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Increasing pressure on freshwater resources due to terrestrial feed ingredients for aquaculture production

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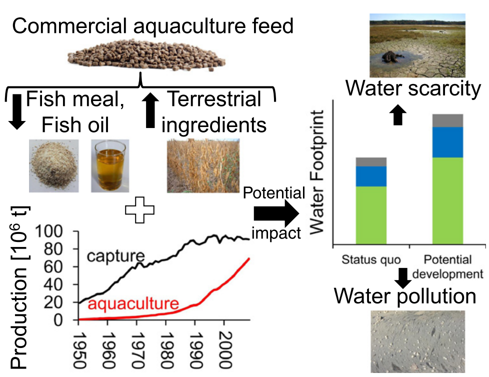
HIGHLIGHTS

- The commercial feed-related water footprint of aquaculture has been determined.
- Terrestrial alternatives for fish meal and fish oil increase the water footprint.
- Economic water productivity may be reduced due to alternative feed formulations.
- Future growth of the aquaculture sector increases pressure on freshwater resources.

GRAPHICAL ABSTRACT



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ABSTRACT

As aquaculture becomes more important for feeding the growing world population, so too do the required natural resources needed to produce aquaculture feed. While there is potential to replace fish meal and fish oil with terrestrial feed ingredients, it is important to understand both the positive and negative implications of such a development. The use of feed with a large proportion of terrestrial feed may reduce the pressure on fisheries to provide feed for fish, but at the same time it may significantly increase the pressure on freshwater resources, due to water consumption and pollution in crop production for aquafeed. Here the green, blue and gray water footprint of cultured fish and crustaceans related to the production of commercial feed for the year 2008 has been determined for the major farmed species, representing 88% of total fed production. The green, blue and gray production-weighted average feed water footprints of fish and crustaceans fed commercial aquafeed are estimated at 1629 m^3/t, 179 m^3/t and 166 m^3/t, respectively. The estimated global total water footprint of commercial aquafeed was 31–35 km^3 in 2008. The top five contributors to the total water footprint of commercial feed are Nile tilapia, Grass carp, Whiteleg shrimp, Common carp and Atlantic salmon, which together have a water footprint of 18.2 km^3. An analysis of alternative diets revealed that the replacement of fish meal and fish oil with terrestrial feed ingredients may further increase pressure on freshwater resources. At the same time economic consumptive water productivity may be reduced, especially for carnivorous species. The results of the present study show that, for the aquaculture sector to grow sustainably, freshwater consumption and pollution due to aquafeed need to be taken into account.

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1. Introduction

Fish and shellfish are an important resource for global human food consumption. Fish consumption grew from 95.8 million tonnes globally in 2000 (15.7 kg per capita) to 115.1 million tonnes (17.1 kg per capita) in 2008 (FAO, 2010). Yet for marine capture fisheries the FAO (2010) states that the increasing trend in the percentage of overexploited, depleted and recovering stocks and the decreasing trend in underexploited and moderately exploited stocks give cause for concern. Management actions such as the implementation of catch quotas (e.g. FAO, 2012a; EU, 2014), have achieved measurable reductions in exploitation rates in some regions, but a significant fraction of stocks will remain collapsed unless there are further reductions in exploitation rates (Worm et al., 2009). Furthermore, the use of wild fish in the form of fish meal and fish oil as inputs for aquaculture feeds, relies on marine species that are renewable, but often overexploited for human use (Klinger and Naylor, 2012). In this context Cao et al. (2015) state that a key question for the future of the oceans is how China – being the main global aquaculture producer – develops its aquaculture sector and whether such development can relieve pressure on wild fisheries.

With the aquaculture sector growing steadily, the percentage of non-fed species in world production has declined from about 50% in 1980 to about 33% in 2010, strongly dominated by changing practices in Asia (FAO, 2012a). The external supply of nutrients and thus feed ingredients will have to keep increasing to maintain the growth of production in the sector, which averaged 6% annually between 2000 and 2008 (FAO, 2010, 2014a). In 2008 about 31.5 million tonnes of farmed fish and crustaceans were dependent on external nutrient inputs in the form of either fresh feeds, farm-made feeds or commercially manufactured feeds (Tacon et al., 2011), that is 46% of total aquaculture production of fish, crustaceans, molluscs and aquatic plants.

Similar to aquaculture production as a whole, the production of fed species is dominated by a few countries, with China having an exceptional role. In 2008 the top fifteen countries account for 28.8 million tonnes, i.e. 91% of total production of fed species globally, with China having a share of 50% of the total (Fig. 1).

There will be growing competition over feed ingredients, such as soybean, corn or wheat, between aquaculture and livestock feed industries in the future (Troell et al., 2014b). The same holds for the bioenergy industry, which has a growing demand for feedstocks. Since both crop by-products and food-quality products are used to produce aquaculture feed, feeding a growing world population will also play an increasingly important role in the decisions to be taken for aquaculture development. While the overall ratio of wild fish input to farmed fish output has been decreasing steadily from 1.04 (kg/kg) in 1995 to 0.63 (kg/kg) in 2007, many production systems still have a ratio that is well over 2 (kg/kg) (Naylor et al., 2009; Tacon and Metian, 2008). The decrease is in part due to the increasing volume of omnivorous fish farmed, thus reflecting a partial shift from the use of aquatic to terrestrial feed ingredients for aquaculture (Powell, 2003). This development raises questions about the sustainability of the various alternatives for aquatic feed ingredients. Fish meal and fish oil are limited and fish oil may in the future be a scarcer commodity than fish meal for use in aquafeeds (Boyd et al., 2007). Furthermore, Tacon et al. (2009, 2011) state that, due to the significant proportion of non-carnivorous species in aquaculture production, it can be assumed that the sustainability of the aquaculture sector will be linked to the sustained supply, market availability and cost of terrestrial animal and plant proteins, oils and carbohydrate sources for aquafeeds.

Naylor et al. (2009) summarize the following terrestrial alternatives to forage fish: terrestrial plant-based proteins (e.g. barley, canola, corn, cottonseed, peas/lupins, soybeans, and wheat); terrestrial plant-based lipids (e.g. sunflower, linseed, canola, rapeseed, soybean, olive, flax and palm oils); single-cell protein and oil (e.g. algae); and rendered terrestrial animal products (e.g. meat and bone meal, feather meal, blood meal, and poultry by-product meal). The suitability of reducing or excluding forage fish in feed for aquaculture production is still the subject of intensive research. In particular for commercial compound aquafeeds, the optimum dietary protein, lipid and carbohydrate levels are investigated in scientific studies on aquaculture nutrition (e.g. Carter and Hauler, 2000; Kaushik et al., 2004; Mohanta et al., 2006; Gatlin et al., 2007; Boissy et al., 2011). Even if these levels have been identified, the inclusion level of feed ingredients can vary, as different feedstuffs can fulfill the intended dietary requirements. In a nutshell, the above mentioned research on aquaculture nutrition shows that aquaculture systems that rely on fish meal, fish oil, or whole fish can use (to varying degrees) terrestrial plant- and animal-based proteins and lipids as substitutes. However, other environmental issues arise. The production of terrestrial feed ingredients can be associated with high nutrient and chemical input use and loss, land use intensification, high energy-dependency ratios, and greenhouse gas emissions (see for example Alexandratos and Bruinsma, 2012; Klinger and Naylor, 2012; Krausmann et al., 2013). Sustainable growth of the aquaculture sector is clearly a multifaceted challenge.

A topic that has to date received less attention is the impact of aquaculture production on freshwater resources. Gephart et al. (2014) allude to freshwater savings through human consumption of marine fish

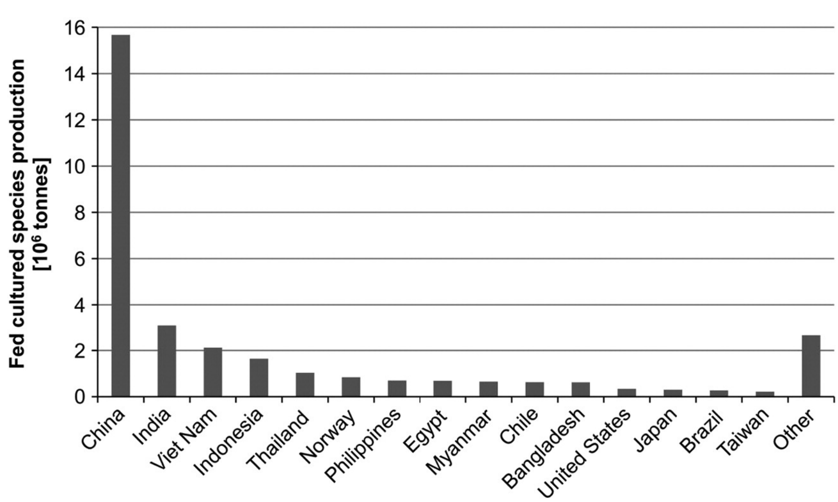

Fig. 1. Fed fish and crustacean aquaculture production in the year 2008. The top 15 countries are shown, the remaining production is summarized as 'Other' (own elaboration based on FAO, 2012b).

protein instead of terrestrial protein. In that work it was assumed that the water footprint of marine capture and marine aquaculture fisheries is near-zero and it was estimated that the water footprint of global food production would increase by 4.6% if current marine protein would be replaced by terrestrial protein – thereby neglecting the feed-related water footprint of marine aquaculture. Troell et al. (2014a) complement the work by Gephart et al. and determine the water footprint of marine aquaculture feed (~8 km^3/year). Naylor et al. (2000) state that "increasing scarcity of freshwater resources could severely limit the farming of herbivorous fish such as carps and tilapia. With a more binding constraint on freshwater systems, there is even more pressure to develop marine aquaculture systems that are ecologically and socially sound".

Direct on site water use in aquaculture systems has been investigated in the studies by Boyd (2005) and Boyd et al. (2007) using a 'water use index', defined as water use divided by production. Going one step further, Verdegem et al. (2006) and Verdegem and Bosma (2009) consider both direct (system associated) and indirect (feed associated) water use of pond aquaculture. Verdegem et al. (2006) identify the reduction of grain utilization in aquafeeds as a research priority. Furthermore, Verdegem et al. (2006) state that feed ingredients requiring little water in the production process should be chosen in order to reduce water use in present aquaculture. In a Life Cycle Assessment comparison of common aquaculture systems to beef, pork and broiler chicken production, Stonerook (2010) finds that the environmental impact of the systems studied could be attributed largely to agricultural production of the feed.

In this paper we address the relationship between aquaculture production and freshwater appropriation. We estimate the commercial feed-related water consumption and pollution of fish and crustacean production in aquaculture, using the water footprint (WF) as an indicator. Water footprint accounting quantifies and locates the water footprint of a process, product, producer or consumer or quantifies in space and time the water footprint in a specified geographic area, thereby uncovering the hidden link between consumption and water use. The water footprint is composed of three colors: green, blue and gray. The green water footprint refers to consumption of rainwater, the blue water footprint refers to consumption of surface- and groundwater and the gray water footprint is the volume of freshwater that is required to assimilate the load of pollutants based on natural background concentrations and existing ambient water quality standards (Hoekstra et al., 2011). Furthermore the economic green and blue water productivity of the species studied is evaluated. Lastly we assess feed compositions that aim at reducing the use of fish meal and fish oil and discuss potential impacts on freshwater resources.

2. Materials and methods

2.1. Methods

The amount of commercial aquafeed used per species is determined as

$$Feed[s] = FCR[s] \times P[s] \times Perc_{feed}[s] \quad (1)$$

where $Feed[s]$ is the total amount of commercial feed consumed by species s in ton/year, $FCR[s]$ is the feed conversion ratio (kg of feed/kg of product) of this species, $P[s]$ is the production (ton/year) of species s and $Perc_{feed}[s]$ is the fraction of commercial feed of total feed, where total feed includes fresh, farm-made and commercial feed types.

The amount of specific feed ingredient used per species is determined as:

$$Feedi[s,p] = f[s,p] \times Feed[s] \quad (2)$$

where $Feedi[s,p]$ is the annual amount of feed ingredient p in ton/year fed to species s, and $f[s,p]$ is the fraction of feed ingredient p in the composition of the commercial feed applied to species s. The amount of feed ingredient was distributed over the different life stages until harvest according to the feeding strategy for the individual life stages of a species. If this information was unknown, then it was assumed that the same feed composition was used in all life stages.

We employ the water footprint concept by Hoekstra et al. (2011). The water footprint related to commercial feed WF_{feed} (m^3/year) is determined for each species s as:

$$WF_{feed}[s] = \sum_{p=1}^{n} Feedi[s,p] \times WF_i[p] \quad (3)$$

where $WF_i[p]$ is the green, blue and gray water footprint of feed ingredient p in m^3/ton, and n the number of feed ingredients. Water use to prepare the feed is considered negligible.

The water footprint of production per species is computed by dividing the water footprint of the feed $WF_{feed}[s]$ by the annual production of that species $P[s]$ based on commercial feed.

The economic consumptive (green + blue) water productivity [US\$/m^3] is determined by dividing the unit value [US\$/t] by the sum of the green and blue water footprint [m^3/t].

2.2. Materials

2.2.1. Fed species production

The FAO estimates that worldwide about 600 aquatic food fish and algae species are farmed in aquaculture, of which about 330 are finfishes and 60 crustaceans (FAO, 2012a). In this study the 39 major fish and crustacean species fed commercial aquafeed are studied in detail. Production based on farm-made and semi-commercial aquafeeds is an important part of the aquaculture sector. However, no statistical information on the size and extent of farm-made/semi commercial feed-based production is currently available (Tacon et al., 2011). Species such as oysters, mussels, clams, scallops and other bivalve species, which are grown with food materials that occur naturally in their culture environment in the sea and lagoons are not considered in this study. Filter feeders, such as silver carp and bighead carp, feed on planktons proliferated through intentional fertilization and the wastes and leftover feed materials of fed species grown in the same multispecies polyculture systems. The farming of such fish species does not require artificial feeding either and is excluded from the analysis. The same holds for aquatic plants. Production of fed freshwater fishes that are classified as "not elsewhere included", i.e. their species is not given in official statistics, was 1.24×10^6 tonnes in 2008 (Tacon et al., 2011). These are not considered here in detail as the feed formulation is unknown.

According to Tacon et al. (2011) of the 31.5 million tonnes of farmed fish and crustaceans, about 17.5 million tonnes were produced using commercially manufactured feeds and the remaining 14 million tonnes were fed with fresh feed items and farm-made feeds. Tacon et al. (2011) exclude Indian major carps (Catla, Rohu and Mrigal). However, Veerina et al. (1993) report that 8% of Indian major carp aquaculture production was based on commercial aquafeeds. Over the years this practice did not change significantly, as a recent study by Ramakrishna et al. (2013) showed. It was found that in Andrah Pradesh in India 1.3% of the farmers relied solely on commercial aquafeed, 33.3% used commercial compound aquafeed to supplement farm made feed and the majority (65.4%) used farm made feed only. Here we make the conservative estimate that 10% of Indian major carp production was based on commercial aquafeed in 2008. The feed conversion ratio was obtained from Ramakrishna et al. (2013). Adding Indian major carp to the data given by Tacon et al. (2011) results in a total of 17.9 million tonnes of aquaculture production based on commercially manufactured feeds. The 39 fish and crustacean types considered here thus add up to a production of

15.7 million tonnes, i.e. 88% of the total production based on commercial feed is included in the analysis.

2.2.2. Commercial aquafeed production and feed composition

Data on aquafeed production, the feed conversion ratios for the major cultivated species groups and the percentage of those groups that is cultured using commercial feed given by Tacon and Metian (2008) and updated by Tacon et al. (2011) for the year 2008 are used here. Total commercial aquafeed production in 2008 was 29.7 million tonnes (Tacon et al., 2011; Ramakrishna et al., 2013). The share of global production of commercial aquaculture feeds by major species grouping for the year 2008 is shown in Fig. 2.

Aquaculture production of the 39 species studied here in the year 2008, the percentage of fish and crustaceans cultured using commercial compound aquafeed, the feed conversion ratios (FCR) and the species-specific amount of commercial feed are summarized in Table S1.

In order to determine the water footprint of feed, the feed composition for 39 major species or species groups, covering all species groups shown in Fig. 2, have been compiled from the literature. As mentioned before, some species are, alas, not specified and hence no appropriate feed formulation can be selected. Feed composition is taken from various sources: the Aquaculture Feed and Fertilizer Resources Information System (AFFRIS) of the FAO (FAO, 2014b), Hasan et al. (2007), and numerous other literature sources (see SI 2 for details) were employed if data were missing in the former two sources. Commercial feed formulations for every producing country are not easily accessible. If a country specific formulation was available, a production-weighted value of the water footprint was determined. In general we have taken the approach of selecting a feed formulation for the analysis if it was classified as being a reference, or standard, feed formulation, i.e. it is known to satisfy dietary needs and is commonly used in commercial production. If more than one feed formulation was classified as being common for a certain species, the water footprint was determined individually for each formulation – thereby, data allowing, accounting for differing feeding habits in the individual life states – and the average water footprint was used for further analysis in order to account for the uncertainty in the water footprint values due to the feed composition chosen. Estimates of the fraction of commercial aquafeed production for the study year 2008 were taken from Tacon et al. (2011) and Ramakrishna et al. (2013). The duration of different life stages of the various species was obtained from the cultured aquatic species fact sheets of the FAO (FAO, 2014c). If no detailed information was available, the same diet had to be assumed for the entire lifespan until harvest. Production data were taken from the FAO FishStatJ (FAO, 2012b). The economic value per fish species as given by Tacon et al. (2011) was utilized.

The different feed compositions of the species studied here are shown in Fig. 3. Whenever detailed information regarding inclusion levels for the different life stages was available, it was taken into account in the analysis. However, to simplify the graphical presentation the inclusion levels were averaged over the different life stages for Fig. 3 and, in cases where multiple diets were studied, those were averaged as well to ease the graphical presentation. Details regarding the individual feed compositions are given in SI 2. All feed ingredients and the related green, blue and gray water footprints are listed in Table S3.

The feed ingredients are of animal origin (fishery products, terrestrial livestock products, terrestrial invertebrate products), of plant origin (cereal protein products, oilseed protein products, pulse and grain legume seed products, miscellaneous plant protein products), single cell protein, lipids (oils and fats), premixes, additives, fertilizers and manures. Feed ingredients that are used in aquafeeds investigated here are explained in detail in Tacon et al. (2009). A special case is Red swamp crawfish, as an established or encouraged forage crop serves to provide the basis of a food web from which crawfish derive most of their nutritional needs and is therefore not included in Fig. 3. In Fig. 3 the dietary habit of each species investigated in this study is indicated. The freshwater fishes include herbivores, planktivores, carnivores and omnivores. With the exception of rainbow trout (piscivore) and mullet (carnivore in the fry life stage and omnivore in the juvenile and growout stage) the diadromous and marine fish species included are carnivores. All crustaceans in this study are omnivores, with Giant tiger prawns being planktivores in early life stages, changing their feeding behavior later on to carnivorous. The differences in feed composition have a significant effect on the water footprint, which we will allude to in detail.

While aquaculture producing countries depend, to a varying degree, on imports for sourcing the feed ingredients used in aquaculture feed, the origin of the feed ingredients of commercial aquafeed is not documented in official statistics (Tacon et al., 2011). Global average data of the green, blue and gray water footprint of feed ingredients were selected for the current study due to this lack of detailed knowledge regarding the origin of feed ingredients. Data for the individual crops, crop by-products and animal products used as feed ingredients were obtained from Mekonnen and Hoekstra (2010a,b), Mekonnen and Hoekstra (2012) and van Oel and Hoekstra (2012).

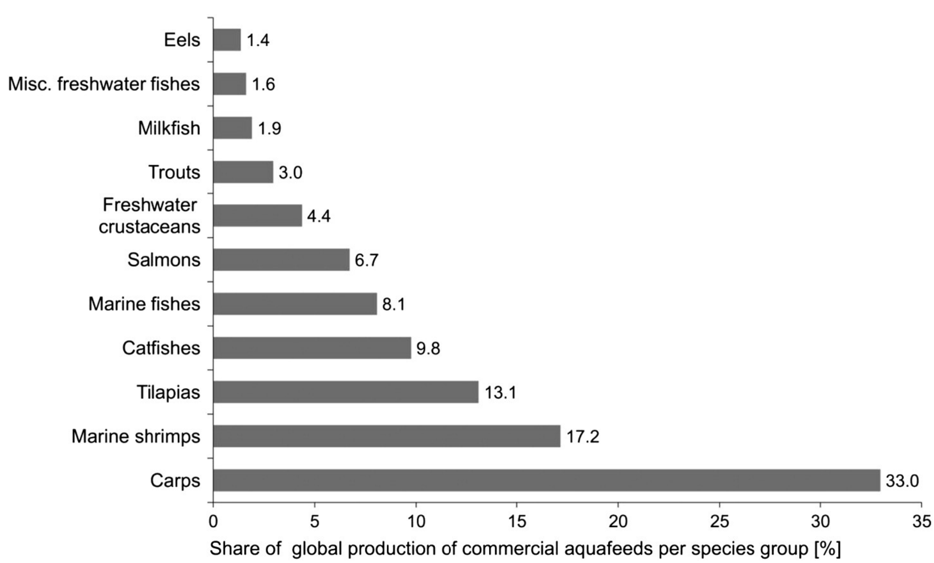

Fig. 2. Share of global production of commercial aquaculture feeds of 29.7 million tonnes by major species grouping for the year 2008 (own elaboration based on Tacon et al., 2011 and Ramakrishna et al., 2013).

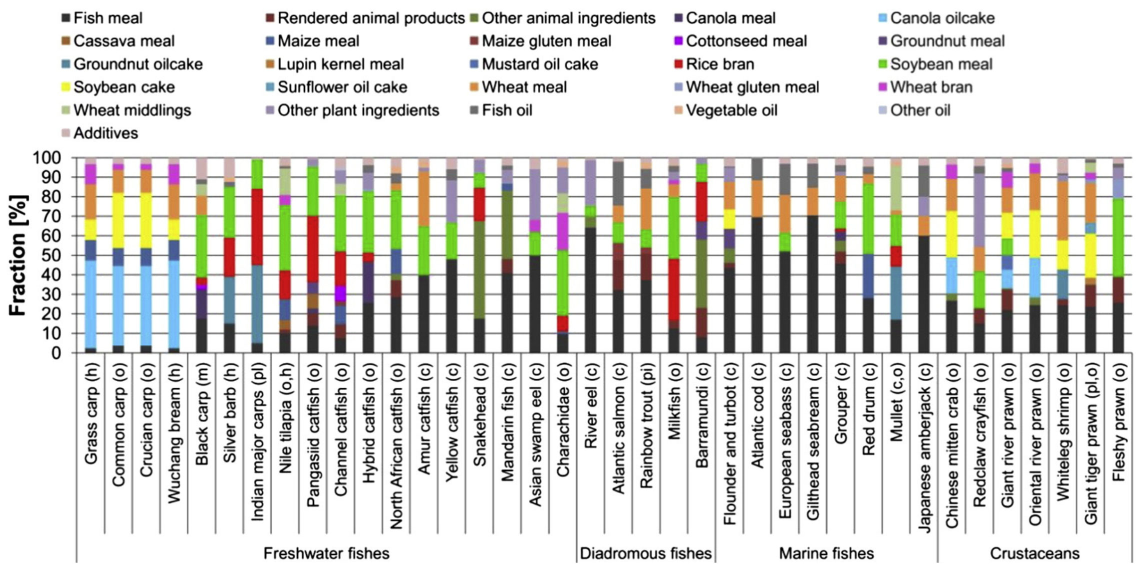

Fig. 3. Composition of the feed of the species studied. To simplify the graphical presentation, feed composition was averaged over the different life stages and, in case where multiple diets were studied, those were averaged as well. The dietary category for each species is also indicated: (c) carnivorous, (h) herbivorous, (pl) planktivorous, (m) molluscivorous, (pi) piscivorous and (o) omnivorous. If more than one category is shown then the species falls under different categories in different life stages.

3. Results

3.1. The commercial feed-related water footprint

The commercial feed-related green, blue and gray water footprint values per ton of the farmed fish and crustacean species analyzed here are shown in Fig. 4.

All fish species studied here, with the exception of the red swamp crawfish, have a feed related water footprint, i.e. not as a result of direct water use in operations, but through indirect water use in the supply chain. The values of the water footprints of carnivores generally tend to be lower than those of omnivores, planktivores and herbivores. There are, however, exceptions, which can be attributed to specific feed ingredients. Overall the carnivore mandarin fish has the lowest water footprint of 88 m^3/t (77.3% green, 6.8% blue and 15.9% gray) due to the large share of fish meal and fresh fish meat in the commerical diet given by FAO AFFRIS. The second lowest water footprint is that of the carnivorous Gilthead seabream with 500 m^3/t (69.8% green, 18.8% blue and 11.4% gray). On the other end of the spectrum the herbivore silver barb has the largest total water footprint of 2861 m^3/t (87.3% green, 7.4% blue, 5.3% gray).

Next, feed ingredients that have a large influence on the individual water footprint values are identified and discussed in terms of comparison of the species water footprints and close inspection of the feed formulation. In the group of freshwater fishes the water footprint values for Indian major carp were found to be significantly lower than for Chinese carps (Grass carp, Common carp, Crucian carp, Wuchang bream and Black carp) (Fig. 4), since rice bran – a feed ingredient with a low water footprint – plays an important role in the diet of Indian major carp, with an inclusion level of 39% in the commercial diet by Biswas et al. (2006) used here. For black carp the resulting water footprint values for the two diets given by Hu et al. (2014) ($WF_{green} = 2181$ m^3/t, $WF_{blue} = 222$ m^3/t, $WF_{gray} = 131$ m^3/t) and Sun et al. (2011) ($WF_{green} = 2172$ m^3/t, $WF_{blue} = 192$ m^3/t, $WF_{gray} = 212$ m^3/t) studied here were comparable, with the gray water footprint values differing most. The average water footprint values are shown in Fig. 4 and were used for further calculations. The higher WF values for black carp compared to other Chinese carps is in part due to the higher levels of

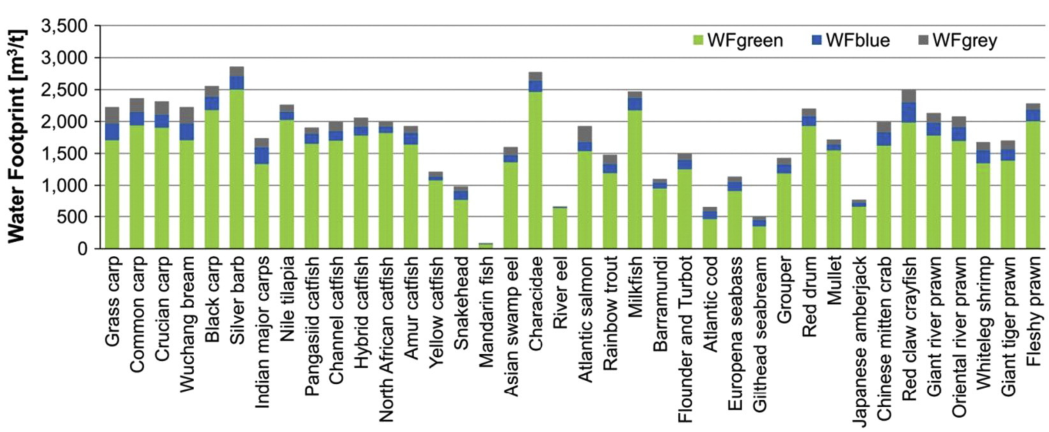

Fig. 4. Feed-related green, blue and gray feed water footprint per tonne of fish and crustacean for the species investigated. Mean values are shown where applicable. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

soybean meal included in the diets given by Hu et al. (2014) and Sun et al. (2011). The comparably high total WF values of silver barb, which exceed the values found for the other cyprinids studied here, are due to the high levels of soybean meal (26%) and groundnut oilcake (24%) described in the reference diet by Mohanta et al. (2006) that was used here. For Nile tilapia two diets were studied. These are considered typical and include significant levels of soybean meal for all life stages (see Table S4), but otherwise differ significantly in the feed composition. For the feed formulation according to Weimin and Mengqing (2007) $WF_{green} = 1998\ m^3/t$, $WF_{blue} = 94\ m^3/t$ and $WF_{gray} = 121\ m^3/t$ and for the feed formulation of FAO AFFRIS (FAO, 2014b) $WF_{green} = 2049\ m^3/t$, $WF_{blue} = 155\ m^3/t$ and $WF_{gray} = 107\ m^3/t$. These green, blue and gray water footprint values resulting from the two diets were averaged (shown in Fig. 4) and used for further analysis. The omnivorous Pangasiid, Channel, Hybrid and North African catfishes have similar total water footprint values. For Pangasiid catfishes, an alternative diet to the one given in FAO AFFRIS (FAO, 2014b) is described by Paripatananont (2002). The Paripatananont (2002) diet relies largely on fish meal and rice bran, which resulted in lower values of the green water footprint when compared to the FAO AFFRIS diet (FAO AFFRIS diet: $WF_{green} = 1888\ m^3/t$, $WF_{blue} = 126\ m^3/t$, $WF_{gray} = 94\ m^3/t$; Paripatananont (2002) diet: $WF_{green} = 1421\ m^3/t$, $WF_{blue} = 183\ m^3/t$, $WF_{gray} = 107\ m^3/t$). Mean values were also utilized here. Among the omnivorous Amur and Yellow catfishes the higher water footprint values for Amur catfish are mainly due to the inclusion level of soybean meal (25%) and the use of soybean oil instead of fish oil. The Yellow catfish diet includes high levels of fish meal (48%) and fish oil (5.6%), which results in comparably low values of the water footprint. The reference diet for Asian swamp eel given by Yuan et al. (2011), includes a high level of alpha starch (26%), which results in relatively high water footprint values. The feed formulations for Characidae provided in the work by Fernandes et al. (2004) and Lochmann et al. (2009) used here reflect natural feeding behavior, which is omnivorous and rich in plants and fruits. The resulting comparably high water footprint values were averaged.

The two feed formulations of FAO AFFRIS (FAO, 2014b) for diadromous milkfish investigated here yielded high water footprint values due to soybean and other plant ingredients inclusion levels, such as copra meal in one of the diets (diet 1: $WF_{green} = 2061\ m^3/t$, $WF_{blue} = 206\ m^3/t$, $WF_{gray} = 113\ m^3/t$; diet 2: $WF_{green} = 2288\ m^3/t$, $WF_{blue} = 176\ m^3/t$, $WF_{gray} = 99\ m^3/t$). Again the mean values were used.

A general diet formulation for each flounder and turbot of the ISSCAAP marine fishes group of flounders, halibuts and soles, given in Weimin and Mengqing (2007), was adopted. The diets do not differ significantly, which resulted in little variation of the water footprint values (Flounder: $WF_{green} = 1192\ m^3/t$, $WF_{blue} = 130\ m^3/t$, $WF_{gray} = 94\ m^3/t$; Turbot: $WF_{green} = 1253\ m^3/t$, $WF_{blue} = 147\ m^3/t$, $WF_{gray} = 104\ m^3/t$). The mean water footprint values are used for further analysis. The resulting feed water footprint values for red drum ($WF_{green} = 1930\ m^3/t$, $WF_{blue} = 152\ m^3/t$, $WF_{gray} = 120\ m^3/t$) must be considered high, given that it is a carnivorous fish. The two reference feed formulations used here (McGoogan and Reigh, 1996; Gatlin, 2002) are dominated by soybean meal (McGoogan and Reigh: 36% and Gatlin: 26%) and grain (23% and 26%) content, whereas the percentage of fish meal is 28% and 32% and of fish oil 4% and 5%, respectively.

The formulated diet for the crustacean redclaw crayfish by Saoud et al. (2008) used in this study has high proportions soy (19%), wheat (12.5%) and wheat starch (37.5%) content and hence results in comparably high water footprint values. Fleshy prawn feed water footprint values are also high due to the levels of soybean (40%) and wheat gluten meal (10%) included in all life stages of the diet given by Weimin and Mengqing (2007).

The diadromous fishes Atlantic salmon and rainbow trout, the marine fishes European seabass, Gilthead seabream and Atlantic cod, and the crustacean Giant Tiger prawn are discussed in detail later on.

Based on the water footprint values per species the green, blue and gray feed-related water footprint for the species-specific production in 2008 has been computed (Fig. 5).

The total water footprint of the feed results from the percentage of the total production that is produced based on commercial feed, the feed conversion ratio and the composition of the feed. The water footprint per ton of fish is comparable for Nile tilapia ($WF_{total} = 2263\ m^3/t$), grass carp ($WF_{total} = 2229\ m^3/t$) and common carp ($WF_{total} = 2364\ m^3/t$). The total production volume of Nile tilapia (2.3 million tonnes in 2008) does not exceed production volumes of these carp species (grass carp: 3.8 million tonnes; common carp: 3 million tonnes) and whiteleg shrimp (2.3 million tonnes). Yet with 83% of production on commercial feed and a FCR of 1.7, Nile tilapia has a larger total water footprint than those species and has the largest overall water footprint of the fed fish and crustacean types studied here. The top five species Nile tilapia (4.38 km^3), Grass carp (4.04 km^3), whiteleg shrimp (3.53 km^3), common carp (3.39 km^3) and Atlantic salmon (2.81 km^3) have a combined water footprint of 18.15 km^3.

In order to provide an estimate of the water footprint of total production based on commercial feed, i.e. 29.7 million tonnes of commercial feed in 2008, we determined a lower bound and a realistic, yet not upper bound value of the total water footprint. The lower bound is based on the assumption that the remaining 12% of production not included here do not have a water footprint. In this case the total water footprint is 31 km^3. For the second bound we assume that the remaining 12% have a water footprint equal to the production-weighted average ($WF_{green} = 1629\ m^3/t$, $WF_{blue} = 179\ m^3/t$, $WF_{gray} = 166\ m^3/t$), in which case the total water footprint is 35 km^3 for the year 2008.

For several fish and crustacean types China was the sole producer in the year 2008 (Asian swamp eel, Chinese longsnout catfish, Chinese mitten crab, Large yellow croaker, Largemouth black bass, Mandarin fish, Oriental river prawn, Wuchang bream and Yellow catfish) and for some of the most important fish types it is by far the leading producer, such as for crucian carp (99.9% of global production), grass carp (98.2%) and common carp (78.7%). A detailed assessment for China is provided in SI 5 due to its leading role in the aquaculture sector.

3.2. Water footprint variation for alternative feed formulations

The influence of variations in feed formulations of selected fishes and crustaceans is investigated in detail. Next to the general increase of plant feed ingredient usage due to increased production, replacement of fish meal and fish oil with plant-based ingredients is a highly relevant development and it is important to study this potential shift in aquaculture nutrition provision from a water resources point of view.

The water footprint analysis was carried out with alternative research diets taken from the literature for piscivorous rainbow trout, carnivorous Atlantic salmon, carnivorous Atlantic cod, carnivorous European seabass, carnivorous gilthead seabream and giant tiger prawn, which is planktivorous in early life stages and is omnivorous later on. The resulting green, blue and gray water footprint values are shown in Fig. 6.

The diet for rainbow trout adopted here was compared with two diets studied by Boissy et al. (2011) as part of the EU FP6 research project "Aquamax". The major objective of Aquamax was to achieve maximum replacement of both fish meal and fish oil in fish diets. Boissy et al. (2011) used a standard (STD) diet and a low fishery product diet (LFD) (see Table S6a for details). An interesting aspect of the STD feed composition is the usage of vegetable oils, particularly rapeseed oil and palm oil. These resulted in a high water footprint when compared to the diet given in FAO AFFRIS. The higher LFD diet water footprint values, exceeding the total water footprint of the FAO AFFRIS diet by 257%, are mainly due to the high inclusion levels of corn gluten meal, soybean cake and rapeseed oil in the feed formulation.

In the study by Boissy et al. (2011), diets low in fish meal and fish oil for Atlantic salmon have also been investigated. We adopted these here and compared the results obtained with the diet given by FAO AFFRIS

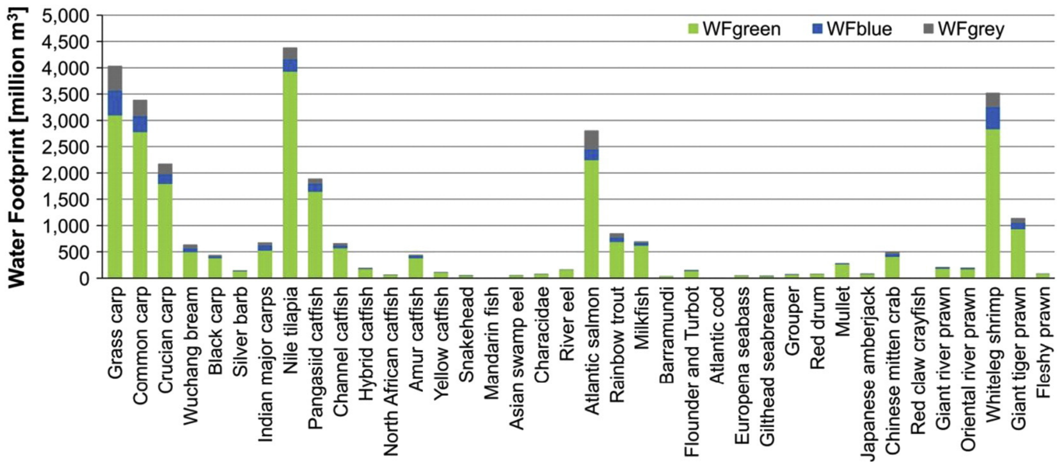

Fig. 5. Total feed-related green, blue and gray feed water footprint in the year 2008 of the species investigated in this study. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

(full diet composition given in Table S6b). While the STD research diet of Boissy et al. (2011) does result in a 14% increase in total water footprint, the LFD diet with its total replacement of fish oil by vegetable oils, leads to a total water footprint that is 83% higher than the one obtained with the diet provided by FAO AFFRIS.

One reference fish meal-based diet and four research diets, which were formulated to investigate the replacement of fish meal with plant proteins (25%, 50%, 75% and 100% plant protein) in diets for the Atlantic cod, with special attention to growth, protein retention (Hansen et al., 2007) and health aspects (Olsen et al., 2007), were investigated (full feed composition given in Table S6c). The plant ingredients chosen by Hansen et al. and Olsen et al. were soybean meal (14% protein), soy protein concentrate (36% protein) and wheat gluten (50% protein). These plant sources were chosen due to the high protein content required to reach a target protein level of 52% of the total diet formulation. Hansen et al. (2007) find that high growth and feed utilization were reached for up to 50% of plant protein inclusion. Growth and feed utilization were reduced beyond this inclusion level. Water footprint values increased as fish meal replacement with plant ingredients increased (see Fig. 6).

FAO AFFRIS (FAO, 2014b) provides a reference diet and four alternative feed formulations for the European seabass, where the level of fish meal included is reduced from 52% to 5% by replacing it with terrestrial feed ingredients (full feed composition in Table S6d). The green, blue and gray water footprint values increase for increasing terrestrial feed ingredient inclusion levels. The value of the total water footprint of diet 5 exceeds the value of diet 1 by 577%.

Using the diets given in FAO AFFRIS (FAO, 2014b), we can investigate the potential of a plant protein based diet to decrease the fish meal dependence in gilthead seabream feed formulations. Among other ingredients, corn and wheat gluten meal are used to decrease the fish meal use from 70.4% to 17.6%, the fish oil inclusion level remaining similar (from 12.4% to 15.0%) (diets given in Table S6e). The resulting water footprint values for this plant based feed formulation are comparably high with a total WF of 6587 m^3/t, compared to 500 m^3/t for the fish meal based diet.

FAO AFFRIS (FAO, 2014b) provides five diets with different inclusion levels of the various feed ingredients for giant tiger prawn (Table S6f). The diets must contain adequate levels of protein, fiber, carbohydrate, etc., which can be accomplished through different ingredients. The percentage of fish meal varies between 33.7% for diet 1 and 6% for diet 5. As the range of green, blue and gray water footprint values here – in accordance with the other examples shown above – also varies considerably for the five diets, it becomes evident that research on feed formulations needs to consider water consumption and pollution due to feed ingredients in order to provide sustainable diets for aquaculture production.

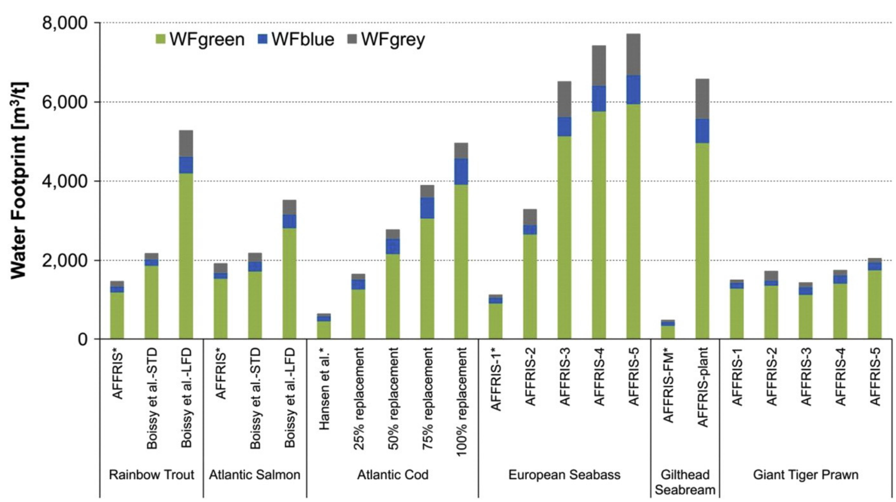

Fig. 6. Resulting water footprint values due to alternative diets. The diets are given in SI 6. The star * indicates the diet used in this study (Fig. 4). The mean based on the 5 FAO AFFRIS Giant Tiger Prawn diet was used here.

However, this particular example also points to the complexity involved, as the replacements for fish meal and fish oil can be selected from a number of options.

Lastly, we contrast the water footprint of commercial feed with the water footprint of farm made feed for the one case where sufficient information was available. The dominant feeding method for Indian major carp is farm made feed and farmers will generally use a simple 'mash' feed, with the main ingredients being rice bran and oil cake. However, Mazid et al. (1997) found that this feeding practice resulted in lower fish growth, less net production, a lower apparent feed conversion ratio and less protein utilization than for commercial feed. To evaluate the water footprint of farm made feed we made a rough estimate using an average FCR from Ramakrishna et al. (2013) of 3.1. The estimate was based on a diet given by Nair and Salin (2007) and Ramakrishna et al. (2013) for Indian major carp polyculture with 70% deoiled rice bran, 10% groundnut cake, 10% cottonseed cake and 10% raw rice bran, and the resulting $WF_{green} = 1839$ m^3/t, $WF_{blue} =$ 493 m^3/t , and $WF_{gray} = 264$ m^3/t. The total water footprint of farm made feed (2596 m^3/t) exceeds the total water footprint of the commercial feed formulation (1739 m^3/t) shown in Fig. 4. The reasons for the different water footprint values are the differences in the ingredients and their inclusion levels in the respective aquafeed, as well as the differing feed conversion ratios. Using a very simple traditional mash feed with 75% rice bran and 25% mustard oil cake given by Mazid et al. (1997) results in even higher water footprint values, with WF_{green} 4063 m^3/t, $WF_{blue} = 360$ m^3/t and $WF_{gray} = 597$ m^3/t.

3.3. Economic water productivity

The key trigger for change in aquaculture practices are market opportunities, combined with the need for increased production and productivity to reduce costs. Two fundamental changes in farming practices that contributed to this increase are evident: the increase in the use of formulated farm-made and commercial aquafeeds and the concomitant aeration of ponds/tanks (Rana and Hasan, 2013). In terms of monetary value, production of whiteleg shrimp generated the highest revenue (9.2 billion US$), followed by grass carp (5.3 billion US$), silver carp (5.3 billion US$) and common carp (4.2 billion US$) in the year 2008 (FAO, 2010).

We determined the monetary value of each fish species in relation to the green and blue water consumption due to feed. The economic green and blue water productivity (unit value [US$/t] divided by green + blue water footprint [m^3/t]) is shown in Fig. 7 for the species studied here. Overall, freshwater fishes have lower economic green and blue water productivity than most diadromous fishes, marine fishes and crustaceans. Milkfish, mullet and red drum are exceptions, due to their rather low monetary value and comparably high water footprint values. Since red swamp crawfish has a water footprint of zero and a unit value of 4460 US$/t (for 2008) it is a special case. Similarly Mandarin fish, with an exceptional low water footprint, due to the fish meal skewed diet and a unit value in 2008 of 9310 US$/t, has an economic water productivity of 125.8 US$/m^3, exceeding all other fish and crustacean types.

However, it must be noted that a special situation is observed in China in the culture of high-value Mandarin fish (Siniperca chuatsi; 230,000 tonnes in 2008–100% production in China), which is estimated to have consumed about 1 million tonnes of low-price carps (culter alburnus), purposely cultured in small sizes as live "feed fish" in 2008 (FAO, 2010). It is assumed here that these carps feed on zooplankton and hence do not have a feed-associated water footprint.

4. Discussion

In this study feed formulations that are considered standard for a certain species have been selected. However, the dietary requirements of fish and crustaceans are still being studied extensively. It must also be considered that feed formulations are often termed "standard" in the literature, but aquafeed for a certain fish type may differ significantly from country to country or within countries, depending on the producer's practice, feed ingredient availability, financial means of the farmers and the farming system. The overall uncertainty related to feed formulations cannot easily be quantified. Tacon et al. (2009) state that listing an ingredient within an aquafeed formulation just as "fish meal" or "soybean meal" is meaningless, as there are literally scores of different types and grades of fish meal, and to a lesser extent of soybean meal, depending on the species and origin of the raw fish or bean and processing method employed. Clearly, full ingredient descriptions and nutrient composition data must be given if precise conclusions are to be drawn. This level of detail would be in sharp contrast to the accuracy that can be achieved with currently available data.

Due to a lack of data on feed ingredient trade we turned to global average values for the water footprint of feed ingredients. Country values may deviate from those values and in-depth follow-up studies should take this into account.

Only commercial feed, not fresh and farm-made feed were considered, since information regarding FCR and/or amount of feed used was unavailable for the latter two. Also, the feed composition of fresh and farm-made feed can at best be guessed. Furthermore, some species are documented in FAO statistics employed here under the category "not elsewhere included". This only allows for an incomplete treatment of fed aquaculture production.

Full water footprint accounting would require the inclusion of all direct and indirect water consumption and pollution, both in operations and in the supply chain. While this study provides a comprehensive analysis of the commercial feed-related water footprint of aquaculture,

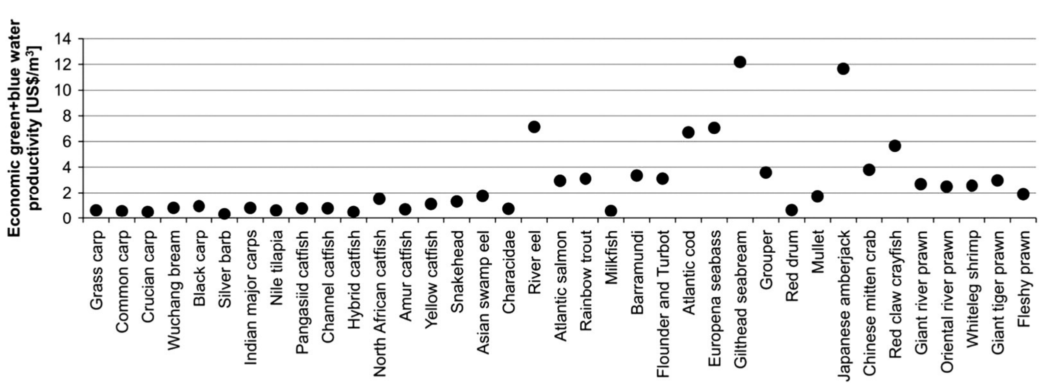

Fig. 7. Economic green and blue water productivity of the fish and crustacean types studied here. Mandarin fish is not shown, as the economic water productivity (US$/m^3) exceeds the other values significantly.

it falls short of shedding light on the overall water footprint of aquaculture production. Verdegem and Bosma (2009) investigated the water use in pond aquaculture. They estimate system-associated water use of global pond aquaculture due to evaporation to be, on average, 5200 m^3/t of production and average feed-associated consumptive water use as 1700 m^3/t of production of farmed fish, demonstrating the importance of direct water use in operations of pond culture for full accounting. Also, pollution of inland and marine waters due to fish and crustacean waste, uneaten feed, drugs, and chemicals from aquaculture systems is of great importance to fully assess the sustainability of aquaculture production. One example is clustered, small scale inland cage farming operations in Asia. These are commonly found in reservoirs in Indonesia and in the Mekong Delta. Collectively, such activities can be environmentally damaging (De Silva and Phillips, 2007).

Estimates for feed-related water footprint values range from 500 m^3/t for gilthead seabream feed (heavily relying on fish meal and fish oil) to 2862 m^3/t for the feed formulation of silver barb with high inclusion levels of soybean meal and groundnut oilcake. Note that Mandarin fish feed has the lowest total water footprint (88 m^3/t), but in this case one should rather acknowledge that the feed of this carnivore has a water footprint at all. An exception is the red swamp crawfish, whose feed does not have a water footprint, because of the established forage crop that provides the basis of a food web from which the fish derives most of its nutritional needs. The resulting production-weighted average green, blue and gray water footprints of farmed fish and crustaceans fed commercial aquafeed investigated here are 1629 m^3/t, 179 m^3/t and 166 m^3/t, respectively, and in total 1974 m^3/t.

A detailed comparison of the results obtained here for commercial aquafeed to industrial meat production from livestock is not feasible, since the results shown focus on feed and do not include all direct and indirect water consumption and pollution of aquaculture production and does not provide data for the final edible fish or crustacean market product. However, considering that livestock meat production has little direct water use for drinking water, servicing the animals and mixing of the feed, but that the feed has by far the largest share of the total water footprint of livestock, we put the values side by side. The global average water footprint of goat meat in industrial farming system is 2862 m^3/t, for chicken meat 2872 m^3/t, for pig meat 5224 m^3/t, for sheep meat 5623 m^3/t and for beef meat 10,244 m^3/t (Mekonnen and Hoekstra, 2010b). The values of the water footprint of fish and crustaceans must include the water evaporated from the system (most important for pond aquaculture) and the pollution of freshwater resources due effluents from aquaculture systems. A species-specific comparison is not feasible here, but evaporation from the ponds (Verdegem and Bosma (2009) give a global average value of pond evaporation of 5200 m^3/t of farmed fish) would increase the production-weighted feed-related water footprint of fish to potentially exceed individual livestock water footprint values. This must also be viewed in light of the fact that the commercial aquaculture production sector has achieved high efficiency regarding feed conversion, with FCR ratios ranging from 1.3 to 2.0 (see Table S1), which are lower than industrial livestock farming FCR values (Mekonnen and Hoekstra, 2010b).

Tacon et al. (2009) note that, whereas humans and livestock do have specific dietary requirements for particular food or feed, farmed fish and shrimp do not have a specific dietary requirement for a particular feed ingredient such as fish meal or fish oil, but rather have a specific requirement for 40 or so essential dietary nutrients. Tacon et al. (2009) therefore stipulate that in the short term, efforts should focus on further improvements in feed formulation techniques and on formulating rations on the basis of individual digestible nutrient levels rather than on crude gross nutrient levels, and at the same time aim to minimize the environmental and ecosystem impact of feeds and feeding regimes (Tacon et al., 2011). While this study can support decisions on feed ingredients with respect to their water footprint, it is essential that growth and health of the species are investigated before new diets are used in practice. For example the replacement of fish meal and fish oil chosen must not be detrimental to health and growth. In early work Kaushik et al. (1995), for example, find that the replacement of fish meal with soy protein concentrate (33% to 100% replacement) had no negative effects on growth and nutrient utilization of rainbow trout, whereas the replacement of fish meal with soy flour of up to 50% reduced the growth rate.

Soybean is the source of plant protein most often used in compound aquafeeds and the most prominent protein ingredient substitute for fish meal in aquaculture feeds (Tacon et al., 2011). For 2008 it was estimated that the aquaculture sector used 6.8 million tonnes of soybean meal, which was 25.1% of total compound aquafeed (Tacon et al., 2011). Using global average water footprint values for soybean meal (see Table S4), this translates into green, blue and gray water footprints of $16,300 \times 10^6$ m^3, 564×10^6 m^3 and 299×10^6 m^3, respectively. Of that, China is using about 6.0 million tonnes of soybean meal within compound aquafeed (Tacon et al., 2011). Hu et al. (2014) investigated the potential of replacing soybean meal with cottonseed meal in black carp diets. The results showed that up to 75% of soybean meal could be replaced by cottonseed meal without a significant reduction in growth. The resulting water footprint changed significantly from the zero percent replacement with 2534 m^3/t (86% green, 9% blue, and 5% gray) to 1756 m^3/t (72% green, 19% blue, and 9% gray) for 75% replacement. However, negative influence on immune system function was found even for 25% replacement and liver function was affected if 75% or more was replaced Hu et al. (2014). If no detrimental health effects are found, then soybean meal replacement of less than 25% could in this case be a valid soybean use and, at the same time, a water footprint reduction option.

5. Conclusions

Each fish and crustacean has certain needs in terms of protein, fat, carbohydrates, vitamins, minerals, among others. The question is how those needs can be met in a sustainable way, thereby also considering the pressure on freshwater resources. Fish meal and fish oil use are on the decline, yet a shift towards higher plant protein inclusion levels should also consider freshwater consumption and pollution, as can be deduced from the results shown here, in order to determine sustainable future feed formulations. However, the replacement of fish meal and/or fish oil with terrestrial feed ingredients can substantially increase the water footprint of aquafeed and hence of aquaculture production as a whole. While the selection of species is not exhaustive in the present study, the result is universal. Replacing aquafeed ingredients that stem from e.g. pelagic marine fishes, that do not depend on external feed, with terrestrial feed ingredients, that have a related water consumption and pollution in the production process, must lead to an increasing water footprint of the feed. There will of course be differences among the terrestrial plant-based proteins and lipids with respect to their green, blue and gray water footprint, which must have implications when different goals are to be reached, e.g. reduction of the blue water footprint, reduction of pollution or reduction of the overall water footprint. The choice depends on the goal and we therefore do not strive to provide explicit recommendations regarding the choice of terrestrial feed ingredients. Yet it is important to realize that all fish types need to be considered in this discussion. The aquaculture sector is steadily growing and so is the demand for aquafeed. Hence, while the water footprint per ton of production for herbivores or planktivores may remain the same, the pressure on freshwater resources will also increase in that case, not only for a reduction or replacement of fish meal and fish oil with terrestrial plant-based feed ingredients for carnivores and omnivores. Therefore it is crucial to select feed ingredients that can be sustainably produced and grow with the sector (Tacon et al., 2011).

Fish meal and fish oil are at present important feed ingredients for freshwater carnivorous fishes, diadromous fishes, marine fishes and also for crustaceans. The economic green and blue water productivity of these species tends to be higher than that of herbivorous and omnivorous freshwater fishes (exceptions being carnivorous freshwater fishes, milkfish, mullet and red drum). The results shown here suggest that larger shares of specific terrestrial plant feedstuffs in fish diets can lead to a reduction of the economic water productivity due to increasing water footprints.

Opportunities to reduce the water footprint in aquaculture lie in increasing productivity (higher yield per unit of water consumed and/or polluted) and in optimizing feed composition to, on the one hand, allow for optimal health and growth of species cultured in aquaculture systems and, on the other hand, limit pressure on freshwater resources. Soybean, at present the most used terrestrial aquafeed ingredient, and potential alternatives, will play an important role regarding this matter. There is considerable room for expansion and increased usage of rendered products such as terrestrial animal by-product meals and oils (Nates et al., 2009; Tacon et al., 2011). Even more so, since we find that any of the plant-based lipids investigated here as feed ingredient would lead to an increase of the feed water footprint when compared to usage of fish oil. Furthermore, the results shown here support the recommendation that, in line with Naylor et al. (2009), Tacon et al. (2009) and Tacon et al. (2011), aquaculture producing countries should place more emphasis on maximizing the use of locally available feed-grade ingredient sources and make best use of by-products (from agriculture, livestock and fishery). By-products often otherwise go to waste, but could provide a good source for fish feed and put low pressure on freshwater resources. Troell et al. (2014b) foresee that the use of fish processing wastes for feeds is expected to become more prevalent. While largest positive changes can be achieved in China, due to its leading role in aquaculture production, measures to improve the situation should be implemented globally.

Tacon et al. (2011) project that production and usage of commercial aquaculture feed will increase from 29.7 million tonnes in 2008 to about 71 million tonnes in 2020, which will be accompanied by an increase in the related water footprint. Such future projections should at least take into account that fish meal and fish oil usage will change, that feed compositions will differ in the future, that the percentage of fish fed will increase per species and that productivity will improve. We do not strive to assess future scenarios, yet it is clear that for a 'business as usual scenario' the increasing production will put further pressure on freshwater resources, and even more so for feed compositions that partly or fully replace fish meal and fish oil with certain terrestrial plant ingredients. Therefore, identification of alternate plant sources for formulating fish diets could play an important role in the sustainable future growth of the aquaculture sector. Even more so since additional pressure on freshwater resources results from the global production of farm-made aquafeeds, which was estimated to be between 18.7 and 30.7 million tonnes in 2006 (Tacon et al., 2011).

The present results suggest that aquaculture production is not a water saving alternative to livestock food production. The continued growth of the aquaculture sector and the efforts to replace fish meal and fish oil, at least in part, with terrestrial feed ingredients, will further aggravate the situation in the future, if feed formulation research does not include the aspect of freshwater consumption and pollution in aquafeed production.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.scitotenv.2015.07.124.

References

Alexandratos, N., Bruinsma, J., 2012. World Agriculture Towards 2030/2050: The 2012 Revision. ESA Working paper No. 12–03. FAO, Rome, Italy.

Biswas, G., Jena, J.K., Singh, S.K., Muduli, H.K., 2006. Effect of feeding frequency on growth, survival and feed utilization in fingerlings of Catla catla (Hamilton), Labeo rohita (Hamilton) and Cirrhinus mrigala (Hamilton) in outdoor rearing systems. Aquac. Res. 37, 510–514. http://dx.doi.org/10.1111/j.1365-2109.2006.01457.x.

Boissy, J., Aubin, J., Drissi, A., van der Werf, H.M.G., Bell, G.J., Kaushik, S.J., 2011. Environmental impacts of plant-based salmonid diets at feed and farm scales. Aquaculture 321 (1–2), 61–70.

Boyd, C.E., 2005. Water use in aquaculture. World Aquacult. 36 (3), 12–15 (and 70).

Boyd, C.E., Tucker, C., Mcnevin, A., Bostick, K., Clay, J., 2007. Indicators of resource use efficiency and environmental performance in fish and crustacean aquaculture. Rev. Fish. Sci. 15 (4), 327–360.

Cao, L., Naylor, R., Henriksson, P., Leadbitter, D., Metian, M., Troell, M., Zhang, W., 2015. China's aquaculture and the world's wild fisheries. Science 347 (6218), 133–135. http://dx.doi.org/10.1126/science.1260149.

Carter, C.G., Hauler, R.C., 2000. Fish meal replacement by plant meals in extruded feeds for Atlantic salmon, Salmo salar L. Aquaculture 185 (3–4), 299–311.

De Silva, S.S., Phillips, M.J., 2007. A Review of Cage Aquaculture: Asia (Excluding China). In: Halwart, M., Soto, D., Arthur, J.R. (Eds.), Cage aquaculture — Regional reviews and global overviewFAO Fisheries Technical Paper, No. 498. FAO, Rome, Italy, pp. 18–48.

EU, 2014. Council Regulation (European Union) No 43/2014 of 20 January 2014 fixing for 2014 the fishing opportunities for certain fish stocks and groups of fish stocks, applicable in Union waters, and to Union vessels, in certain non-Union waters. Available at:, http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2014:024:0001:01:EN:HTML (last accessed 11 March 2014).

FAO, 2010. The State of World Fisheries and Acquaculture 2010. FAO Fisheries and Aquaculture Department, FAO, Rome, Italy.

FAO, 2012a. The State of World Fisheries and Aquaculture 2012. FAO Fisheries and Aquaculture Department, FAO, Rome, Italy.

FAO, 2012b. FishStatJ: Universal Software for Fishery Statistical Time Series.Version 2.0.0. FAO, Rome, Italy.

FAO, 2014a. Aquaculture Feed and Fertilizer Resources Information System (AFFRIS). FAO, Rome, Italy (Available at: http://www.fao.org/fishery/affris/species-profiles/en/ (last accessed: 15 May 2014)).

FAO, 2014b. Food and Agriculture Organization (FAO). Faostat Database. Available at:, http://faostat.fao.org/ (last accessed: 30 April 2014).

FAO, 2014c. Cultured Aquatic Species Fact Sheets. FAO Fisheries and Aquaculture Department, Rome, Italy (Available at: http://www.fao.org/fishery/culturedspecies/search/en (last accessed: 03 March 2014)).

Fernandes, J.B.K., Lochmann, R., Bocanegra, F.A., 2004. Apparent digestible energy and nutrient digestibility coefficients of diet ingredients for pacu Piaractus brachypomus. J. World Aquacult. Soc. 35, 237–244.

Gatlin, D.M., 2002. Red Drum, Sciaenops Ocellatus. In: Webster, C.D., Lim, C.E. (Eds.), Nutrient requirements and feeding of finfish for aquaculture. CABI Publishing, New York, N.Y., USA, pp. 147–158.

Gatlin, D.M., Barrows, F.T., Brown, P., Dabrowski, K., Gaylord, T.G., Hardy, R.W., Herman, E., Hu, G., Krogdahl, Å., Nelson, R., Overturf, K., Rust, M., Sealey, W., Skonberg, D., J Souza, E., Stone, D., Wilson, R., Wurtele, E., 2007. Expanding the utilization of sustainable plant products in aquafeeds: a review. Aquac. Res. 38, 551–579. http://dx.doi.org/10.1111/j.1365-2109.2007.01704.x.

Gephart, J.A., Pace, M.L., D'Odorico, P., 2014. Freshwater savings from marine protein consumption. Environ. Res. Lett. 9 (1), 014005.

Hansen, A.-C., Rosenlund, G., Karlsen, Ø., Koppe, W., Hemre, G.-I., 2007. Total replacement of fish meal with plant proteins in diets for Atlantic cod (Gadus morhua L.) I: effects on growth and protein retention. Aquaculture 272, 599–611.

Hasan, M.R., Hecht, T., De Silva, S.S., Tacon, A.G.J., 2007. Study and Analysis of Feeds and Fertilizers for Sustainable Aquaculture Development. FAO Fisheries Technical Paper No. 497. FAO, Rome, Italy.

Hoekstra, A.Y., Chapagain, A.K., Aldaya, M.M., Mekonnen, M.M., 2011. The Water Footprint Assessment Manual: Setting the Global Standard. Earthscan, London, UK.

Hu, Y., Huang, Y., Feng, F., Zhong, L., Ai, Q., Xiao, T., Wen, H., 2014. Effect of soybean meal replacement by cottonseed meal on growth, feed utilization and some blood physiological/biochemical indices of juvenile black carp, Mylopharyngodon piceus. Aquac. Res. http://dx.doi.org/10.1111/are.12409.

Kaushik, S.J., Cravedi, J.P., Lalles, J.P., Sumpter, J., Fauconneau, B., Laroche, M., 1995. Partial or total replacement of fish meal by soybean protein on growth, protein utilization, potential estrogenic or antigenic effects, cholesterolemia and flesh quality in rainbow trout, *Oncorhynchus mykiss*. Aquaculture 133 (3–4), 257–274.

Kaushik, S.J., Covès, D., Dutto, G., Blanc, D., 2004. Almost total replacement of fish meal by plant protein sources in the diet of a marine teleost, the European seabass, *Dicentrarchus labrax*. Aquaculture 230 (1–4), 391–404.

Klinger, D., Naylor, R., 2012. Searching for solutions in aquaculture: charting a sustainable course. Annu. Rev. Environ. Resour. 37, 247–276.

Krausmann, F., Erb, K.-H., Gingrich, S., Haberl, H., Bondeau, A., Gaube, V., Lauk, C., Plutzar, C., Searchinger, T.D., 2013. Global human appropriation of net primary production doubled in the 20th century. Proc. Natl. Acad. Sci. U. S. A. 110 (25), 10324–10329. http://dx.doi.org/10.1073/pnas.1211349110.

Lochmann, R., Chen, R., Chu-Koo, F.W., Camargo, W.N., Kohler, C.C., Kasper, C., 2009. Effects of carbohydrate-rich alternative feedstuffs on growth, survival, body composition, hematology, and nonspecific immune response of Black Pacu, Colossoma macropomum, and Red Pacu, Piaractus brachypomus. J. World Aquacult. Soc. 40, 33–44. http://dx.doi.org/10.1111/j.1749-7345.2008.00232.x.

Mazid, M.A., Zaher, M., Begum, N.N., Ali, M.Z., Nahar, F., 1997. Formulation of cost-effective feeds from locally available ingredients for carp polyculture system for increased production. Aquaculture 151 (1–4), 71–78.

McGoogan, B.B., Reigh, R.C., 1996. Apparent digestibility of selected ingredients in red drum (*Sciaenops ocellatus*) diets. Aquaculture 141, 233–244.

Mekonnen, M.M., Hoekstra, A.Y., 2010a. The Green, Blue and Gray Water Footprint of Crops and Derived Crop Products. Value of Water Research Report Series No. 47. UNESCO-IHE, Delft, The Netherlands.

Mekonnen, M.M., Hoekstra, A.Y., 2010b. The Green, Blue and Gray Water Footprint of Farm Animals and Animal Products. Value of Water Research Report Series No. 48. UNESCO-IHE, Delft, The Netherlands.

Mekonnen, M.M., Hoekstra, A.Y., 2012. A global assessment of the water footprint of farm animal products. Ecosystems 15 (3), 401–415.

Mohanta, K.N., Mohanty, S.N., Jena, J.K., Sahu, N.P., 2006. Apparent protein, lipid and energy digestibility coefficients of some commonly used feed ingredients in formulated pelleted diets for silver barb, *Puntius gonionotus*. Aquac. Nutr. 12, 211–218. http://dx.doi.org/10.1111/j.1365-2095.2006.00403.x.

Nair, M.C., Salin, K.R., 2007. Carp polyculture in India — Practices, Emerging Trends. Global Aquaculture Advocate pp. 54–56 (January/February 2007).

Nates, S.F., Bureau, D.P., Lemos, D., Swisher, K., 2009. Rendered Ingredients and Their Use in Shrimp Diets: Status and Prospects. In: Browdy, C.L., Jory, D.E. (Eds.), The Rising Tide, Proceedings of the Special Session on Sustainable Shrimp FarmingWorld Aquaculture 2009. World Aquaculture Society, Baton Rouge, USA, pp. 137–146.

Naylor, R.L., Goldburg, R.J., Primavera, J.H., Kautsky, N., Beveridge, M.C.M., Clay, J., Folke, C., Lubchenco, J., Mooney, H., Troell, M., 2000. Effect of aquaculture on world fish supplies. Nature 405 (6790), 1017–1024.

Naylor, R.L., Hardy, R.W., Bureau, D.P., Chiu, A., Elliott, M., Farrell, A.P., Forster, I., Gatlin, D.M., Goldburg, R.J., Hua, K., Nichols, P.D., 2009. Feeding aquaculture in an era of finite resources. Proc. Natl. Acad. Sci. U. S. A. 106 (36), 15103–15110.

Olsen, R.E., Hansen, A.-C., Rosenlund, G., Hemre, G.-I., Mayhew, T.M., Knudsen, D.L., Tufan Eroldogan, O., Myklebust, R., Karlsen, Ø., 2007. Total replacement of fish meal with plant proteins in diets for Atlantic cod (Gadus morhua L.) II: Health aspects. Aquaculture 272, 612–624.

Paripatananont, T., 2002. Snakehead and Pangasius Catfish. In: Webster, C.D., Lim, C. (Eds.), Nutrient Requirements and Feeding of Finfish for Aquaculture. CAB International and CABI Publishing, pp. 396–398.

Powell, K., 2003. Eat your veg. Nature 426 (6965), 378–379.

Ramakrishna, R., Shipton, T.A., Hasan, M.R., 2013. Feeding and Feed Management of Indian Major Carps in Andhra Pradesh, India. FAO Fisheries and Aquaculture Technical Paper No. 578. FAO, Rome, Italy.

Rana, K.J., Hasan, M.R., 2013. On-farm Feeding and Feed Management Practices for Sustainable Aquaculture Production: An Analysis of Case Studies From Selected Asian and African Countries. In: Hasan, M.R., New, M.B., Hasan, M.R., New, M.B. (Eds.), On-farm feeding and feed management in aquacultureFAO Fisheries and Aquaculture Technical Paper No. 583. FAO, Rome, Italy.

Saoud, I.P., Rodgers, L.J., Davis, D.A., Rouse, D.B., 2008. Replacement of fish meal with poultry by-product meal in practical diets for redclaw crayfish (Cherax quadricarinatus). Aquac. Nutr. 14, 139–142. http://dx.doi.org/10.1111/j.1365-2095.2007.00513.x.

Stonerook, E., 2010. The Water Footprint of Aquaculture: A Life Cycle Assessment Comparison of Common Aquaculture Systems to Beef, Pork, and Chicken Production M.S. Thesis, University of Florida (110 pp.).

Sun, S., Ye, J., Chen, J., Wang, Y., Chen, L., 2011. Effect of dietary fish oil replacement by rapeseed oil on the growth, fatty acid composition and serum non-specific immunity response of fingerling black carp,Mylopharyngodon piceus. Aquac. Nutr. 17, 441–450. http://dx.doi.org/10.1111/j.1365-2095.2010.00822.x.

Tacon, A.G.J., Metian, M., 2008. Global overview on the use of fish meal and fish oil in industrially compounded aquafeeds: trends and future prospects. Aquaculture 285 (1–4), 146–158.

Tacon, A.G.J., Metian, M., Hasan, M.R., 2009. Feed Ingredients and Fertilizers for Farmed Aquatic Animals: Sources and Composition. FAO Fisheries and Aquaculture Technical Paper No. 540. FAO, Rome, Italy.

Tacon, A.G.J., Hasan, M.R., Metian, M., 2011. Demand and Supply of Feed Ingredients for Farmed Fish and Crustaceans: Trends and Prospects. FAO Fisheries and Aquaculture Technical Paper No. 564. FAO, Rome, Italy.

Troell, M., Metian, M., Beveridge, M., Verdegem, M., Deutsch, L., 2014a. Comment on 'Water footprint of marine protein consumption–aquaculture's link to agriculture' Environ. Res. Lett. 9, 109001. http://dx.doi.org/10.1088/1748-9326/9/10/109001.

Troell, M., Naylor, R.L., Metian, M., Beveridge, M., Tyedmers, P.H., Folke, C., Arrow, K.J., Barrett, S., Crépin, A.-S., Ehrlich, P.R., Gren, Å., Kautsky, N., Levin, S.A., Nyborg, K., Österblom, H., Polasky, S., Scheffer, M., Walker, B.H., Xepapadeas, T., de Zeeuw, A., 2014b. Does aquaculture add resilience to the global food system? Proc. Natl. Acad. Sci. U. S. A. 111 (37), 13257–13263. http://dx.doi.org/10.1073/pnas.1404067111.

Van Oel, P.R., Hoekstra, A.Y., 2012. Towards quantification of the water footprint of paper: a first estimate of its consumptive component. Water Resour. Manag. 26 (3), 733–749.

Veerina, S.S., Nandeesha, M.C., Gopal Roa, K., 1993. Status and technology of Indian major carp farming in Andhra Pradesh, India. Aquac. Res. 30, 805–814.

Verdegem, M.C.J., Bosma, R.H., 2009. Water withdrawal for brackish and inland aquaculture, and options to produce more fish in ponds with present water use. Water Policy 11, 52–68.

Verdegem, M.C.J., Bosma, R.H., Verreth, J.A.J., 2006. Reducing water use for animal production through aquaculture. Int. J. Water Resour. Dev. 22 (1), 101–113.

Weimin, M., Mengqing, L., 2007. Analysis of Feeds and Fertilizers for Sustainable Aquaculture Development in China. In: Hasan, M.R., Hecht, T., De Silva, S.S., Tacon, A.G.J. (Eds.), Study and analysis of feeds and fertilizers for sustainable aquaculture developmentFAO Fisheries Technical Paper No. 497. FAO, Rome, Italy, pp. 141–190.

Worm, B., Hilborn, R., Baum, J.K., Branch, T.A., Collie, J.S., Costello, C., Fogarty, M.J., Fulton, E.A., Hutchings, J.A., Jennings, S., Jensen, O.P., Lotze, H.K., Mace, P.M., McClanahan, T.R., Palumbi, S.R., Parma, A.M., Rikard, D., Rosenberg, A.A., Zeller, D., Minto, C., 2009. Rebuilding global fisheries. Science 325 (5940), 578–585.

Yuan, H., Gong, S., Chu, Z., Zhang, G., Yuan, Y., Gong, W., Yan, J., 2011. Effects of low dietary protein level on serum oestradiol, testosterone and sex reversal in rice field eel, Monopterus albus (Zuiew). Aquac. Res. 42, 1752–1763. http://dx.doi.org/10.1111/j.1365-2109.2010.02772.x.