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Life Cycle Assessment of fish fed with insect meal: Case study of mealworm inclusion in trout feed, in France

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1. Introduction

Food demand continues to increase in response to the growing world population. The human diet increasingly includes meat and fish; therefore, the demand for protein is expected to escalate in the future based on an estimated world population of over 9 billion by 2050 (Godfray et al., 2010). Due to impacts of agriculture on the environment and resources, alternative sources of protein are required to address this issue. Insects are expected to be a potential solution in the future (van Huis and FAO, 2013). A significant portion of the human diet has included insects for centuries in many countries (Bukkens, 1997). Insects are highly nutritious (Bukkens, 2005) and convert food to body mass more efficiently than most other animals (Paoletti and Dreon, 2005). Although nearly 2 billion people in the world are entomophagous (Makkar et al., 2014), incorporating insects directly into certain populations' diets is expected to encounter challenges due to a lack of societal acceptance. In such cases, it is more reasonable and acceptable to introduce insects into the diets of domestic animals to reduce environmental impacts of current ingredients in their feeds. For example, it could replace some soybean, often singled out for its environmental impacts, in pig and poultry feed or replace fishmeal in farmed fish feed. In addition, stocks of many marine fish are depleted, which decreases the amount of fishmeal available for fish farming and increases its price, making alternatives economically competitive.

Including insects in fish feed (Bondari and Sheppard, 1981) is not a new idea; however, its environmental advantages are rarely reported in the literature. However, environmental impacts of insect rearing practices have been studied thanks to LCA with different scopes. One study estimated impacts of black soldier fly (*Hermetia illucens*) and housefly (*Musca domestica*) up to larvae stage (Muys and Roffeis, 2014). Two others studies are dedicated to the production of mealworm (*Tenebrio molitor*) for human food (Oonincx and de Boer, 2012; Miglietta et al., 2015). The latter focuses on water footprint. Three LCA studies have assessed potential impacts of including black soldier fly and housefly meals in animal feed (Hexebert Rustad, 2016; Salomone et al., 2017; van Zanten et al., 2015). One recent study performed an LCA of black soldier fly production and compared its environmental impacts to those of other protein sources both for human food and animal feed (Smetana et al., 2016). Another study provided recommendations for future LCA studies of insect production systems (Halloran et al., 2016). The latter studies however did not consider insect processing into meal and its incorporation in animal diets. Finally, the use of housefly to treat pig manure is assessed in another paper (Roffeis et al., 2015). Nonetheless, the literature remains insufficient, as noted during the First International "Insects to Feed the World" Conference in Wageningen (Netherlands) in 2014: "*… additional life cycle assessments are required to further confirm the sustainability of rearing edible insects and/or to compare with the traditional systems for the production of food (meat, fish in case of proteins), or for rearing insects as animal feed protein supplements (comparing with coarse grains, fish or soybean meal for example)*" (Vantomme et al., 2014). We studied the production of mealworms for incorporation into trout feeds. The objective was to design a production system in France that produces large amounts of insect meal. This article presents results of attributional LCA (A-LCA) of three production systems of "pan-sized" trout whose feed included different percentages of mealworm meal. This meal was assumed to come from a hypothetical agricultural cooperative that produces 10,000 t of mealworm meal per year. No mention of such a cooperative system has been found in literature despite its social and sanitary advantages.

2. Materials and methods

The LCA was performed in agreement with international standards ISO 14040 and 14,044 (ISO, 2006a,b). System boundaries and the goal and scope were defined to compare the use of insect-based meal instead of fish-based meal in pan-size trout production. Three scenarios were compared.

2.1. Goal and scope

The goal of the study was to compare insect-based and fish-based diets in trout production. The study forms part of the DESIRABLE

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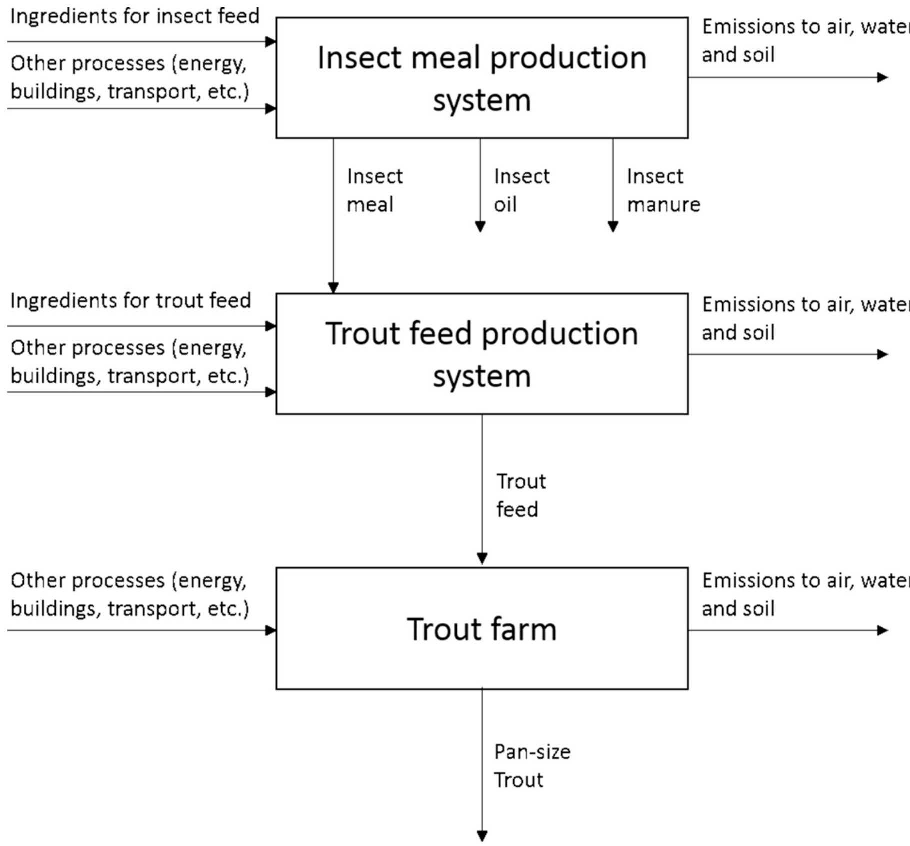

Fig. 1. General scheme of the insect meal production for feed in trout production system.

project funded by the French National Research Agency (ANR) to include insects as an alternative to conventional farmed fish and poultry diets. It compared a baseline scenario to three scenarios: one fish-based baseline feed with 0% of mealworm meal and two that replaced 15% and 30%, respectively, of fish meal in fish feed with mealworm meal. To compare feeding strategies of trout farms and assess the influence of mealworm percentage in feed on overall impacts, the functional unit was the service provided by production of 1 kg of pan-size trout.

2.1.1. System description

2.1.1.1. General description. The system consists of subsystems that produce mealworm meal, trout feed and trout (Fig. 1). All characteristics of the trout farm except for direct emissions (e.g. egg production, farm organization, energy use) were identical in the three scenarios. They are based on the process modeled in Agribalyse database (AGB) "Small trout, 250-350g, conventional, at farm gate/FR U" (Colomb et al., 2015; Koch et al., 2016). Stages for distribution, selling and consumption of trout were excluded (as in AGB). The main differences among scenarios occurred in the feed-production stage. The three scenarios are based on experimental fish-based formula which digestibility and rearing performances have been tested and validated (Burel et al., 2016).

2.1.1.2. Choice of the mealworm meal production scenario. An important step of the research project that support the present work was to design multiple scenarios able to produce 10,000 t of mealworm meal per year. These scenarios can differ from common production systems (i.e. all-in-one farms). To design the full range of possible scenario, a simplified method for generating scenarios inspired from (Godet, 2007) was mobilized. Experts involved in the project identified six stake variables which dramatically change the scenario depending on the value they take (insect feed origin, biorafinery profile, location, products form, market dynamics, coproducts value). By crossing the different modalities of the six variables, we got about 300 scenarios. Finally, experts selected two scenarios on socio-technical basis which were comprehensively studied: (1) one agricultural cooperative system with separated reproduction, fattening farms and mill on different locations; (2) one industrial system gathering the whole insect and meal production on the same site. In the Life Cycle Assessment presented in the present article, the first strategy, called agricultural cooperative has been chosen for several reasons:

- It stimulates local employment;
- It reduces sanitary risks by geographically split the livestock;
- It can be fully modeled thanks to existing installations of partners involved in our study;
- It is realistic with physiologic constraints. Notably, it ensures that separate larvae from nymphs is technically possible that is not guaranteed in large scale farms;
- It allows to evaluate the potentiality of cooperative systems that is currently not documented in literature.
- It is a possible alternative to all-in-one farms which faces technological challenges not currently solved for a 10,000 t of mealworm meal production level

The case study was a hypothetical insect meal production system that produces 10,000 t of mealworm meal per year in France. Because this system does not exist currently, the case study was designed by collecting primary technical data from a reference farm in Besançon, France, from which the LCI was created by extrapolating data to the relevant scale. This small insect farm (SIF) produces 17 t of fresh mealworm larvae per year. Additional information about this farm is available in another publication (Thevenot et al., 2017).

Consequently, the hypothetical system is an agricultural cooperative composed of 23 insect reproduction farms (RF) that provide larvae to 92 insect fattening farms (FF) (Fig. 2). The fattened larvae are sent to