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The water, energy, and land footprint of tilapia aquaculture in Mexico, a comparison of the footprints of fish and meat

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ABSTRACT

In the food-energy-water (FEW) nexus, livestock has a dominant place. It is generally considered as water, energy and land-intensive. Aquaculture could provide additional animal protein and contribute to meeting the food demand. However, aquaculture requires natural resources and causes freshwater pollution due to aquafeed, fertilizer, and hormone use. This study assesses the sustainability of aquaculture using the indicators water footprint (WF), energy footprint (EF) and land footprint (LF), comparing results with livestock. It uses extensive, semi-intensive and intensive Tilapia aquaculture in Mexico as a case study including broodstock, breeding, fattening, processing, and transportation phases. Tilapia production in intensive aquaculture has the largest footprints. Blue WFs are smallest in semi-intensive systems; green WFs, EFs and LFs are smallest for extensive systems. For protein, tilapia from intensive systems has the largest WF (126 l/g protein), beef (51 l/g), pork (33 l/g) and poultry (14 l/g) have smaller WFs. EFs per unit of protein or nutritional energy fall in the range of values for beef, poultry and pork. LFs of Tilapia (m²/kg) are larger than LFs of poultry but fall in the range of beef and pork. Per unit of nutritional energy EFs are similar to EFs for beef but larger than EFs of poultry and pork. From a FEW nexus perspective, it is not more sustainable to replace livestock with Tilapia. Tilapia requires more freshwater than beef, pork and poultry and pollutes larger amounts of water. For energy and land, Tilapia is not the better choice, because footprints are comparable.

1. Introduction

Energy, water and land are the main natural resources to produce food. Globally, population and affluence increase might challenge the provision of sufficient food and constrain our basic natural resources (Liu et al., 2020). Food, energy and water are closely interlinked in the so termed food energy water nexus (FEW nexus) that can be considered as a complicated web with many relationships (Liu et al., 2019). The nexus approach, introduced at the Bonn conference in 2011 in preparation of the UN Conference on Sustainable Development, for the first time showed the importance of a system approach and the relationships amongst water, energy, food security and land use (Hoff, 2011). The nexus provides a framework to identify trade-offs and synergies, aiming to invest to sustain ecosystem services, create more with less, and to

improve access, integrating the poorest. Addressing the nexus requires systems thinking to find linkages, especially important for policy in an attempt to improve the provision of food, energy and water (Bazilian et al., 2011). Studies on energy, water and food systems showing these linkages should evaluate them in terms of sustainability, resilience and feasibility, indicating how they can be managed (Stigson, 2013). In the context of the nexus approach, Lele et al. (2013) recognize water as the most critical natural resource, because of its complex management. Some regions experience more nexus challenges than others do. For example, South Asia, encountering pressure on water resources, limited energy security and land resources, faces difficulty to feed its growing populations, requiring proper management to handle synergies and trade-offs in food, water and energy on a river basin-level (Rasul, 2014). Pittock et al. (2015) argue that there are considerable opportunities to

; Abbreviations: CO₂, carbon dioxide; COD, chemical oxygen demand; EF, energy footprint; Ha, hectare; Hp, horsepower; LCA, life cycle analysis; LF, land footprint; L, litre; g, milligram; MJJ, megajoule; N, nitrogen; NH₃, non-ionized ammonia; NO₂, nitrites; NO₃, Nitrates; NOM, Mexican Official Standard (Norma Oficial Mexicana acronym in Spanish); SI, supporting information; TJ, Terajoule; WF, Water Footprint; yr, year.

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improve sustainable development when nexus linkages are addressed better. For the research community, FEW nexus improvements also include access to relevant data and the availability of independent experts to advice on nexus issues.

An important component in the FEW nexus is animal food. Livestock production systems to produce meat and other animal products have large requirements for natural resources. For example, 29% of the water footprint (WF) of global agriculture is needed to produce animal feed, while one third of the global WF is related to beef (Mekonnen and Hoekstra, 2012). It is expected that the global consumption of animal foods rises further (OECD/FAO, 2019). The large existing pressure of meat production on natural resources might cause a shift towards other animal products, e.g. towards fish from aquaculture. However, aquaculture did not receive much attention from the scientific community so that consequences on, for example, WFs are uncertain (Vanham, 2016).

Several sources provide animal protein for human nutrition, such as terrestrial animals (e.g. cows, chickens and pigs) or aquatic animals (e.g. Tilapia). In general, meat and fish are important high-quality protein sources (Bohrer, 2017). Fish from aquaculture shows great potential to contribute to food security (Pauly et al., 2002). Especially Tilapia (*Oreochromis* sp.) production is important. Behind carps, it is the second most farmed fish in aquaculture with 4 million metric tons of fish produced globally (Wang and Lu, 2016). Mexico is the ninth global Tilapia producer with a production of 180,000 tons in 2017. Aquaculture provides 91% of the Mexican Tilapia production (SAGARPA, 2013), but production is related to environmental impacts (Troell et al., 2004).

In Mexico, aquacultural production systems vary from low to high intensity. Extensive, semi-intensive and intensive systems require different inputs, translating into different environmental impacts (FAO, 2005; Boyd et al., 2007). For instance, semi-intensive and intensive aquacultural production systems are characterized by their maximization of production, with high yields from 100 to 500 Mt/ha/yr. These systems totally depend on aquafeed, energy input and constant water refreshments (Muir et al., 2000). Moreover, semi-intensive and intensive aquaculture also needs energy, e.g. for pumping, and land, e.g. to grow feed crops, causing natural resource use (Pelletier and Tyedmers, 2010; Troell et al., 2004). Extensive systems, on the other hand, require fertilizer to stimulate natural feed productivity in the fishponds. Aquafeed and fertilizer use in aquaculture pollute water, especially through nitrogen (N) and phosphorous (P) (Verdegem and Bosma, 2009).

To evaluate environmental impacts of food production systems, such as aquaculture, assessment tools have been developed, e.g. the WF, energy footprint (EF) and land footprint (LF). The WF is a tool to calculate freshwater amounts appropriated and polluted along the production chain of a certain good or service, expressed in water volumes per unit of product (Hoekstra et al., 2011). The concept includes three components: i) the blue WF related to consumption of surface or groundwater lost due to evaporation, incorporated into a product or transferred to another water body; ii) the green WF referring to rainwater consumed along production chains; and iii) the grey WF, freshwater amounts required to assimilate contaminant loads (Hoekstra et al., 2011). The EF refers to the sum of direct and indirect energy required along a production chain of a product or service. It is expressed in either KWh or MJ per unit of product (Troell et al., 2004; Aina and Agustina, 2015). The LF addresses the land required to produce a product expressed in area per unit of product (Borucke et al., 2013).

Several studies assessed natural resource use of meat. For instance, Ibidhi et al. (2017) assessed the WF, LF and carbon footprint of sheep and chicken meat in four different farming systems in Tunisia, showing that chicken meat production is more efficient than producing sheep meat. Gerbens-Leenes et al. (2013) calculated the WF of poultry, pork and beef, comparing different production systems in four countries, showing that animal feed is an important factor that determines WFs, and that green WFs of meat are larger than blue and grey WFs. Studies on EFs of meat show enormous ranges depending on the type of production system considered. For example, the EF of beef ranges between

30 MJ/kg (Williams et al., 2006) to 110 MJ/kg (Kramer and Moll, 1995), a difference of a factor of almost four.

Regarding the WF of fish, Gephart et al. (2014) analysed the replacement of meat by marine fish saving 5% of total annual freshwater use (350 km³/yr). Verdegem et al. (2006) analysed freshwater use of inland and offshore pond aquaculture, but only focused on the fattening phase, excluding other stages in the production chain. Yacout et al. (2016) made an LCA of Tilapia production for semi-intensive and intensive systems, excluding the processing from alive fish to fillet. Pahlow et al. (2015) assessed green, blue and grey WFs of different types of commercial aquafeed for the major farmed fish and crustacean species, such as Nile Tilapia. For Tilapia, they included two formulated diets with different aquafeed composition. They argued that WFs need to be included in aquaculture in the future, especially aquafeed WFs. However, Pahlow et al. (2015) only considered WFs related to aquafeed, excluding freshwater needed for the fishponds.

So far, there are no studies that assessed WFs, EFs and LFs of fish for human consumption produced in aquaculture that included the complete production chain. This study aims to fill this gap by assessing the WF, EF and LF of Tilapia produced in extensive, semi-intensive and intensive aquacultural systems and to compare results with footprints of different meat types. The study uses Mexico as the case study area and answers the following three questions: (i) What is the WF, EF and LF of extensive, semi-intensive and intensive aquacultural production systems in Mexico? (ii) What is the grey WF along the production chain due to chemical substances coming from balanced aquafeed, fertilizers and hormones? (iii) Which animal protein source, i.e. Tilapia, beef, poultry or pork is favourable in terms of WFs, EFs and LFs?

Results of this study indicate differences amongst footprints of animal foods and provide a tool to stimulate production and consumption in the direction with optimal resource use in the FEW nexus.

2. Tilapia aquaculture

2.1. General aspects of tilapia

Tilapia (*Oreochromis* sp.) is a fish species profitable for aquaculture due to its rapid growth, resistance to diseases, low mortality rate, tolerance to high-density conditions, resistance to low oxygen concentrations and flexibility in feed acceptance (Maclean et al., 2002). Tilapia prefers freshwater of good quality. Critical water parameters are temperature, dissolved oxygen, pH, non-ionized ammonium, nitrites, nitrates, and carbon dioxide (García and Calvario, 2008). Table A1 in the supporting information (SI) shows optimal levels of these parameters for Tilapia aquaculture. Parameters should remain in the optimal range since they influence fish survival and feed consumption (Nicovita, 2007). Tilapia lives in warm areas so temperature must remain within the optimal range. Parameter values outside optimal ranges translate in Tilapia feeding behaviour decline (Nicovita, 2007).

2.2. Tilapia production chain

Fig. 1 shows the Tilapia fish life stages including four phases: (i) the broodstock phase; (ii) the breeding phase; (iii) the fattening phase and (iv) the processing phase (Bhujel, 2013; SAGARPA, 2013; Snir, 2001). The figure also shows the body weight per phase (Bhujel, 2013; SAGARPA, 2013; Snir, 2001).

The production chain from eggs to fillet takes nine months (SAGARPA, 2013), starting in the broodstock phase. Breeders reproduce in nursery tanks at a stocking density of four fishes per m³ with a sex ratio of one male to three females, each weighing 125 gs (Bhujel, 2013). Tilapia females produce around 1000 eggs and incubate embryos in the mouth for 20 to 25 days. After larvae reabsorb the egg yolk sac, females provide parental care for 10 to 15 days. In this phase, females do not eat (Baltazar, 2007).

The second stage is the breeding phase when fry get their first feed

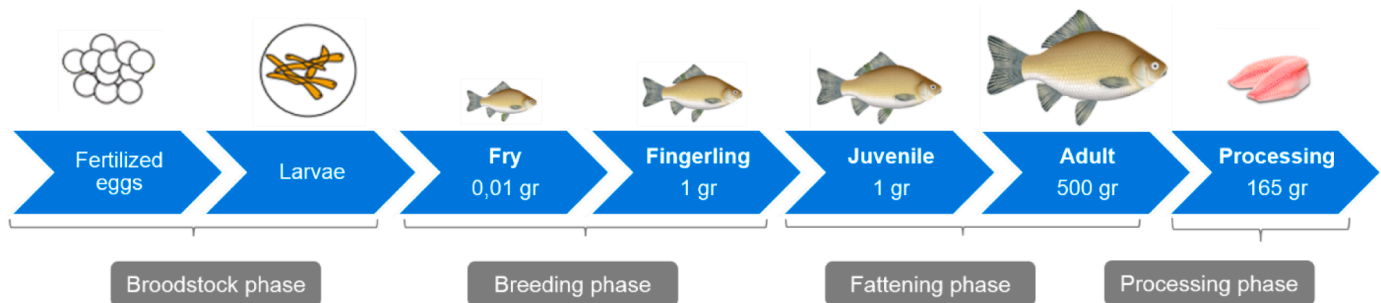


Fig. 1. Tilapia fish life stages with four phases: (i) the broodstock phase; (ii) the breeding phase; (iii) the fattening phase and (iv) the processing phase. The fish life stage and body weight depend on the phase (Source: Bhujel, 2013; SAGARPA, 2013; Snir, 2001).

(Bhujel, 2013). Female Tilapias grow slower than males which is more expensive for aquaculture. Therefore, fingerlings receive a sex reversal process treatment using hormones to change females to males (Junior et al., 2012). For 30 days, fingerlings receive feed mixed with masculine hormone of 60 mg per kg of feed. Juvenile fish have a faster metabolism than adult fish, translating in higher growth rates. Therefore, feed is adjusted to the Tilapia life stage (Miao and Liang, 2007). At the end of the breeding phase, fish reach a body weight of one gram (Bhujel, 2013). After the first two phases, fingerlings are transported to fattening phase locations.

In the fattening phase, fingerlings reach the commercial size of 500 gs, reached within seven to eight months, depending on the aquaculture system used. This means there is one production cycle per year (SAGARPA, 2013; Maclean et al., 2002).

In the processing phase, buyers take adult Tilapia from fattening farms and transport it to processing plants. To maintain freshness, reduce meat decomposition and decrease stress, fishes enter the slaughter area by a thermal shock sacrifice with ice water (Rivelli, 2001). In the Tilapia processing industry, most processes are mechanized using machines that i) stun the fish; ii) de-ice and wash it; iii) remove head, fins and gut; iv) make fillet and v) remove skins (Ghaly et al., 2013; Islam et al., 2004). The machines require large amounts of water and electricity (Tomczak-Wandzel et al., 2015). Tilapia has a relatively small fillet yield of 33%. Residues include head, internal organs, fins and skin (Snir, 2001). Tilapia residues do not meet human consumption standards, and are used to produce fishmeal, fertilizer, animal feed and silage (Botero-Silva et al., 2009).

Transportation occurs in between the four phases. Fingerlings are transported to fattening farms in regular lorries. To avoid mortality due to oxygen lack, a common method to transport live fingerlings is the use of plastics bags with water and pressurized oxygen at low fish densities (Orina et al., 2014). Adult, commercial size Tilapia is transferred to processing plants in polystyrene boxes with cold water and carbon aeration stones in refrigerated trucks to decrease the metabolism and avoid mortality and stress. With this method, fish survives a twelve hours-journey with zero mortality rates (Singh and Daud, 2001).

2.3. Aquaculture production systems in Mexico

In Mexico in 2015, there were 47 fry breeding centers and 3970 fattening centers registered in the National Council for Fisheries and Aquaculture (SAGARPA, 2015). However, some companies or private fish-men are not registered, so that there is no exact number. In Mexico, Tilapia production systems are classified in three types depending on culture technology and stocking density: i) extensive, ii) semi-intensive and iii) intensive systems (Flores-Nava, 2007). Extensive systems use open water bodies, semi-intensive and intensive systems are set up in ponds. Extensive Tilapia production systems stock fish at low densities of three fishes per m^3 (Mojica et al., 2010). They have relatively low survival rates of 75% (SAGARPA, 2013). The systems have no energy input for operation but require energy for harvesting by boat. They are

commonly set up in open water bodies, such as water reservoirs with dams creating an enclosed reservoir only used for aquaculture. This system uses natural feed in the form of phytoplankton, adding fertilizers to stimulate phytoplankton growth (Flores-Nava, 2007). Semi-intensive systems have fish-ponds with densities of 50 fishes per m^3 (Mojica et al., 2010). Since there is water quality control and aquafeed and fertilizer inputs, the survival rate is higher than the rate in the extensive system, 85% (SAGARPA, 2013). Energy is mostly needed for water exchange of 30% refreshments per day (Cantor, 2007). Intensive systems have the highest stocking densities with 80 fishes per m^3 (Mojica et al., 2010). Even though there is a high stocking density rate, due to water quality control, the survival rate of 95% (SAGARPA, 2013) is higher than in extensive and semi-intensive systems. Intensive systems use formulated aquafeed and high-energy inputs for water refreshments of 100 to 400% per day to maintain water quality (Flores-Nava, 2007). Besides aquafeed, intensive systems use fertilizer to stimulate phytoplankton growth and create favourable water conditions for Tilapia. A common fertilizer applied in Mexico is urea at 20 to 24 kg/ha (Flores-Nava, 2007).

In Mexico, Tilapia aquaculture is widely practiced and contributes to 91% of total aquaculture production. Fig. 2 shows that the largest producers are located in Sinaloa, Nayarit, Jalisco, Michoacán, and Chiapas (SAGARPA, 2013).

In Mexico, there are freshwater quality issues. In many places, surface water is polluted (Bautista-Covarrubias et al., 2011). For aquaculture, freshwater for extensive systems comes from open surface water of suitable water quality filling a reservoir. For intensive and semi-intensive aquaculture, pond water mainly comes from groundwater, because it meets freshwater quality standards. There is a lack of official regulations that control wastewater discharge from aquaculture activities though (Hermoso, 2016). Most farms do not treat their wastewater, although some re-use wastewater for agriculture (García and Calvario, 2008).

3. Method and data

The indicators to assess the sustainability of Tilapia fillet from aquaculture in Mexico were the WF, EF and LF. The study used a chain analysis approach that includes the five production phases: (i) broodstock, (ii) breeding, (iii) fattening, (iv) processing and (v) the transportation phase. The functional unit was one ton of Tilapia fillet. The study excluded packaging, retailing, and transportation and cooking by consumers. For the WF, the study used the WF method from the Water Footprint Assessment Manual (Hoekstra et al., 2011). We considered blue, green and grey WFs. For the EF and LF, the study used the same chain analysis approach.

The number of fish that enters the fattening phase varies amongst extensive, semi-intensive and intensive systems, because mortality rates differ. Extensive systems have relatively high mortality rates and intensive systems low rates. First, the study calculated fish numbers per aquaculture production system required to reach one ton of Tilapia fillet. Table A3, A4 and A5 in the SI show the fish numbers.

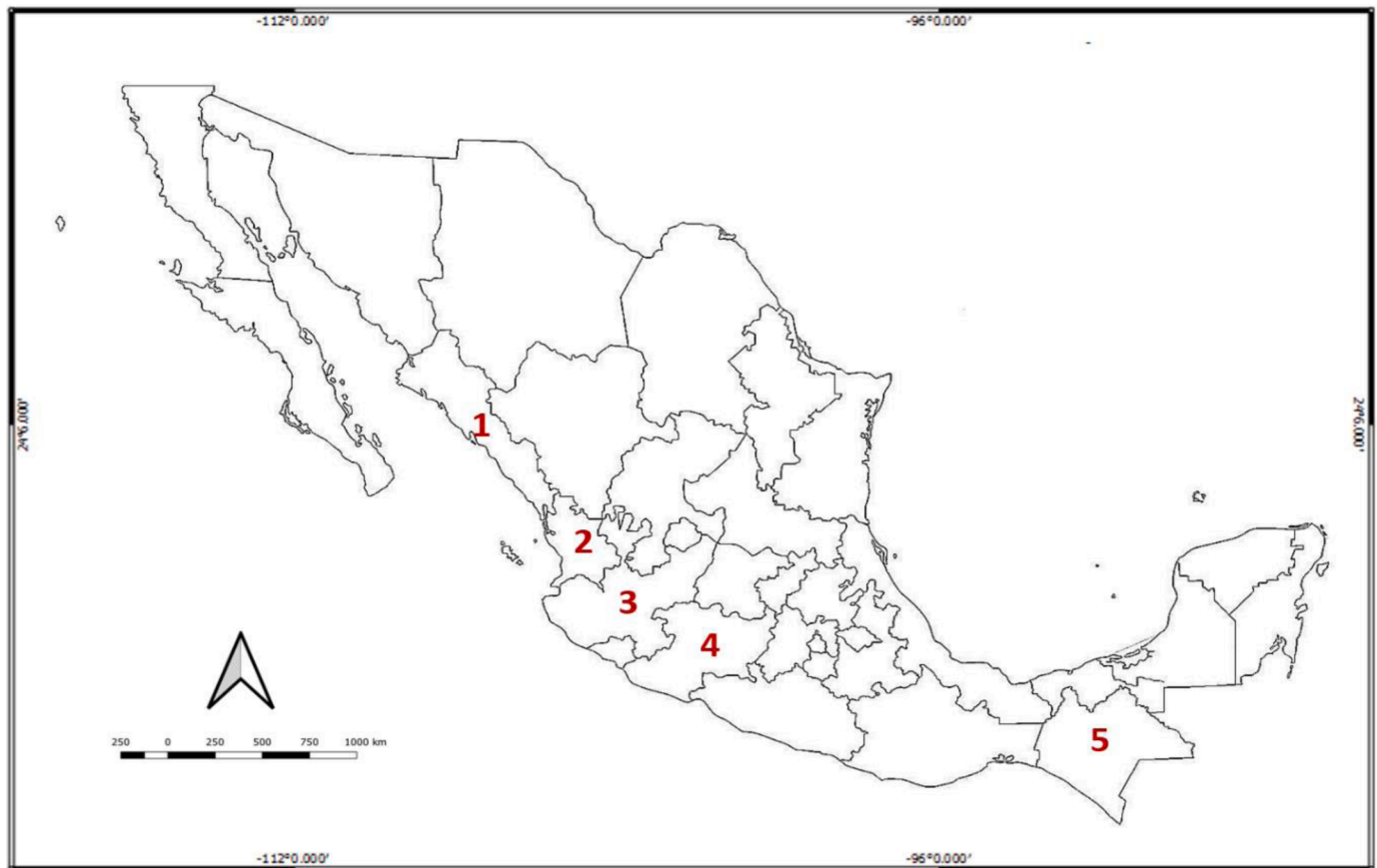


Fig. 2. States of Mexico recognized as the main producers of Tilapia in Mexico. Number 1 is Sinaloa, 2 is Nayarit, 3 is Jalisco, 4 is Michoacán, and 5 is Chiapas (Source: SAGARPA, 2013).

Fig. 3 shows the three production systems (extensive, semi-intensive and intensive) to produce Tilapia fillet and the five production phases along the chain. WFs, EFs and LFs were calculated per phase. Each production system has different inputs to operate. Aquafeed, fertilizer and hormones were the inputs considered. For aquafeed, WFs, EFs and LFs were included; for fertilizer only the EF since the fertilizer used is an inorganic fertilizer. Moreover, aquafeed, fertilizer and hormones were taken into account for the effluent load calculation since these inputs generate a grey WF. Two types of transportation were considered, regular lorries to take fingerlings to fattening farms and refrigerated lorries to transfer adult Tilapia to processing plants.

First, the study defined the system and system boundaries, i.e. the Tilapia production system in Mexico from fish eggs in the broodstock phase till Tilapia fillet after the processing phase, excluding packaging, retailing and consumer transportation and cooking. Fig. 4 shows that for the assessment of the WF, EF and LF per ton of Tilapia fillet in Mexico, the study used seven calculation steps. The steps are: 1. Estimation of direct blue WF; 2. Calculation of direct LF; 3. Calculation of aquafeed offered; 4. Allocation of aquafeed; 5. Estimation of the WF from aquafeed; 6. Calculation of EF; and finally, 7. Calculation of the direct grey WF. The steps and data sources for the calculation are described in the SI.

The blue WF includes a direct and an indirect blue WF. The direct WF relates to freshwater in the aquaculture production system itself, either in the reservoirs or ponds, as well as the freshwater used for transportation. The indirect blue WF relates to freshwater in agriculture to produce crops for aquafeed.

Finally, the study compared results for Tilapia with WFs, EFs and LFs for beef, poultry and pork meat produced in industrial systems. We derived data on WFs from Mekonnen and Hoekstra (2010b), on EFs from Williams et al. (2006), De Vries and De Boer (2010) and from Kramer and Moll (1995). Data on LFs were taken from Gerbens-Leenes et al.

(2002). Next, we expressed footprints per unit of protein and nutritional energy based on protein contents and energy values from the Dutch nutrition council (Voorlichtingsbureau voor de voeding, 1986). For beef (average fat content) and poultry we took the value of 200 gs of protein/kg, 1970 kcal/kg for beef and 1700 kcal/kg for poultry; for pork (average fat content) 160 gs of protein/kg and 2800 kcal/kg. For Tilapia we took the value for fresh fish with low fat content of 180 gs of protein/kg and 760 kcal/kg.

4. Results

Table 1 shows the WF, EF, and LF of Tilapia fillet for three production systems per ton of Tilapia fillet. Results show that the footprints vary amongst the three production systems.

4.1. Water footprint

Fig. 5 shows blue, green and grey WFs (m^3/ton) of Tilapia fillet for the extensive, semi-intensive and intensive production system in Mexico.

Tilapia production carried out in an intensive aquaculture system has blue WFs larger than WFs of extensive and semi-intensive systems. This is partly due to the dependency of intensive systems on high refreshment rates of 250% of the pond water per day, in the semi-intensive system rates are only 30%. The extensive system does not refresh at all, and blue WFs are caused by evaporation. Other factors are the survival rate that is smallest in the extensive and largest in the intensive system and the stocking density that is largest in the intensive system. As a result of the factors, the blue WF of the intensive system is 14 times the blue WF of the extensive and 4.5 times the blue WF of the semi-intensive system. The extensive system has the smallest green WF ($5 m^3/ton$) due to the

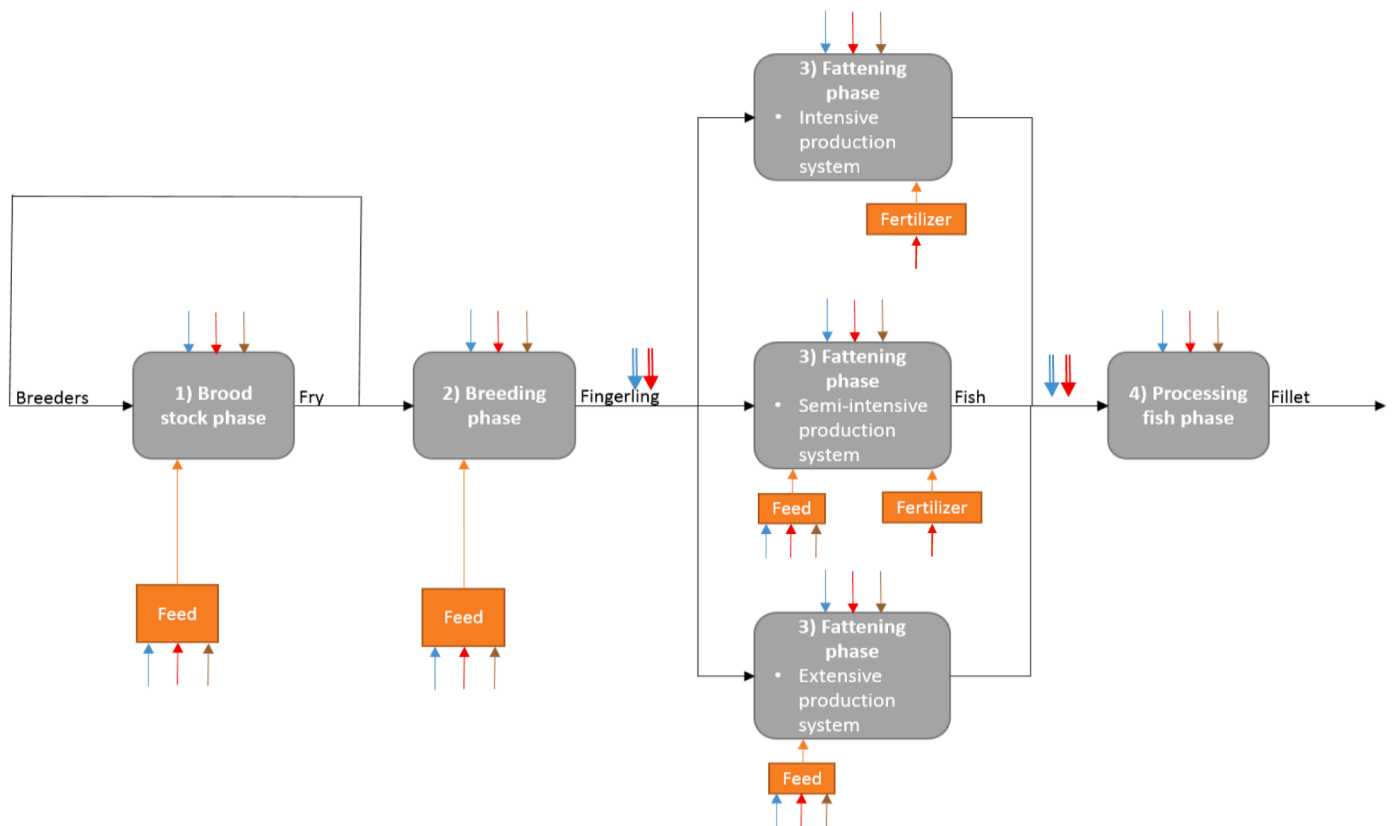


Fig. 3. Three production systems (extensive, semi-intensive and intensive) to produce Tilapia fillet and the five production phases along the production chain. The blue colour refers to the water footprint (m³), the red colour to the energy footprint (MJ) and the brown colour to the land footprint (m²). Single lines are related to inputs in each phase and double lines refer to transportation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

lack of aquafeed use in the fattening phase. The green WF is generated in the broodstock and breeding phases when aquafeed is required to feed breeders and fingerlings. The intensive system has a green WF of 7831 m³/ton, the semi-intensive system a WF of 7827 m³/ton and both systems have a grey WF of 1873 m³. The grey WF is smallest for the extensive system. The supporting information (Tables A6, A7) gives direct and indirect inputs in each phase per production system.

Fig. 6 shows the WFs of the intensive system per phase. The SI shows the results for the semi-intensive (Figure A1) and extensive system (Figure A4).

In the intensive system, the fattening phase, the longest phase in the production chain, has the largest WFs. The blue WF dominates with 12,740 m³/ton, determined by daily water refreshments and water used for the transportation of the fingerlings, while, 134 m³/ton is related to the indirect WF of crops needed for aquafeed. The green WF is also largest in the fattening phase due to the aquafeed offered with a requirement of 2591 m³/ton to grow feed crops. The fattening phase also generates the largest grey WF, 1177 m³/ton of which 1014 m³/ton is due to large amounts of aquafeed and refreshment rates. The indirect grey WF to produce aquafeed in agriculture is small, 163 m³/ton.

The second phase, after fattening, with relatively large blue and grey WFs is the processing phase. There is no need of aquafeed, and thus there is no indirect blue, green and grey WF, but large amounts of freshwater are needed to process the fillet, while at the same time water pollution takes place.

4.2. Energy footprint

Fig. 7 shows the EF of one ton of Tilapia fillet per production system in Mexico.

The intensive system requires far more energy than extensive and

semi-intensive systems, 22,200 MJ/ton. In general, electricity has the largest contribution to the total EF rather than fuel. Figure A2 and A5 in the SI give the contribution of electricity and fuel for the semi-intensive and extensive system. The EF in the extensive system is mainly caused by fuel for transportation and harvesting and for the breeding and processing phase, which is the same as for the semi-intensive and intensive system. The large EFs of the semi-intensive and intensive systems are caused by larger fuel use in agriculture where aquafeed is produced and large electricity use in aquaculture due to pumping and aeration of the ponds, where especially intensive systems require much electricity, two times more than in the semi-intensive system, mainly due to more intensive aeration and pumping.

Figure A7 shows the EF of intensive aquaculture per phase along the aquaculture production chain in Mexico. Energy for transport is included in the phase where the fish is transported to. Intensive fattening farms have the largest energy contribution of 18,023 MJ/ton to the total energy use of 22,200 MJ/ton. Energy for fuel use in the fattening phase is mainly determined by feed production rather than by fuels for transportation to the fattening farms. Total electricity use in the fattening phase is mostly needed (90%) for aeration and water pumping.

4.3. Land footprint

Fig. 8 shows the LF of one ton of Tilapia fillet per production system in Mexico. The LF includes direct land use for reservoirs and ponds and indirect land use related to the aquafeed (See also Figure A3 and A6 in the SI).

Semi-intensive and intensive production systems, which are feed-dependant systems, have similar LFs, 10,723 m²/ton and 10,711 m²/ton respectively. Extensive systems have smaller LFs, because no feed is applied and the total LF is mainly determined by the facilities of the

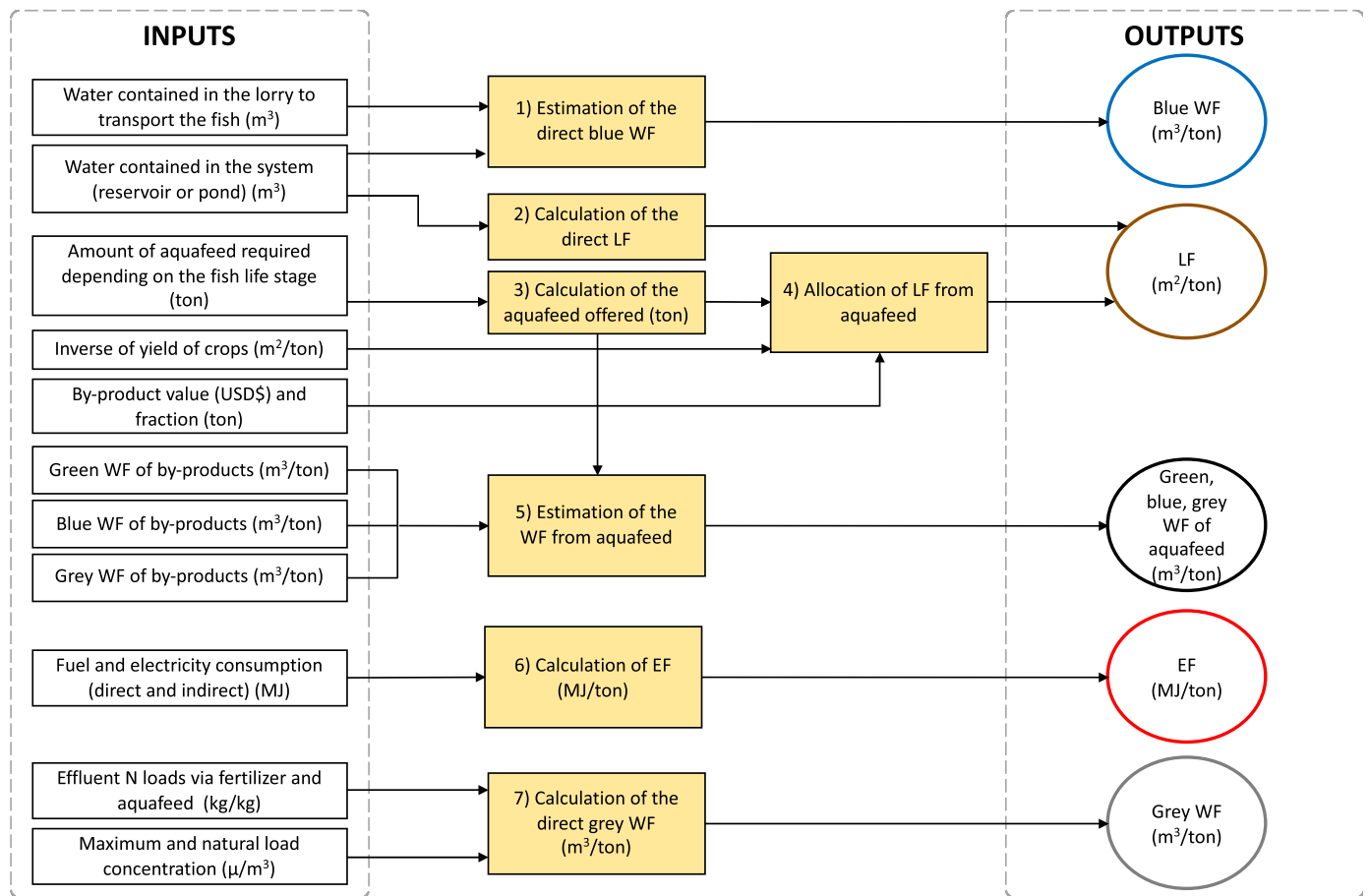


Fig. 4. Flow chart with seven calculation steps for the assessment of the WF, EF and LF of one ton of Tilapia filet in Mexico.

Table 1

Water, energy and land footprint of one ton of Tilapia filet produced in the extensive, semi-intensive and intensive production system in Mexico.

	Production system		
	Extensive	Semi-intensive	Intensive
Blue water footprint (m ³ /ton)	927	2909	13,027
Green water footprint (m ³ /ton)	5	7827	7831
Grey water footprint (m ³ /ton)	398	1873	1873
Energy footprint (MJ/ton)	4241	14,451	22,200
Land footprint (m ² /ton)	1193	10,723	10,711

reservoir. The LF of the extensive system is two times larger than the direct LF of the semi-intensive and intensive system. For the semi-intensive and intensive system, the LF of the feed dominates the total LF and contributes 95%. Figure A8 shows the LF per phase of the intensive system along the aquaculture production chain in Mexico. The largest LF is caused by the fattening phase related to aquafeed of 10,194 m²/ton. The LF of the facilities contribute only 25 m².

4.4. Comparison tilapia and meat

The study compared the WF, EF and LF of Tilapia fillet produced in the intensive system with the footprint of the most common meat types consumed, beef, poultry and pork produced in an industrial system (Table 2 and 3). Table 3 shows the blue, green and grey WF of different animal foods produced in an industrial or intensive production system, expressed in m³/ton, l/kcal nutritional energy and in l/g protein.

The production of Tilapia fillet from a cradle-to-processing phase perspective not only consumes more blue water than the other animal

foods, 13,027 l/kg, but also generates the largest grey WF, 1873 l/kg. The green WF of Tilapia fillet is comparable to the green WF of beef, 7831 l/kg and 8849 l/kg respectively, but larger than green WFs of poultry and pork. If WFs are expressed per unit of protein content, Tilapia fillet has the largest total WF compared to meat of 126 litre per gram of protein, almost ten times as much as the meat type with the smallest WF, poultry. The WF of Tilapia fillet protein is two times larger than the WF of beef protein, and four times more than pork. If WFs are expressed per unit of nutritional energy, differences are even larger.

Table 3 shows the EF and LF of different animal proteins in an intensive system expressed in m²/kg, m²/kcal nutritional energy and in m²/gram protein.

Table 3 shows the large ranges that exist in literature of the EF and LF of beef, poultry and pork, depending on the production system where meat is produced. The EF (MJ/kg) of Tilapia is smaller than the average value of meat. Expressed per unit of protein and nutritional energy, it falls in the range of the values for beef, poultry and pork. The LF of Tilapia (m²/kg) is larger than the LF of poultry but falls in the range of beef and pork. Expressed per unit of nutritional energy it falls in the range of the value for beef but is also larger than the LF of poultry and pork. This has to do with the relatively small nutritional value of Tilapia of 76 kcal/kg, much smaller than pork (200 kcal/kg), beef (197 kcal/kg) or poultry (170 kcal/kg).

5. Discussion

5.1. Comparisons with other studies

The comparison of beef, pork and poultry footprints with Tilapia footprints does not favour a specific animal food. This has to do with

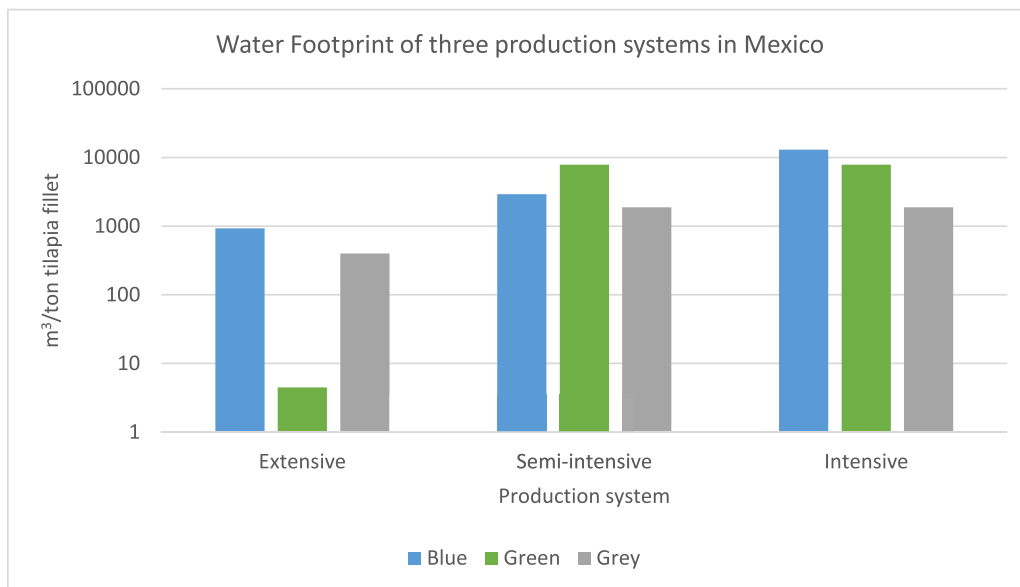


Fig. 5. The blue, green and grey water footprint of one ton of Tilapia fillet for the extensive, semi-intensive and intensive production system in Mexico (logarithmic scale). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

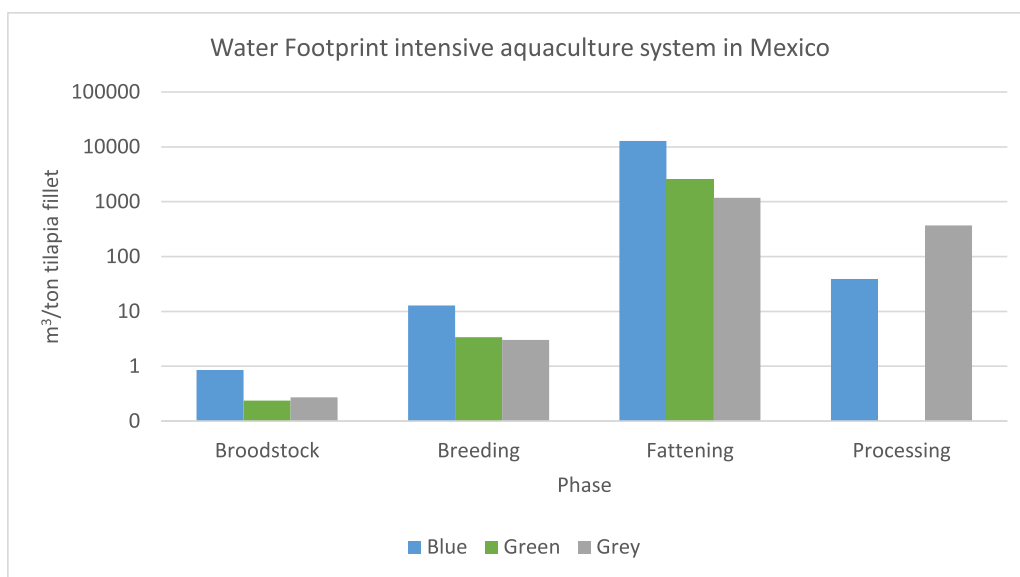


Fig. 6. The blue, green and grey water footprint for the broodstock, breeding, fattening and processing phase of intensive aquaculture in Mexico (logarithmic scale). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

large WF, EF and LF ranges of meat. For example, EFs of beef range between 30 MJ/kg (Williams et al., 2006) to 110 MJ/kg (Kramer and Moll 1995), a difference of a factor of almost four. Another study reports a range between 34 and 52 MJ/kg (De Vries and De Boer, 2010). The study of Kramer and Moll was done twenty-five years ago, while the study of De Vries and De Boer is ten years old. Possibly meat production systems have become more efficient, although a study of EFs related to meat processing showed increasing meat EFs between 1991 and 2006 of 14 to 48%. That would mean that the EF of the oldest study would be smaller than more recent values, which is not the case. Another issue making it difficult to compare footprints is the fact that databases are not publicly available. To make a good comparison between meat and fish production systems, more publicly available research is needed.

If we compare WF results from this study with results of Pahlow et al. (2015), who assessed green, blue and grey WFs of balanced aquafeed production per unit of fish, our results give larger WFs. For Nile Tilapia,

Pahlow included two formulated diets. The first diet showed a green WF of 1998 m³/ton, a blue WF of 94 m³/ton and a grey WF of 121 m³/ton and the second one a green WF of 2049 m³/ton, a blue of 155 m³/ton and a grey WF of 107 m³/ton. Taking a fillet yield of only 33% into account, our results for aquafeed are similar to results of Pahlow et al.. However, we also included blue and grey WFs related to fish-ponds, so that our WFs are larger. It is possible, though, to decrease blue and grey WFs if proper water recycling and wastewater treatment is introduced, probably increasing EFs.

5.2. Data uncertainty and assumptions

Although we had detailed information on aquaculture in Mexico, assumptions had to be made considering most common practices based on literature and fieldwork experience. In aquaculture, there is no general standard for operations and depending on the aquaculture

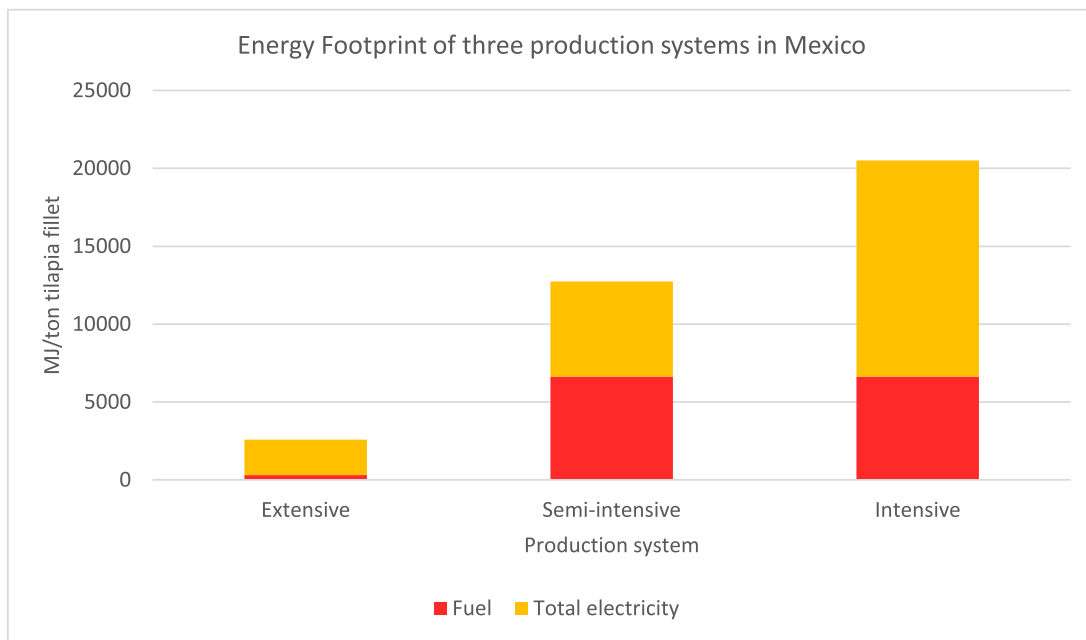


Fig. 7. The energy footprint of one ton of Tilapia fillet for the extensive, semi-intensive and intensive production system in Mexico (logarithmic scale).

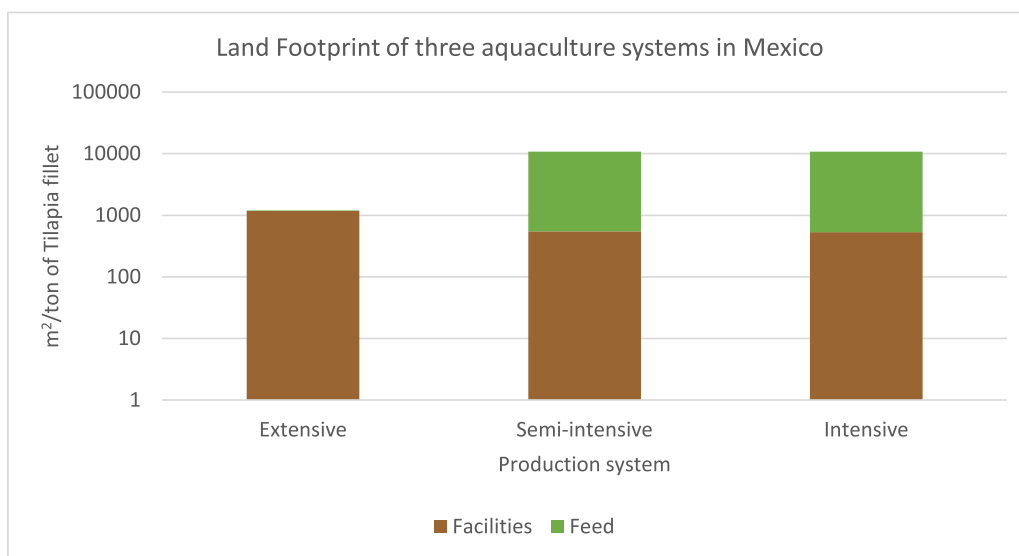


Fig. 8. The land footprint of one ton of Tilapia fillet for the extensive, semi-intensive and intensive aquaculture production system in Mexico (logarithmic scale).

Table 2
Global average water footprint of beef, poultry and pork produced in an industrial system, and Tilapia produced in an intensive system in Mexico.

Animal food	Water Footprint (l/kg)					
	Blue WF	Green WF	Grey WF	Total WF	WF protein (l/g)	WF nutritional energy (l/kcal)
Beef ^a	683	8849	712	10,244	51	52
Poultry ^a	210	2337	325	2872	14	17
Pork ^a	487	4050	687	5224	33	19
Tilapia ^b	13,027	7831	1873	22,731	126	299

^a Global average water footprint of beef, chicken and pork meat. Source: Mekonnen and Hoekstra (2010b).

^b Tilapia produced in an intensive system.

company and/or region, different practices are carried out. The most important variables are refreshment rates, transportation and aquafeed composition.

For semi-intensive and intensive systems, refreshment rates, especially in the fattening phase, determine blue WFs. Semi-intensive system refreshment rates in the fattening phase are 50%; for intensive systems, however, rates vary from 100 to 400% (Flores-Nava, 2007). For the WF assessment for intensive systems, we took the average value and arrived at a blue WF for the fattening phase of 12,000 m³/ton. However, this value might be smaller or larger, between 5000 and 20,000 m³/ton, so that also the total blue WF of 22,733 m³/ton might range between 15,732 and 30,733 m³/ton.

The second variable important for EFs is transportation. We assumed an average distance of 100 km a lorry travels to its destination. Nevertheless, when changing distances within a range of +/- 100%, the trend remains, because transportation has relatively small energy

Table 3

Energy (EF) and land footprint (LF) of different animal proteins in an intensive system.

Source protein	EF (MJ/kg)	LF (m ² /kg)	EF protein (MJ/gram)	LF protein (m ² /gram)	EF nutritional energy (MJ/kcal)	LF nutritional energy (m ² /kcal)
Beef	30 ^a – 110 ^b	3,7 ^c – 49,0 ^d	0,15 – 0,55	0,14 – 0,25	0,15 – 0,56	0,14 – 0,25
Poultry	12 ^a – 86 ^b	3,9 ^e – 9,0 ^f	0,06 – 0,43	0,04 – 0,05	0,07 – 0,56	0,05 – 0,06
Pork	17 ^a – 86 ^b	5,2 ^g – 12,1 ^d	0,10 – 0,54	0,06 – 0,08	0,06 – 0,31	0,03 – 0,04
Tilapia	22	10,7	0,12	0,05	0,25	0,13

^a Source: Williams et al. (2006).

^b Source: Kramer and Moll (1995).

^c Land footprint for beef from milking cows. Source: Gerbens-Leenes et al. (2002).

^d Source: De Vries and De Boer (2010).

^e Land footprint of poultry from chickens that have residues from the food industry in their feed. Source: Gerbens-Leenes et al. (2002).

^f Source: Ibidhi et al. (2017).

^g Land footprint of pork from pigs that have residues from the food industry in their feed. Source: Gerbens-Leenes et al. (2002).

Source: Williams et al. (2006). Source: Kramer and Moll (1995). Source: De Vries and De Boer (2010). Source: Ibidhi et al. (2017).

requirements compared to energy needed in the whole production chain.

The third variable is aquafeed. Aquaculture depends on ingredient availability for aquafeed. In general, producers use what is available on the market for a balanced feed. Aquafeed has a large impact on WFs, EFs and LFs of Tilapia fillet, depending on feed ingredients. Some important parameters on aquafeed were drawn from the literature of several decades ago (e.g. feed composition for the Tilapia brooder, breeding and fattening phase were taken from New, 1988). Since aquaculture technologies and patterns are always in the process of change and development, the use of these parameters may have influenced the estimations. We assumed that all crops are grown in Mexico. If crops are imported, the EF increases because more energy is needed for transportation. WFs and LFs also change, depending on the water and agricultural characteristics in the countries of origin. We assumed that fishmeal in the feed originated from tuna waste due to its large availability in Mexico. However, tuna fishmeal availability is limited, so that it is impossible to expand tuna fishmeal production if more aquafeed is needed. Moreover, tuna is considered an endangered and overexploited fish species. Other fish species might be considered for fishmeal. Tuna is a saltwater fish without a blue WF. However, if freshwater fish with a blue WF is used for fishmeal, the Tilapia fillet WF is also influenced and would increase. Another option is to replace fishmeal by crop ingredients, also increasing WFs and LFs. In this research, feed with a fishmeal protein source (tuna) was taken into consideration since most of the Mexican farmers use this feed type. It is possible to replace fishmeal by crop ingredients such as soybeans (Nguyen et al., 2009). If tuna fishmeal is replaced by soybean, the LF increases by 0.001% and the green WF only 0.0008%.

Table 4

Water, energy and land footprint of aquaculture in extensive, semi-intensive and intensive systems to supply Mexico with 2 kg Tilapia fillet per capita per year.

	Extensive	Semi-intensive	Intensive
Blue WF (Gm ³)	0.23	0.75	3.36
Green WF (Gm ³)	0.0013	2.02	2.20
Grey WF (Gm ³)	0.103	0.483	0.483
EF (TJ)	1094	3728	5727
LF (km ²)	307	2766	2763

5.3. Improvements in the system

To reduce the blue WF of Tilapia fillet, it is important to concentrate on the phase with the highest WF, the fattening phase and for the grey WF, the fattening and processing phase. New technologies, such as the biofloc technology (BFT), might support future aquaculture farms in Mexico to decrease water pollution. In general, the BFT is a system recognized for water and feed recycling, in which fish waste is transformed in feed by adding bacteria and flocculation in the system (Luo et al., 2014). However, this technology increases the EF since it requires aerating and mixing the water constantly.

We expected that the phase with the highest water pollution would be the breeding phase due to hormone use. However, according to previous research related to hormone use in aquaculture and its contribution to wastewater, the amount of testosterone used for sex reversal is very small (Megbowon and Mojekwu, 2013), which matches with the outcome in this research. For grey WF reduction it is more important to consider inputs like fertilizer and/or aquafeed. The WF, EF and LF of Tilapia fillet also relates indirectly to aquafeed production due to its crop components in the formula. It is important to optimize feed production to decrease footprints and at the same time meet fish nutrition requirements as recommended by Pahlow et al. (2015).

5.4. Scaling up aquaculture in Mexico

Most fish produced in aquaculture in Mexico comes from inland fisheries, or extensive systems that have encountered decreasing production (FAO, 2003). It is relevant to know the limitations of a production system in case the functional unit is put into context and scaled up. In Mexico, the population of 129 million inhabitants (World Bank, 2017) has an average Tilapia fillet consumption of 2 kg per capita per year (SENASICA, 2018), requiring an annual production of 258 10³ tons of Tilapia fillet. If all production would take place in semi-intensive or intensive systems, WF, EF, and LF increase. Table 4 shows the consequences of scaling up in order to supply Mexican inhabitants with 2 kg of Tilapia fillet per year on WFs, LFs and EFs.

Producing Tilapia fillet in an intensive system generates the largest blue and green WF, EF, and LF, requiring 3.4 10⁹ m³ of freshwater (surface or groundwater), equivalent to the water capacity of the 19 MW-Alvaro Obregon dam in Sonora, Mexico. Water pollution is also large, 4.8 10⁸ m³ of freshwater is required to assimilate pollutants. Aquafeed has a large influence on the green WF, 2.2 10⁹ m³ of green water (rain) is needed for crops.

The EF of 2 kg of Tilapia per person per year in an intensive system would demand 5727 TJ, or 0.4% of total electricity generated in 2017 in Mexico (SENER, 2018), five times larger than the EF of production in an extensive system. In terms of land, in spite of the fact that intensive systems have relatively small direct LFs, the indirect LF related to aquafeed using crops is large. The LF of the intensive system is 2763 km², nine times the LF of the extensive system or two times the Mexico City area.

It is a challenge to scale up aquaculture in Mexico and produce all Tilapia in intensive systems. Freshwater and land availability, water pollution, and energy required are the main limitations. Today, Tilapia demand is 2 kg per capita per year, which is small compared to total fish consumption of 11 kg per capita per year (FAO, 2017). A shift towards more fish from aquaculture systems would increase footprints even more. The total WF of Mexico is 140.16 Gm³/yr, so that the consumption of only 2 kg of Tilapia from intensive systems would represent 4% of the total WF. If all fish would be produced in intensive systems, footprints would even be larger.

6. Conclusions

This research assessed WFs, EFs and LFs of Tilapia fillet in three aquaculture production systems in Mexico and compared results with

previous research into footprints of beef, poultry and pork. Tilapia WF are relatively large, especially for intensive production systems. Blue WF for the intensive system are 13,000 l/kg, for the extensive system 927 l/kg and for the semi-intensive system 2900 l/kg. This is large compared to other animal foods. The average global blue WF of beef is about 700 l/kg, of pork 500 l/kg and of poultry 200 l/kg. Green WF of Tilapia produced in semi-intensive and intensive systems are also relatively large, 7800 l/kg, while for extensive systems not adding aquafeed, green WF are negligible. However, extensive system production is limited, because it depends on fish availability in natural waters. Green WF of fish from semi-intensive and intensive systems are comparable to green WF of beef, but two times larger than WF of pork and four times larger than green WF of poultry. Especially grey WF of Tilapia are large compared to meat. Semi-intensive and intensive systems have grey WF of 1900 l/kg, substantially larger than grey WF of beef, poultry or pork.

Tilapia EFs are largest for intensive systems (22 MJ/kg), followed by semi-intensive (14 MJ/kg) and extensive systems (4 MJ/kg). EFs for meat show large differences in literature, ranging between 12 MJ/kg for poultry to 110 MJ/kg for beef. Even if Tilapia is produced in an intensive system, EFs are smaller than the average EF of meat.

Tilapia LF are relatively large for semi-intensive and intensive systems, 10.7 m²/kg, for the extensive system the LF is 1 m²/kg. LFs of semi-intensive and intensive systems are related to crop use in aquafeed. Beef, poultry and pork production are also based on crop use. Tilapia LFs fall in the range of LFs of beef and pork but are slightly larger than LFs of poultry. When Tilapia footprints are expressed per unit of nutritional energy, footprints increase compared to meat footprints, because nutritional energy of Tilapia is relatively small.

When the five phases along the Tilapia production chain are analysed separately, the fattening phase contributes most to the footprints. In the fattening phase of semi-intensive and intensive systems, total WF are determined by water refreshments and aquafeed use. In semi-intensive and intensive systems, EFs are mainly determined by water pumping and aeration. Total LFs are determined by crops in aquafeed.

From a FEW nexus perspective, it is not more sustainable to replace terrestrial animal protein with Tilapia fillet protein. Tilapia fillet not only requires more freshwater than beef, pork and poultry, but also pollutes larger amounts of water than terrestrial animals due to constant effluent loads coming from the ponds. From a freshwater perspective, it is more sustainable and efficient to obtain animal protein from terrestrial animal sources. For energy and land, Tilapia is not the better choice, because footprints are comparable. If aquaculture in Mexico would be scaled up, so that all presently available Tilapia would be produced in intensive systems, the availability of sufficient freshwater and water pollution would be the main challenges. To reduce the Tilapia WF, it is important to focus on decreasing water exchange rates, thus a reduction of blue WF, also reducing energy use related to water pumping. LF reduction is possible with new aquafeed formulas with smaller LFs are used. Future aquaculture needs to take footprints into account and develop new technologies to make the system more efficient.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.resconrec.2020.105224](https://doi.org/10.1016/j.resconrec.2020.105224).

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