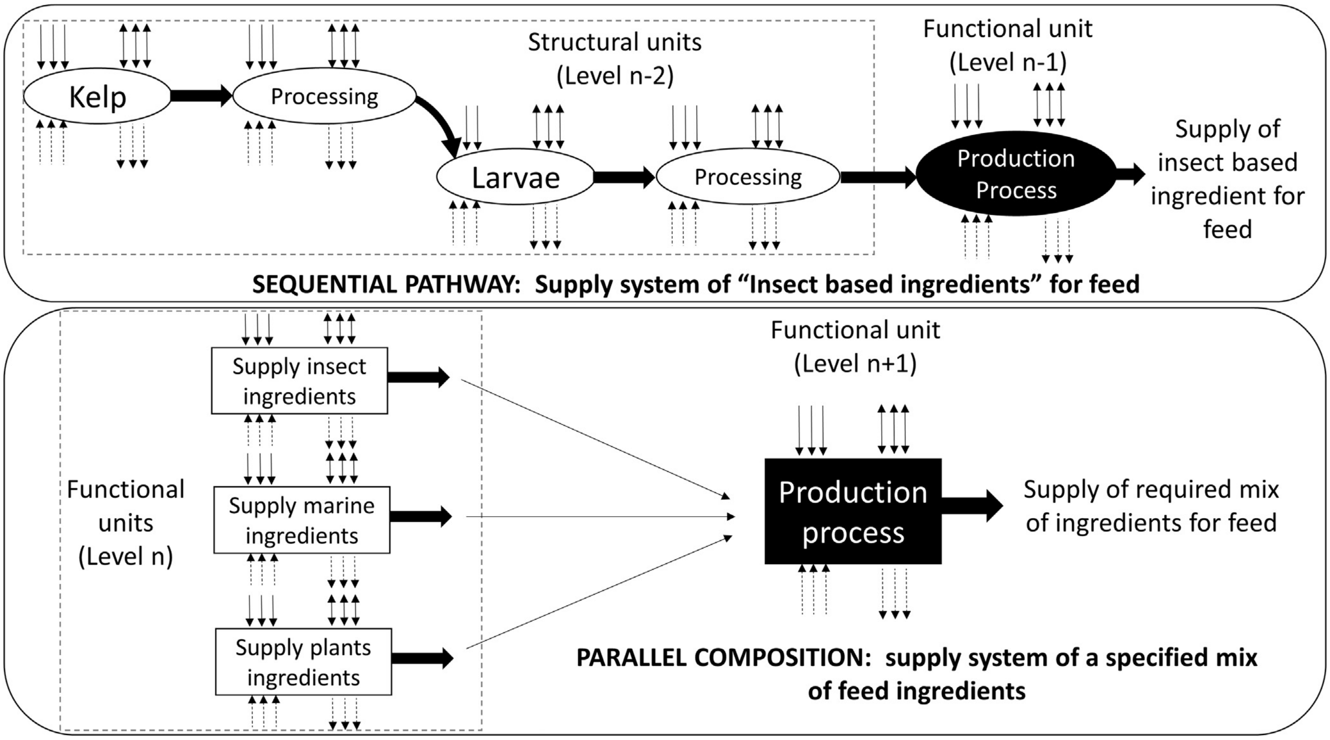

Fig. 4. Methods of aggregation of information carried by processors: Sequential pathway or material entailment (upper graph) and parallel composition (lower graph).

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the logic of ‘parallel composition’ (Fig. 4, lower graph). In this case, relevant data for establishing a bridge across levels are: (i) the profile of inputs and outputs of the individual sequential pathways making up the functional units (defined at lower levels) and (ii) the *relative contribution* of these functional units in the overall salmon feed mix. In this way, we can move one level up in the hierarchy.

For example, in Fig. 2, the mapping of the structural elements (the specific individual production processes) onto the corresponding functional element (the supply system) is done with the parallel composition for holons 1 and 2, and the sequential pathway for holon 3. The processor for the salmon ‘feed supply system’ (holon 4) is calculated from the processors of the functional elements of holons 1–3 following the functional pathway. Finally, an overall processor, assessing the overall profile of input requirements and outputs for the salmon production system as a whole (holon 5, made up by ‘feed production’, ‘salmon production’ and ‘salmon processing’) is obtained following the sequential pathway. In this way, the overall requirement of internal and external inputs of the salmon production system can be tracked. Thus, given the network of relations established, it is possible to scale-up (establishing a causal relation) the effects of changes in the feed supply systems in relation to the desired amount of salmon production. Implementation of this scaling requires knowledge of the technical characteristics of the specific systems of production (the structural elements) adopted in the various supply systems.

Quantitative representations based on relations over processors can be tailored to describe a specific existent situation (diagnostic mode) or scenarios (anticipation mode). Scenarios may consist of changes in the existing feed supply systems (e.g., change in relative contribution of marine ingredients; change in technological coefficients within a feed supply system) or the introduction of new feed supply systems (holon 3 in Fig. 2).

2.4. *Assessment of external inputs for the current salmon production system*

The information about the current feed mix (plant-based feed, fish-based feed and insect-based feed) is represented by the vector vA1 (Fig. 5). This vector defines the relative contribution (in %) of the different feed inputs per unit of salmon feed produced: [vA_{11} – plant-based feed; vA_{12} – fish-based feed; vA_{13} – insect-based feed; and vA_{14} – additives (Premix)].

Moving to a lower level of analysis, subsystems can be defined for each element of *v*A1. These subsystems are represented by other vectors that describe their relative composition (see Fig. 5):

- *v*B1 – is the vector describing the relative contribution of crop types in the plant-feed supply system: [vB_{11} – cereals; vB_{12} – oil-bearing; vB_{13} – pulses]

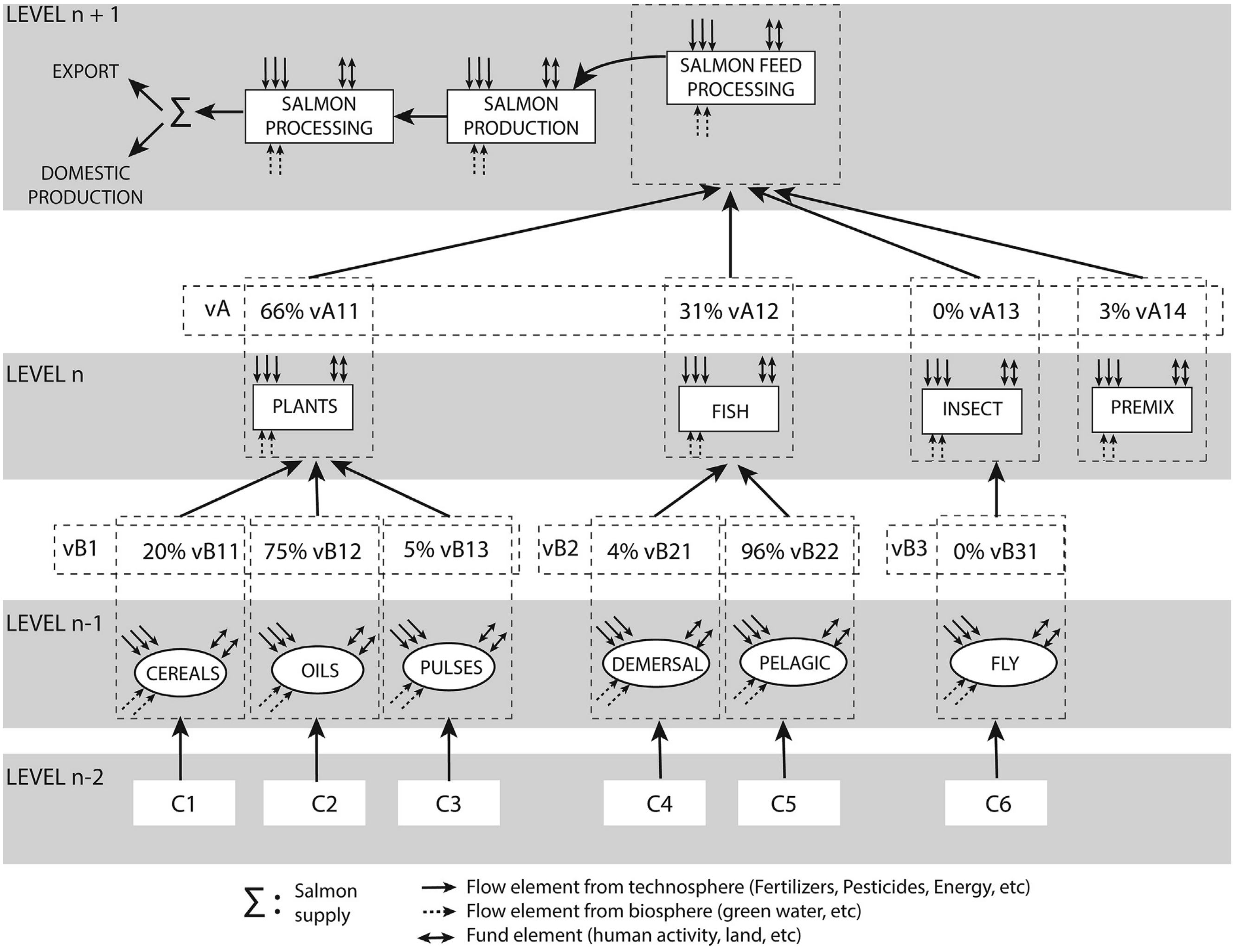

Fig. 5. The set of relations over the various pieces of information required to assess the external inputs of salmon production.

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- *v*B2 – is the vector describing the relative contribution of fish types in the fish-feed supply system: [vB_{21} – demersal fish; vB_{22} – pelagic fish]
- *v*B3 – is the vector describing the profile of the different percentages of feed inputs in the insect-feed supply system. In Fig. 8 this vector has only one typology of feed-input and its value is zero because this figure corresponds to the diagnostic analysis and this component is not yet used in the elaboration of salmon feed. It will be used for the anticipatory mode.

At the lowest level in Fig. 5 we have the specification of the unitary processors related to production and processing (level n-2) that make up each of the subsystems defined at level n-1. For example: the element vB_{11} (cereals) is defined by the unitary processors related to the production and processing of maize and wheat: [vC_{11} – Maize; vC_{12} – Wheat]. In Figs. 6–8 vectors at level n-2 are shown in detail.

Using this set of relations in diagnostic mode, the profile of external inputs required for salmon production was assessed based on the information about the characteristics of existing production processes.

2.5. *Anticipatory mode*

Due to the modular features that were described in the previous section, MuSIASEM facilitates the generation of scenarios at any level. For example, exploring the effects generated by: an increase in salmon production, changes in the relative contribution of the feed supply system, or both. In this case, the second option will be evaluated. It is assumed that the necessary amount of feed of the different combinations is the same, although this really is not the case, because the quantity can vary according to the nutritional contributions that each ingredient contributes (see section 2.5.3). However, this analysis goes beyond the scope of the objective of this article. Fig. 9 shows the actual mix employed (described by vector *v*A1), predominant use of marine products (*v*A2), a total reliance on plant-based ingredients (*v*A3), and two scenarios with varying amounts of insect ingredients (*v*A4 and *v*A5). These combinations reflect the objectives of the Aquafly project (for more details, see Tables A1, A2 and A3 in *Supplementary data*).

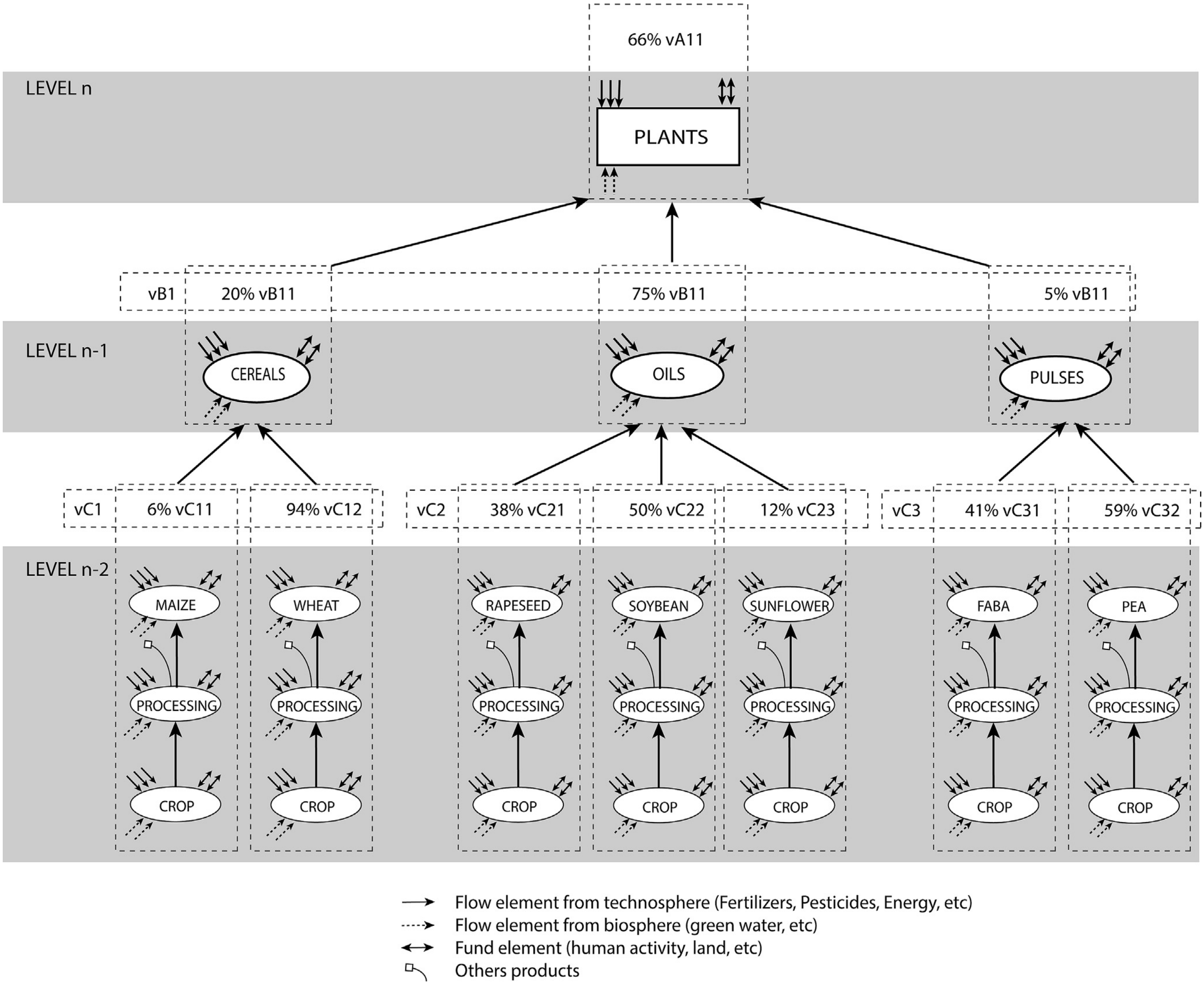

Fig. 6. Unitary processors of feed-ingredient supply at level (n-2) in the plant-based supply system.

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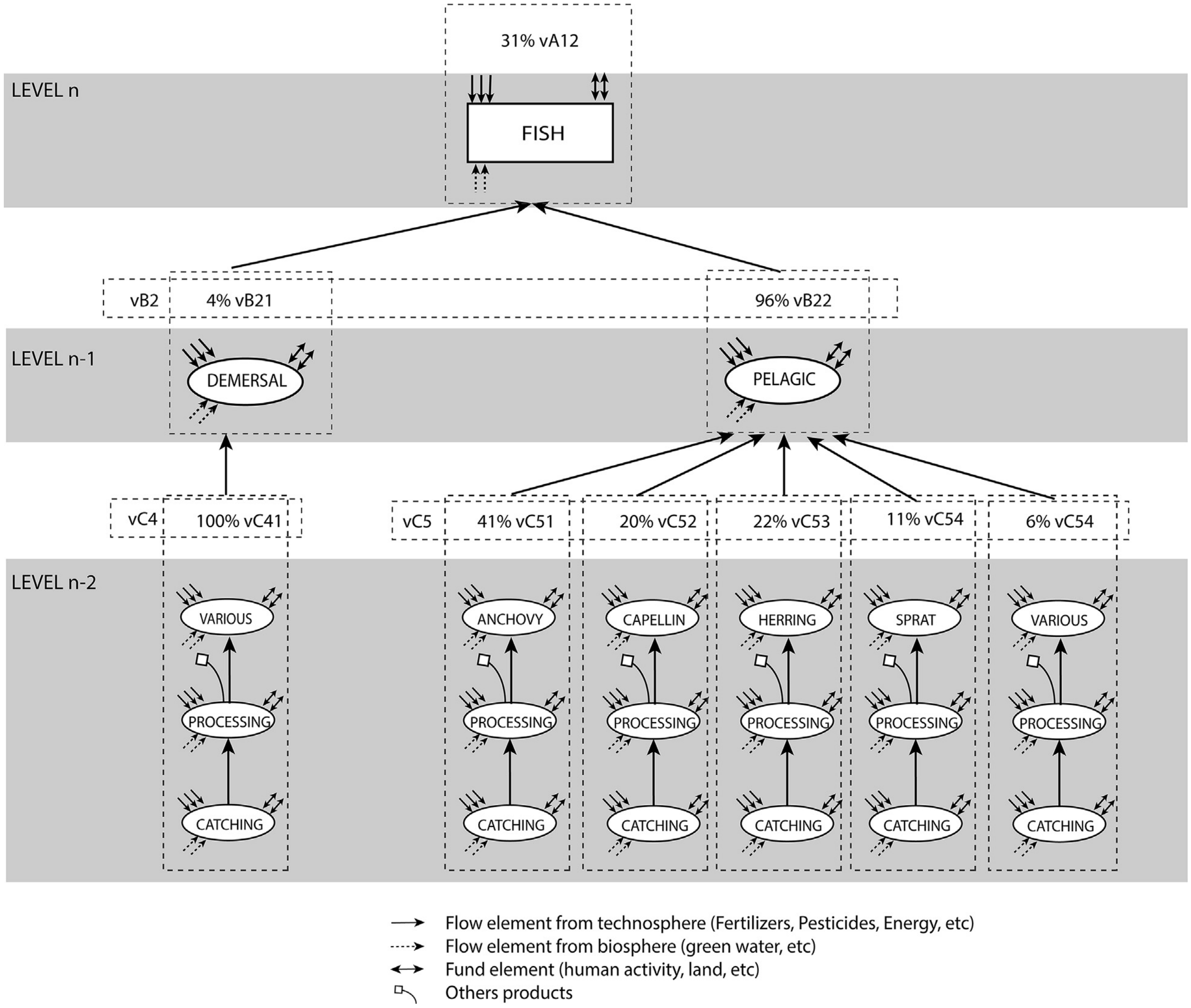

Fig. 7. Unitary processors of feed-ingredient supply at level (n-2) in the fish-based supply system.

2.6. Data sources

2.6.1. Feed production

For agricultural production:

- Faba beans and pea: It was assumed that both were produced in France. The inputs required for the crop production were estimated from the following sources: land, pesticide, fertilizers and energy were estimated from (Wilfart et al., 2016) and labour from (UAB, 2018). For processing, due to the lack of information, wheat processing data was used as suggested by (Hognes et al., 2014).
- Maize was assumed to be produced in the United States of America. The inputs required for the crop production were estimated from the following sources: land, labour, pesticide and energy from (Pimentel and Pimentel, 2008) and fertilizer from (UAB, 2018). For processing, the blue water, energy and outputs were estimated from (Buratti et al., 2008; Galitsky et al., 2003). Due to lack of data on the labour required, an estimate based on European data was used (European Comission, 2016; Logatcheva and Galen, 2015).
- Rapeseed was assumed to be produced in Germany. The inputs required for the crop production were estimated from the following sources: land, labour and fertilizer were obtained from (UAB, 2018); pesticide and energy from (Queirós et al., 2015). For processing, the inputs and outputs are from (Schmidt, 2007), the labour data was considered the same as for maize processing.
- Sunflower was assumed to be produced in Ukraine. The data of land, fertilizer, energy and pesticide were estimated from (Wilfart et al., 2016) and labour input was assumed to be 32.8 h/t (UAB, 2018). For processing, due to the lack of information Denmark data was used. The inputs and outputs are from (Schmidt, 2007), the labour data was considered the same as for maize processing.
- Soybean: production data from Brazil were used. The data of land, energy and fertilizer were estimated from (Wilfart et al., 2016) and labour from (Ortega, 2003). For processing, the inputs and outputs are from (Schmidt, 2007), the labour data was considered the same as for the maize processing.
- Wheat: It was assumed that it was produced in Germany. The data of land, pesticide and fertilizer were obtained from (UAB, 2018), blue and green water from (Mekonnen and Hoekstra, 2010), energy from (Visser et al., 2012) and pesticide from (Marinussen et al., 2012). For the elaboration of salmon feed, two by products which come from different processes are used, dry gluten and wheat starch. Due to the lack of information, Belgium data was used. Moreover, it was assumed that both processes had the same inputs (Buchspies and Kaltschmitt,

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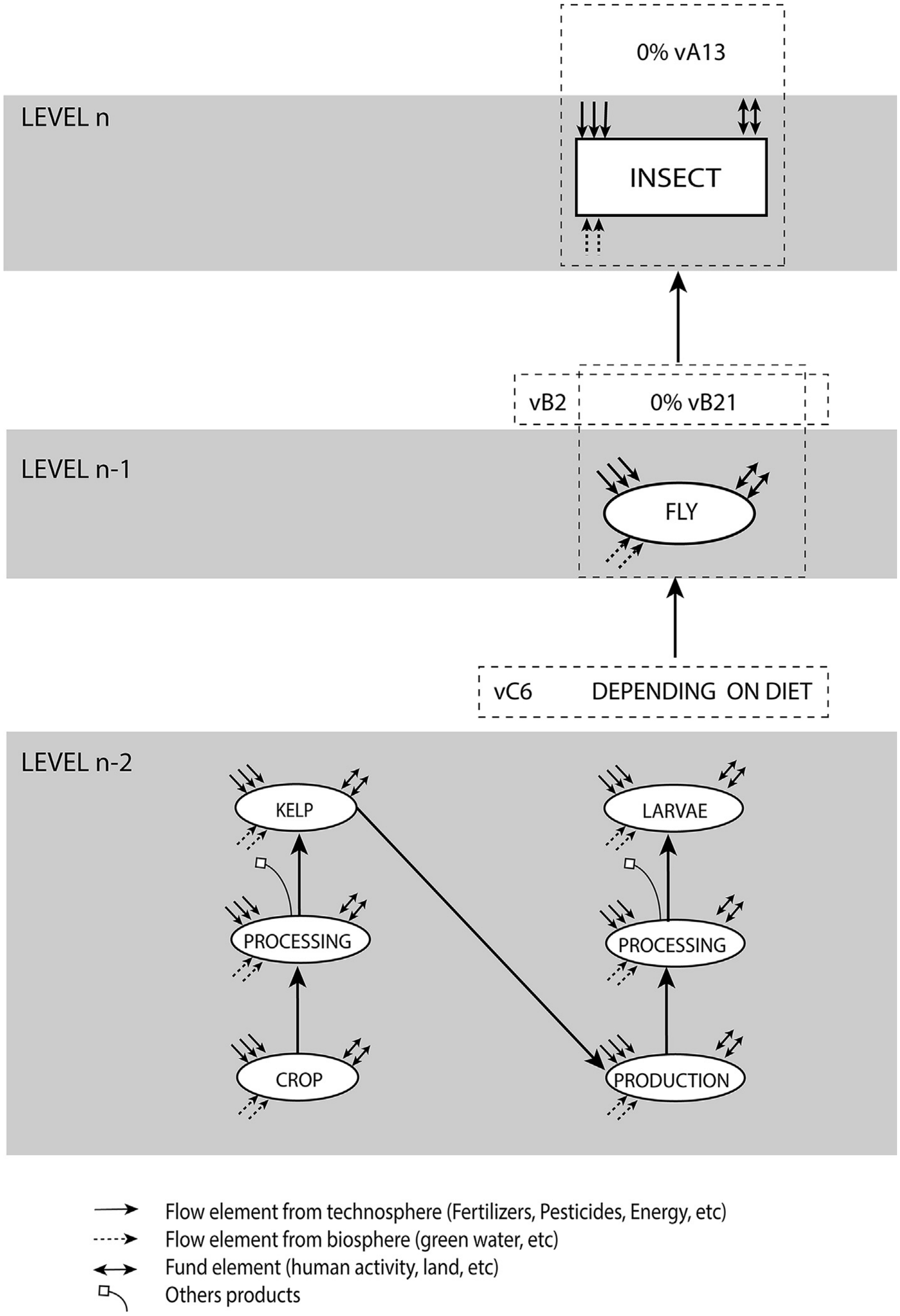

Fig. 8. Unitary processors of feed-ingredient supply at level (n-2) in the insect-based supply system.

2016). The proportion of outputs for the wheat starch process was estimated from (FAO, 2017). The labour data was considered the same as for the maize processing.

- Unless otherwise indicated, the data of blue and green water used in the agricultural production was obtained from (Mekonnen and Hoekstra, 2010).

For marine products:

- The energy required by the different species was estimated from (Hognes et al., 2014, 2011). The labour in the catching and processing for anchovy was estimated from (TASA, 2010, 2008). For the rest of the fish the labour was estimated from (Directorate of fisheries, 2018; Norway Working Days, 2018; Salz et al., 2005; SSB, 2018a). The procedure is presented in the supplement. For processing, the data are from (Winther et al., 2009), The procedure for calculating the labour was similar to that of fishing and the data used is from (FAO, 2013).
- Regarding the analysis of externalization, it was assumed that Blue whitling, Herring, Sande el, Norwau pout, Sprat and Capeling were of local origin.

For insect products:

- The data for kelp production was obtained from the following sources: the energy and blue water from (Alvarado-Morales et al., 2013), yield from (Skjermo et al., 2014), labour was estimated from (Meland and Rebours, 2012; Skjermo et al., 2014).

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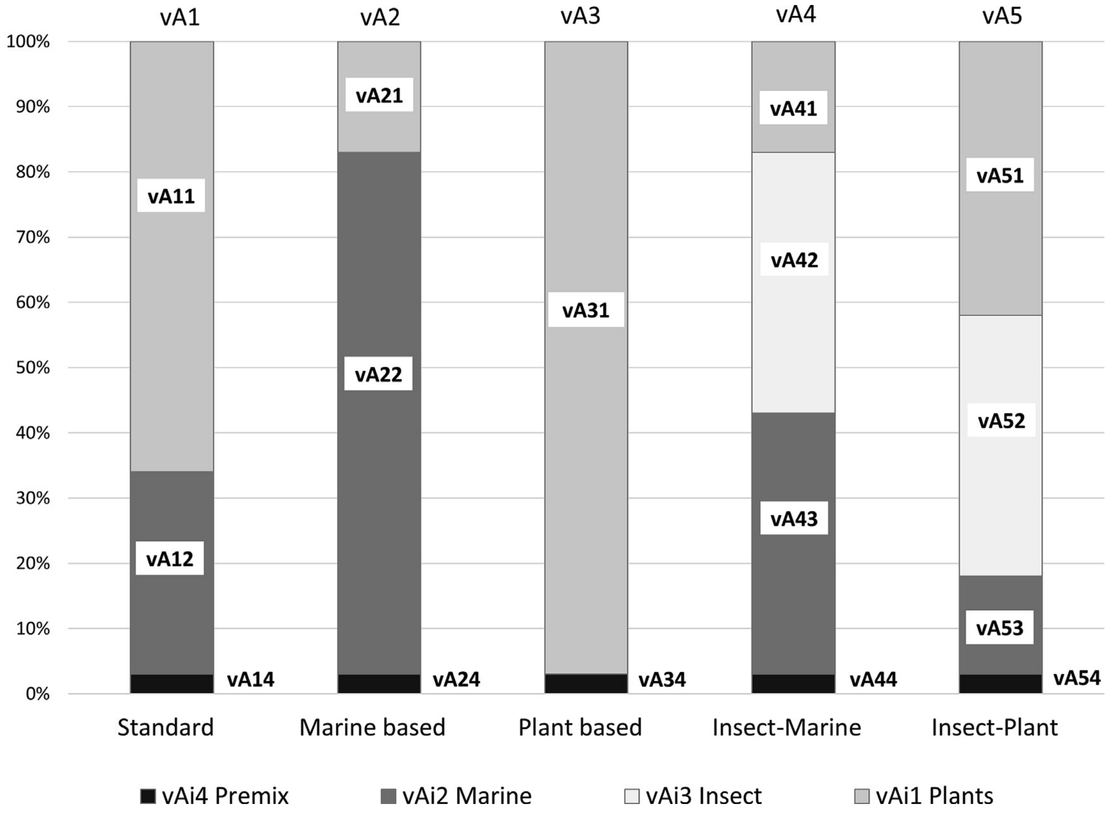

Fig. 9. Hypothetical mixes of feed-products to feed the salmon.

- The data for the production of larvae were estimated from (Hexeberg R., 2016; Smetana et al., 2019). Given that these data refer to small-scale experimental production systems, they were slightly adapted to reflect expected benchmarks for industrial-scale production systems. Regarding labour requirements, a value of 130 working hours per ton of insect oil was adopted.

For economic variables:

- The price for fishmeal and fish oil corresponds to the price of imports in Norway at 2017. It was obtained from (FAO, 2018c). Because the prices for the ingredients of vegetable origin were not found for 2017, an average of the 2014–2016 prices was used. The data correspond to the Norwegian import price and were obtained from (FAO, 2018). Due to the difficulty to establish a price for the ingredients coming from insects, the estimations were only made for the diagnosis

2.6.2. Salmon production (feed processing, salmon production and processing)

The inputs and outputs were obtained from (Winther et al., 2009), the labour for feed processing was estimated from (Skretting Norway, 2015), for salmon production from (SSB, 2018b, 2018a; 2017a) and for salmon processing from (FAO, 2013). The salmon feed composition was calculated from (Hognes et al., 2014, 2011).

2.6.3. Data limitations

Despite a major effort in locating data for all the inputs and outputs considered for the selected reference year (2017), some data gaps remained. As a result, some data refer to different years. In particular, coarse assumptions had to be made for the labour hours in the fishery sector (where statistics vary markedly throughout the years). Although this makes the analysis less robust, it should be kept in mind that the objective of this application is to show the potential of the methodological approach and not the outcome per se. Tables A4-A9 of the supplementary data show the processors developed for the analysis.

Note that we did not consider allocation among the co-products. Instead we included the requirements of the entire process given that MuSIASEM considers the processes included in the analysis as functional units being generated by other functional units, generating larger functional units (Giampietro et al., 2012). Any type of allocation dividing categories of flows across different functional units is inconsistent with complex system analysis. In this sense, MuSIASEM differs from the approach used in life cycle analysis (LCA). Difficulties of allocation among co-products have been documented by Ayer et al. (2007).

The feasibility and viability of feed supply alternatives were assessed on a year basis assuming current volume of Norwegian salmon production. This approach has limitations as in reality salmon producers continuously switch feed composition in response to stock reductions and market price variations. Again, we re-iterate the point that quantitative story-telling does not have the goal of representing exactly the existing situation in a rigorous and detailed way. Instead it provides the big picture of an issue in relation to several non-equivalent narratives in order to identify potential bottlenecks and constraints associated with large-scale implementation of investigated policies.

3. Results

3.1. Assessment of Norwegian aquaculture at the national level (diagnostic mode)

Salient environmental and economic features of the current

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Table 1
An overview of the relation of salmon production in Norway to both its local environment and the external context.

Type of variables	Phases	Variables	Unit per year	Norway	Externalization
Biophysics	Production of feed ingredients	Land	10^6 ha	–	0.7
		Labour	10^6 h	32	46
		Energy	10^15 J	10	16
		Fertilizer	10^6 t	–	0.1
		Pesticide (a.i)	10^3 t	–	1.6
		Blue water	10^6 m3	negl	27
		Green water	10^9 m3	–	3.2
	Salmon production & processing	Labour	10^6 h	25	–
		Sea area	10^3 ha	7.4	–
		Energy	10^15 J	8.3	–
		Blue water	10^6 m3	5.1	–
Economic	Trade	Money for the imports	Billions €	–	1
		Money from the exports	Billions €	6	–
Supply	Amount of salmon in terms of weight	Salmon supply	t	1.7 × 10^4	1.1 × 10^6
	Amount of salmon in terms of food energy and nutrients	Food energy from salmon	10^15 Calories	negl	2.3
		Fat from salmon	10^15 Calories	negl	1.4
		Protein from salmon	10^15 Calories	negl	0.9

Norwegian salmon production system are summarized in Table 1 (Further details are available in Table A10 of the supplementary data.). This Table illustrates the biophysical and economic interactions between Norway and the rest of the world – i.e. the level of openness of the system. The majority of the biophysical flows and funds required, either directly or indirectly, come from outside Norway, with the exception of natural gas (mainly of local origin).

Regarding water consumption, the feed that uses more ingredients of vegetable origin will have a higher water consumption. Also, because the main ingredients are imported, the results suggest that there is a significant amount of water externalized. Especially, water captured directly from the biosphere (green water).

Regarding the labour required for the production of salmon (expressed as hours of 'human activity' per year), it is estimated that around 55% are of local origin (57 Mhr) and the remaining 45% are of external origin. The organization of information through scales and levels facilitates the identification of direct and indirect human activity that is involved in this production system. For example, 25 Mhr and 79 Mhr are directly and indirectly linked to the salmon production. While it is true that this type of analysis should include working hours linked to transport and service to obtain more robust results, the usefulness of the MuSIASEM as a useful tool for decision making is already appreciated.

Although the economic analysis is limited, it gives an idea of the trade balance (the relationship between the profits from the export and the money that leaves Norway as a result of the purchase of imported products). Due to the economic return made possible by imports, from an economic perspective it is convenient for the Norwegian industry to keep doing "more of the same": keep growing by importing more inputs from elsewhere. This is also an important point in the quantitative story-telling.

In relation to food security, the analysis shows that the salmon industry generates a supply of high quality nutrients (notably omega 3 fatty acids and protein). However, most of the production is export oriented, reflecting that it is an activity oriented to the generation of economic benefits.

3.2. *Assessment of salmon feed scenarios at the national level (Norway)*

Table 2 shows the profile of inputs that would be required to maintain the actual production of salmon in Norway with the five salmon diets illustrated in Fig. 9 and the definition of supply systems illustrated in Fig. 5. As noted earlier, results reflect a coarse assessment of potential problems and not accurate predictions.

As shown in Table 2, labour requirements vary among the feed supply systems. The greatest labour demand is observed for the marine and insect/marine diets, it being respectively 1.8 and 1.7 times higher than for the standard diet. It should be noted though that the estimates of working hours for the production of insects are based on processes at experimental scale. If production will be scaled to an industrial level these values may decrease.

The lower demand for working hours in the plant-based supply systems comes at the cost of a greater pressure on the land—this scenario requires 5 times more land than the marine-based solution—and a greater consumption of fertilizers, pesticides and water. Water demand in the plant-based supply system is 6 times

Table 2
Comparison of biophysical requirements at the focal level in 5 different feed scenarios (to produce 1.5 × 10^6 t feed).

Biophysical resources		Standard	Marine based	Plant based	Insect -marine	Insect – plant
***Flow elements** (year)*	Crops (10^6 t)	3.0	0.8	5.0	0.8	2.0
	Marine products (10^6 t)	4.0	11	–	5.4	2.0
	Larvae products (10^^6 t)	–	–	–	1.0	1.0
	Energy (10^15 J)	26	43	16	40	32
	Fertilizer (10^6 t)	0.1	negl	0.2	negl	negl
	Pesticide (10^3 t)	1.6	0.4	2.4	0.4	1.0
	Seaweed as feed (10^6 t)	–	–	–	2.0	2.0
	Blue water (10^6 m^3)	27	8.0	38	22	32
	Green water (10^9 m^3)	3.2	0.8	4.7	0.8	2.0
Fund elements	Labour (10^6 h)	78	140	39	135	103
	Land (10^6 ha)	0.7	0.2	1.0	0.2	0.4
	Sea area – seaweed (10^3 ha)	–	–	–	75.0	75.0

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Table 3
Energy carriers required in the various salmon feed scenarios (in PJ to produce 1.5 × 10ˆ6 t feed). Requirements have been calculated from the processors detailed in Tables A4-A9 and the vectors described in Tables A1-A3 of the supplementary data.

Energy carrier	Standard	Marine-based	Plant-based	Insect-marine	Insect-plant
Electricity	3.8	2.9	4.3	7.4	7.8
Fuel	14.5	31.6	3.7	20.6	12.0
Heat	8.3	9.0	8.0	12.0	12.0
Total	**26.6**	**43.5**	**16.0**	**40.0**	**31.8**

higher than in the marine-based scenario and 1.5 times higher than the standard supply system.

Regarding the energy use, the marine-based and the mixed marine-insects systems are the most demanding. The former is 2.7 times higher than the plant-based system and 1.7 times higher than the current diet.

In addition to the total amount of energy required, another key aspect to consider is the type of energy carriers required (see Table 3). For example, the marine-based scenario requires a greater amount of fuel for fishing vessels. On the other hand, the plant-based scenario requires a greater amount of electricity for processing. The production of insects is also an activity that demands a lot of energy (but, again, note that the benchmarks are based on production on an experimental scale), therefore according to their combination (marine or plants) they will increase the energy requirement. Thus it is observed that the marine-insect scenario is 1.6 larger than the standard diet and 2.7 times larger than the lower value scenario (based on plants).

Scenarios that include insects significantly reduce land requirement (the insect-marine scenario and the insect plant compared to the standard are 3.5 and 1.8 times lower respectively) and therefore the pressure on the terrestrial ecosystem in terms of water, fertilizers and pesticides. These results are in line with (Sánchez-Muros et al., 2014; Smetana et al., 2016), who point out that the production of insect-based protein is more beneficial to the environment than the conventional ingredients. But as noted above, they have a greater demand for hours of labour and energy. Also, the proposal to use kelp as a source of omega 3 in order to reduce the dependence on fish oil will create a pressure on this resource in the marine ecosystem. For example, for both scenarios including insects, approximately 75,000 ha in the sea would be required. For comparison, in 2016 the area used in the Norway sea for the cultivation of seaweed was 277 ha (Stévant et al., 2017). On the other hand, the production of seaweed integrated in aquaculture through Integrated Multi-Trophic Aquaculture (IMTA) systems has as its main cost human labour (Chapman et al., 2014). This is another important point for the story-telling.

4. Discussion

The scenario of insect feed considered in the AQUAFLY project refers to an innovation of low technology readiness level (in between ‘basic technology research’ and ‘research to prove feasibility’ on the TRL scale). For this reason, the quantitative assessment is approximate and not sufficiently robust for use as ‘scientific evidence’. All the same, when adopting the logic of quantitative story-telling the results are useful to anticipate potential troubles of a continued growth of the Norwegian salmon industry, both inside and outside the national borders, and to critically examine the justification narratives for a further increase in production: Can further growth be obtained without increasing environmental impacts and is further growth desirable?

An informed discussion about the future of salmon production has to start from the feasibility, viability and desirability of this activity (the quality checks of quantitative story-telling). In relation to biophysical constraints (feasibility) it is expected that the trend of substituting marine feed ingredients with other sources will continue in the future. Since the 1980s the fish catch worldwide has remained constant and is unlikely to increase in the future (FAO, 2017). Moreover, it is expected that fisheries will continue experiencing diminishing return: fishing vessels need to travel a greater distance to find shoal of fish. This will further increase the already high energy (fuel) requirements and CO2 emission. The concomitant increase in price of marine ingredients has already caused a change in the composition of salmon feed. While in 1990 feeds were based predominantly (90%) on marine ingredients, at present, feeds are composed of a mix of terrestrial and marine ingredients (around 30%) (Ytrestøyl et al., 2015). This trend is expected to continue.

Given these considerations it is obvious that salmon production will have to continuously adapt to the emergence of new biophysical limits and threats and eventually ‘become something else’. Scaling up the production of aquaculture translates into an increasing level of uncertainty about the insurgence of possible biophysical problems. This will also imply taking risks and forcing negotiations among social actors to avoid legitimate but unavoidable conflicts among new winners and losers. To support this process it is relevant and timely to start a reflection about what criteria should be used and why for deciding the future of the salmon industry.

4.1. The risk of damaging the reputation of Norwegian high-quality salmon

Replacing marine ingredients with terrestrial ingredients implies a larger demand for land, water, fertilizers and pesticides. This result is in concordance with findings of Torrissen et al. (2011). The production of salmon is currently following the same path of development as intensive beef production in feed-lots. This solution implies further increases in crop production for animal feeds (either salmon or beef) and associated land use changes (e.g., competition with crop cultivation for direct consumption; deforestation leading to soil erosion and loss of biodiversity) and environmental impacts of fertilizers and pesticides in rural areas (Ytrestøyl et al., 2015). The progressive association of salmon production with negative effects on both the environment and rural communities in the developing world may generate a negative imagine for the salmon industry. This is another source of uncertainty.

Results show that from an environmental perspective, insect feed ingredients may represent an interesting alternative, causing less pressure on terrestrial land than plant feed ingredients. However, energy and labour requirements are currently higher for insect feed than for plant-based alternatives. Alternative insect feed substrates (wastes instead of kelp) could reduce sea area requirements. However, both insect and plant alternatives are currently relatively poor in omega-3 and hence potentially endanger the status of salmon as a high quality food (Sprague et al., 2016).

The solution of adding a new element to the metabolic pathway (substrate – insects – salmon) enlarges the options of feed sources. Indeed, while the set of possible feed sources for salmon is limited,

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feed sources for insects are in principle virtually unlimited and open the way to the recycling of organic waste and sewage (circular economy) and modulating omega-3 content. However, this solution may also lead to the emergence of new and unexpected problems, such as bio-accumulation of toxic substances that could damage the image of Norwegian salmon. In this case we are dealing with a very serious source of uncertainty.

4.2. *Is further growth in production desirable?*

A common justification narrative about the future of Norwegian salmon production sees an expansion of the industry into new markets as an option for generating greater economic benefit and direct and indirect jobs (ISFA, 2018). How large are these economic benefits for Norway? Benefits for whom? What type of direct and indirect jobs will be created? For whom?

The results of Table 1 suggest that the main destination of the salmon production in Norway is the export, obtaining from this trade around 6 billion euros in 2017 (SSB, 2017b). When its value is compared with the Norwegian GDP (350 billion euros) it is observed that this represents just the 1.7%. This suggests that it may be more relevant to focus on local employment and preservation of traditional activities and landscapes, rather than increasing the revenues for the country in this way. However also in terms of job creation, the salmon industry does not significantly contribute to employment at the level of the national economy (Bailey, 2014).

In addition, it is reasonable to assume that additional growth of the salmon industry (by increasing installed operational capacity and maintaining current productive efficiency) will increase the impact on the environment in terms of a greater demand of biophysical resources and a greater pressure on the ecological systems, besides a progressive increase in the costs of the local production process associated with increased intensity of salmon farming. When this pressure will exceed the resilience of the ecological systems, a slash-back on the salmon production system may occur.

In the same way, the results in Table 1 suggest that a further increase in the production of salmon cannot be justified in relation to providing food security for Norway. The actual production of salmon is orders of magnitude larger than its internal consumption. As for global food security, salmon is a luxury food item and while its nutritional quality is excellent for preventing cardio-vascular diseases in affluent countries, it is unlikely to contribute to the food security of the low-income classes in developing countries most exposed to the risk of malnutrition due to a systemic problem of low disposable income.

As explained earlier, our analysis does not pretend to identify “the best” pathway for the development of salmon aquaculture, but intends to support a reflection and discussion on the future of Norwegian salmon aquaculture through quantitative story-telling. Quantitative story-telling avoids the trap of ‘solving’ the complexity associated with our interaction with the external world by simplification. Our analysis stimulates a reflection on the following questions: Why does Norway want to further increase its production if salmon is not produced for internal food security nor for boosting the national economy? What is to be gained by whom, and what is to be lost by whom? Is “more” necessarily “better”? The idea of incorporating insects in the food chain certainly has merit because it enlarges the option space for technical innovations, but at the same time it opens a Pandora box of uncertainties. Technological innovations are always associated with justification narratives: Why do we have to change? Decisions about changes require discussions over the moral issues related to the ethical implications of proposed changes. Should we protect the existing values by limiting the options of changes to be considered? Or should we update/replace existing values so as to expand the options? How important is the goal of preserving the existing cultural identity? What is wrong with the idea of remaining at a given level of salmon production and focus on greening of the salmon industry and safeguarding adaptability in the case of perturbations to boundary conditions? Who has decided that we always have to strive for increasing the productivity of existing economic activities? Does the moral of Aesop’s fable about the dog losing its bone “in order to have more” apply here?

To make the proposed analysis more robust for quantitative story-telling, it should be carried out in co-production with the people using the results. This is particularly important with regard to: i) selection of the indicators of performance in setting up the processors (variables included in the analysis); and ii) checking the plausibility of the assumptions adopted in the definition of the various processors describing the production systems (Ci); and iii) checking the choice of the definition of the elements to be included in the two vectors vAi (the diet for the salmons) and vBi (the mix of supply systems used in the production of feed).

This work has focused on salmon feed. Other environmental problems with salmon aquaculture do exist, such as the effect of sea lice on wild fish (Hersoug, 2015; Nilsen et al., 2018), that have put pressure on the Norwegian government to reconsider its policies for expanding the salmon industry.

Acknowledgement

The authors gratefully acknowledge funding from the Research Council of Norway (Norges forskningsråd) under grant agreement 238997/E40 (Insects as natural feed ingredients for sustainable salmon farming—AQUAFLY). The Institute of Environmental Science and Technology (ICTA) has received financial support from the Spanish Ministry of Science, Innovation and Universities, through the “María de Maeztu” program for Units of Excellence (MDM-2015-0552). This work reflects the authors’ view only; the funding agencies are not responsible for any use that may be made of the information it contains.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2019.119210.

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Please cite this article as: Cadillo-Benalcazar, J.J et al., Multi-scale integrated evaluation of the sustainability of large-scale use of alternative feeds in salmon aquaculture, Journal of Cleaner Production, https://doi.org/10.1016/j.jclepro.2019.119210

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Please cite this article as: Cadillo-Benalcazar, J.J et al., Multi-scale integrated evaluation of the sustainability of large-scale use of alternative feeds in salmon aquaculture, Journal of Cleaner Production, https://doi.org/10.1016/j.jclepro.2019.119210