ENVIRONMENTAL RESEARCH LETTERS

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To cite this article: Govoni Camilla *et al* 2022 *Environ. Res. Lett.* **17** 074003

ENVIRONMENTAL RESEARCH
LETTERS

CrossMark

OPEN ACCESS

RECEIVED
12 January 2022

REVISED
30 May 2022

ACCEPTED FOR PUBLICATION
31 May 2022

PUBLISHED
14 June 2022

LETTER

Global assessment of land and water resource demand for pork supply

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Keywords: livestock, pig, feed, land, water, trade, sustainability

Supplementary material for this article is available online

Abstract

Growing population and rising incomes are leading to an ever-increasing demand for animal-based foods. Pigmeat is currently the most consumed meat globally, even exceeding the consumption of poultry meat. Despite the disproportionate environmental burden of animal production—mostly attributable to associated feed demand, up-to-date country-scale quantifications of the land and water impacts of the concentrate feed (mainly cereals and soybean) and co-products required to support pig production are still missing. In addition, the specific role that international feed trade plays in separating resource use from consumption and in altering resource use efficiencies remains unclear. This paper analyses at a country-scale the internal and external consumption of natural resources (i.e. land and water) to support pig feed production in 2018. Combining data on the country- and production system-specific diets and crop-specific yields with an agro-hydrological model, we find that 64.1 Mha of agricultural land (5% of all croplands) and 332.6 km^3 of water (both green and blue) (6% of all agricultural water use) were utilized by China, EU-27 and the United States (accounting for 70% of pigmeat production) to produce pig feed alone. Comparing domestic feed production scenarios with those that also consider the feed trade, we show that global resource consumption tends to be more efficient when considering international feed trade, especially in China and EU-27, while sometimes causing significant environmental impacts. This demonstrates the need to investigate the environmental effects of pig feed associated both with the domestic use of natural resources, but also to the ones displaced by international trade.

1. Introduction

Since the global population and incomes are increasing, the consumption of food of animal origin, particularly from monogastric livestock (i.e. pork and poultry), is also growing (Delgado 2003, Alexandratos and Bruinsma 2012, FAO 2018b, Whitnall and Pitts 2019, Ankeny 2021, Komarek *et al* 2021, Miller *et al* 2022). Meat and animal products play an important role in global food security, giving a significant contribution to both protein and calorie supply, as well as micronutrients, in human diets (Henchion *et al* 2017). However, the production of animal source foods (ASFs) is often also related to food security and food safety issues (Adesogan *et al* 2020).

Since the 1960s, pigmeat has become the most produced and consumed meat, though only slightly more than poultry meat in recent years, and it has become an essential source of nutrition for many people around the world (Szűcs and Vida 2017). The global per capita consumption of pigmeat increased from 8.0 kg in 1961 to 15.6 kg in 2018 (FAOSTAT 2018), almost doubling its value, even despite widespread religious and cultural restrictions associated with this type of meat that affect global food and dietary patterns. One reason for this rapid growth lies in the production in China, which currently amounts to half of all the pigs raised in the world. This is the result of the direct link between the rise in incomes and the increase of meat consumption, accompanied by a series of policies and trade agreements aimed at liberalizing and industrializing Chinese agriculture (Schneider 2011, Chen and Wang 2013, Qiao *et al* 2016, Bai *et al* 2019). On the one hand, this has succeeded in increasing diet protein content, but not without severe implications for the environment, public health, smallholder farmers, and also food safety (Wu *et al* 2020, Rulli *et al* 2017, 2021).

Livestock production systems demand high energy inputs (Makkar and Ankers 2014), but also huge amounts of land and water resources to produce feed crops (Winders and Ransom 2019, Karlsson and Röös 2019), and these natural resources are becoming increasingly scarce in different areas worldwide (FAO 2018c). The surge in feed production observed in the last years (IFIF 2018) and the increase in the use of food-grain for the production of high-value animal protein (FAO 2020) as well, might be exacerbating the competition for arable land and freshwater for primary food (Schader *et al* 2015, Di Paola *et al* 2017, Karlsson and Röös 2019). Specifically, being pigs monogastric, they are more efficient feed converters but they require higher amounts of food-competing feed compared to ruminants as they can only digest simple carbohydrates and struggle to digest fibers (Steinfeld 2006). In the past, food waste was often recycled as livestock feed, particularly for omnivores pigs (Gerbens-Leenes *et al* 2002). However, although swill feeding still plays an important role for pigs reared in backyard systems, its use has declined and been replaced by concentrate feed since production has become increasingly industrialized and several bans have been imposed (Zu Ermgassen *et al* 2016, Luciano *et al* 2020, 2021, 2022). This is proved by cereal grains which, due to low amounts ingested by ruminants, cover only 13% of the world's feed demand in 2010 while they make up 60%–70% of the pig feed demand. Although 2% of livestock was made up of pigs in 2010, cereals used for pig feed accounted for around one-quarter of the entire cereal feed production and, consequently, one-fifth of the agricultural land used for cereals feed crops (Steinfeld 2006, FAO 2011, Mottet *et al* 2017). In addition, to complement the diet with proteins, in 2010, pigs required more than one-third of oilseed demand in the livestock sector and 40% of that of soybeans (Mottet *et al* 2017, FAOSTAT 2018). Added to this, one-third of the global agricultural water demand is devoted to the livestock sector (Mekonnen and Hoekstra 2012, Ran *et al* 2016).

Several authors have, therefore, studied the link between resource use and livestock production (Hoekstra 2012, Gerbens-Leenes *et al* 2013, Bajželj *et al* 2014, Ran *et al* 2016, van Zanten *et al* 2016, Röös *et al* 2017, Conijn *et al* 2018, Heinke *et al* 2020), with global estimates of food-feed competition (Mottet *et al* 2017). Some other authors have estimated water and/or land resources associated with pig production in specific regions or countries (Thoma *et al* 2015, Sporchia *et al* 2021), but often failing to assess the diversity of animal diets between countries and production systems. Consequently, the research question regarding how much land and water resources are needed on a national scale worldwide to feed pigs and the role of international trade on the virtual use of these natural resources remains not fully addressed. In fact, there are still gaps in information on how pigs, which play a major role in the global meat supply and are usually fed through diets high in concentrated feed contribute to the consumption of domestic and international natural resources.

Indeed, to the best of our knowledge, there are no comprehensive studies in the literature that investigates the role played by international trade in animal feed on the consumption of resources for pig production, even on long distances turning into virtual land and water trade. Being the change in dietary supply and the increasing demand for animal products promoted by the development of international trade (Sans and Combris 2015), this is a key aspect in the research on resource-use in the livestock sector, as is clear, for example, from the now recognized link between soybean production and deforestation in the tropics with the soybean imports from China to produce animal feed (Fearnside and Figueiredo 2017, Taherzadeh and Caro 2019, Dou *et al* 2020, Fuchs 2020).

This study aims to fill these gaps, assessing for each country both the internal and external land and water resource consumption in the pig feeding sector in 2018. To this goal, it refers to the amount and type of feed reported in the most up-to-date country and production system based pig diets (FAO 2018a), to crop-specific and country-specific yield data (FAOSTAT 2018), and it uses the spatially distributed crop hydrological model WATNEEDS (Chiarelli *et al* 2020), parametrized with the most up-to-date climate data available. It also analyses the international feed crop trade and the resulting virtual natural resources consumption, which may bring to light several hidden environmental impacts on the partner countries.

The use of land and water resources involved in pigmeat production was assessed under two different scales. An initial analysis at a global level on the natural resources used to produce pig feed in 2018 was performed, based on country-scale data, region-specific animal diets, and assuming a domestic production for all the feed needed (domestic scenario, DS). Then, a detailed analysis focused on the three major producers (China, EU-27, and the United States) was done: in this context country-specific animal data and diets were used, with an estimate of the extent of the impact of feed imports, introducing a measure of virtual international trade of natural resources related to pig feed (trade scenario, TS) (Allan 1993).

The results obtained on the pressure on natural resources caused by the pigmeat sector have several drivers and implications which are addressed in the article, such as the feed-food debate, the adoption of alternative solutions, the effects of international trade, and the impacts of food patterns.

2. Methods

2.1. Pig feed demand: diets, production systems, and herd parameters

In this study, conventional pig diets typical of different production systems were selected based on the Global Livestock Environmental Assessment Model (GLEAM) developed by the Food and Agriculture Organization of the United Nations (FAO) (2018a). GLEAM feed rations were compared with the FAO Statistical Database (FAOSTAT) food balance sheets reporting a country's feed use (FAOSTAT 2018), and some adjustments were made to cereal and oilseed rations while maintaining balanced diets. The diets used are region-specific for the ten global macro-regions for the DS and country-specific for the major producers in the TS. Pig production is differentiated into the backyard, intermediate and industrial systems in GLEAM (Gilbert *et al* 2015), and the same subdivision was maintained in our study.

Crops are used as animal feed in various forms: whole crops, crop residues, and by-products. To assess the land and water resources needed to feed pigs, a distinction was made in both scenarios between human edible feeding stuffs (feed crops), and the so-called crop co-products. The latter are not edible for humans and are not mainly produced for feed, but have an economic value of their own and can be used for other purposes such as the production of bioenergy. Soyatech (2003) reports that *'About 85% of the world's soybeans are processed annually into soybean cake and oil, of which approximately 97% of the meal is further processed into animal feed'*. Although soybean cake is not human edible, it is derived from an edible product and it can be considered as the main driver of soybean production, thus it was analyzed combined with the human edible feeding stuff.

All the ingredients included in the diets are listed in table S1 (available online at stacks.iop.org/ERL/17/074003/mmedia).

The demand for pig feed was estimated according to the number of pigs slaughtered in each production system within the country borders (GLEAM), the associated diets (region- or country-specific), and specific feeding life cycles (see supplementary materials).

2.2. International trade in pig feed

A country's pig feed demand is almost never completely met by domestic production. In DS all the feed items are assumed to be produced domestically, while in TS feed crops could be traded between countries, while co-products must be used in the country in which they are produced.

The same approach by Govoni *et al* (2021) for chicken feed production was used. The country's import share of each feed crop was sub-divided into the different partner countries, according to the FAO Detailed Trade Matrix (DTM) (FAOSTAT 2018). Before using FAO DTM, Kastner *et al* (2011) data treatment approach was applied to identify crop producers and final consumers, avoiding double-counting of re-exports.

2.3. Land and virtual land trade associated with pig feed

Once the shares of local and imported feed demand from each partner country were obtained, in both scenarios, these quantities were converted into the fertile land to be cultivated to produce them. This land comes under the definition of cropland area, which includes all the arable land and land under permanent crops. The fertile land is estimated through crop-specific and country-specific yields from FAO for 2018 (FAOSTAT 2018). Fresh matter yields were converted using crop-specific dry matter contents. When assessing land associated with co-products, yields are calculated using also the Intergovernal Panel on Climate Change (IPCC) formulae (IPCC 2006).

Furthermore, when different co-products are obtained from one crop (e.g. straw, oilseed cakes, molasses), an allocation method adapted from Gerber *et al* (2013) was used to earmark the different shares of land to each feed crop item. This method has been applied based on crop- and co-products-specific factors such as feed use fraction, economic value, mass fraction, and value ratio.

2.4. Water and virtual water trade associated with pig feed

After calculating the land required to produce feed crops and co-products, the water needed for plant growth has to be quantified. The crop-specific agro-hydrological model WATNEEDS was used (Chiarelli *et al* 2020), which is a spatially distributed and physically based model able to differentiate between the demand for green (GW) and blue water (BW), where GW is the water transpired by plants that comes from rainwater stored in soil and BW is the water irrigated from surface and groundwater reservoirs (Hoekstra *et al* 2011). The model solves a vertical soil water balance equation at a resolution of 5 arc-min (approximately 10 km), using as input irrigated and rainfed global maps of cultivated areas, taken from the MIRCA dataset (Portmann *et al* 2010) (see supplementary materials). Irrigated crops have both water components (BW plus GW), while those that are rainfed only have GW.

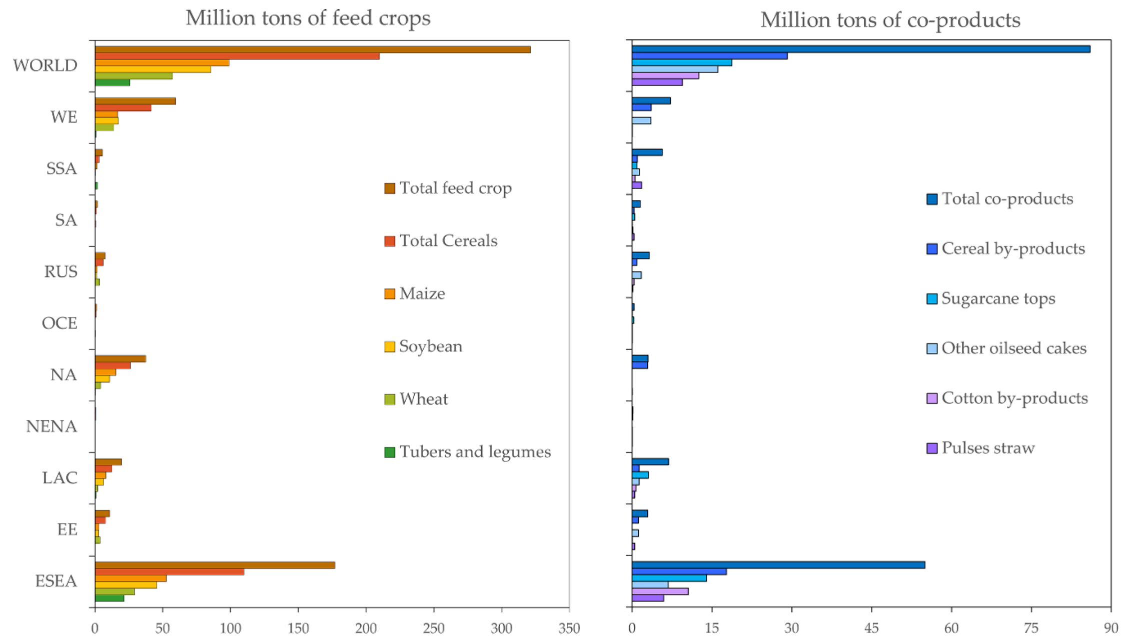

Figure 1. Amounts of feed crops and co-products demands in the ten global macro-regions with region-specific diets. Regions: NA (North America), RUS (Russian Federation), WE (Western Europe), EE (Eastern Europe), NENA (Near East and North Africa), ESEA (East and Southeast Asia), OCE (Oceania), SA (South Asia), LAC (Latin America and the Caribbean) and SSA (Sub-Saharan Africa).

3. Results

3.1. Global pigmeat production—DS

In 2018, a total of 1.5 billion pigs were bred globally, requiring more than 455 Mton of feed, of which 321 Mton (70%) to be produced from crops harvested specifically for pig feed purposes and the remaining 134 Mton (30%) from co-products (86 Mton) and swill feeding. In the DS, this feed-specific demand would stand for an annual agricultural area close to the size of Spain, Italy, and the United Kingdom together (101.5 Mha). This land in turn would require 50.3 km^3 of BW and 439.4 km^3 of GW to grow plants (table S2, figures 1 and 2). The latter results take into account only the feed crops which are grown mainly for feed purposes, thus excluding all co-products and swill feeding (see section 2). Co-products would account for 21% of total feed demand, 28 Mton of crop residues and 58 Mton of by-products, a total of 14 Mha of cropland area, 3.5 km^3 and 55.7 km^3 of BW and GW, respectively (table S3). The remaining 47 Mton of feed include swill feeding and complements.

Cereals represent about 60% of the composition of a pig's diet. However, grains account for only 40%–50% of the land and water demand in the DS, thanks to the high agricultural yields obtained in many countries (i.e. the United States, EU countries). Otherwise, oilseed crops, which make up 20%–25% of a pig's diet, cover 30%–40% of the demand for natural resources due to lower agricultural yields (FAOSTAT 2018).

Cereals would require 52.1 Mha of agricultural land, 18.9 Mha of maize, 14.7 Mha of wheat, and 18.5 Mha of other cereals; at the same time, 40 Mha of soybean, 5.3 Mha for legumes, and 4 Mha of tubers would be consumed. This demand is not evenly divided among the global macro-regions due to the uneven distribution of number of pigs, type of production systems, and agricultural yields. More than half of the land demand is in East and Southeast Asia (57 Mha), where China is the top user. Regions such as Oceania and South Asia require little more than 1 Mton of feed, even less in the Near East and North Africa (table S2, figure 1) due to the extremely low pork consumption, mainly related to religious customs.

The water demand reflects the distribution of land between regions, especially as regards GW. However, BW is also influenced by the distribution of irrigation infrastructure, concentrated in East and Southeast Asia, South Asia, Western Europe, and North America.

The spatial distribution of co-products use in the world shows little amounts in the Western regions despite the large amount of pork production (figure 1). This distribution is strictly related to the production system, where co-products inclusion decreases from backyard to industrial systems. However, countries where industrial systems prevail, such as North America and Europe, use not negligible amounts of cereal by-products and oilseeds cakes, respectively. In addition, it should be noted that the inclusion of co-products (21% of total feed) results in

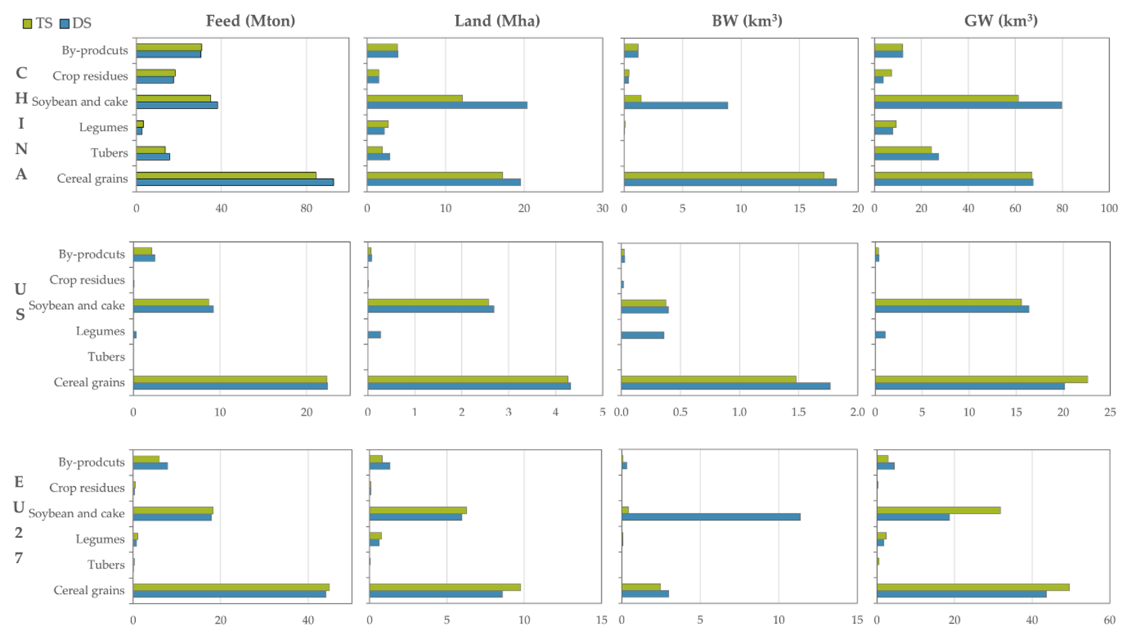

Figure 2. Comparing results of land and water resources used by the three largest producers in the domestic (DS) and trade (TS) scenarios, differentiated in the six feed groups of pig diets.

a reduction in resource use (both land and water, 10% of the total resources). This is a key aspect in evaluating possible sustainable solutions.

3.2. Top pigmeat producers—TS

Unlike other livestock, the pigmeat sector is strongly dominated by China, which hosts about half of the world's pigs. EU-27 own 17% and the United States own 8% of the world's pigs. The remaining production is subdivided among all the other countries in negligible proportions.

The land required by these three countries to meet their pig feed demand in the actual TS includes 64.1 Mha of cropland area. If they were to rear all their pigs with domestic feed, we estimated this number would rise to 74.3 Mha (DS). China, EU-27, and the United States need 39.4 Mha, 17.7 Mha, and 6.9 Mha of agricultural land in the TS, respectively. This figure is roughly the same as that obtained in the DS analysis for the United States (7.4 Mha), where the domestic production is not just an assumption because feed imports account only for 1% of the demand, while the new estimated land is different than before for the other two countries. China's land demand decreased by 11 Mha, considering international feed trade. Trade is necessary to fill the lack or the scarcity in the country's production that is not able to meet its demand, however, trade may also replace domestic production when a locally unproductive crop is imported from a country with higher yields as it is for soybean. The EU-27 countries require a slight increase in demand for land (16.6 Mha–17.7 Mha) because they import feed crops from countries usually have much lower agricultural yields than EU, characterized by low efficiency farming systems and low use of agricultural inputs.

Water use for pig feed production by China, EU-27 and the US is estimated to be less in TS than in DS. BW, in particular, would require 45.9 km^3 if crops were locally grown, value falling to 25.1 km^3 with the actual trade (table 1). Generally, a positive correlation exists between the demand for feed production in term of land and GW, and between the demand for irrigated land and BW. However, if trade leads to a decrease in the demand for land, this does not always imply an associated decrease in GW. In fact, in China, with a 22% saving in agricultural land (table 1), the GW decreases by 9% (from 198.3 km^3 to 181.2 km^3), while the BW by 29% (from 28.6 km^3 to 20.2 km^3). This can be explained by considering that in China most crops are irrigated, particularly soybean, which is the most traded (31 Mton imported and 5 Mton domestic). Therefore crops, in China, use a significant amount of BW if produced locally. In contrast, in Brazil, where China imports most of soybean (75% of its soybean needs), irrigation is negligible, and the crop water requirements is covered almost only by GW. In EU-27 BW savings are significantly high (79%) when moving from local production to imports despite the increase in demand for land and GW. This is because in the EU countries, such as in China, irrigation is widespread compared to the countries they import from (14.8 km^3 to 3 km^3 and 68.7 km^3 to 87.7 km^3, respectively BW and GW) (tables 1 and S8). Results on land and water footprint per unit of pork (TS) are reported in table S7.

North and South America, in particular Brazil, the United States, and Argentina, are net exporters

Table 1. Use of natural resources by the three largest pig producers (China, United States, and EU-27) in terms of land, green and blue water, considering both feed crops and co-products (which are assumed to be produced domestically in both scenarios).

	Top pigmeat producers	Domestic resources	Imported resources	Total resources TS	Total resources DS	Difference between scenarios
LAND (Mha)	China	25.6	13.8	39.4	50.4	−11.0
	United States	6.7	0.2	6.9	7.4	−0.5
	EU-27	6.5	11.2	17.7	16.6	1.2
	Total	38.8	25.2	64.1	74.3	−10.3
GREEN WATER (km^3)	China	92.3	89.0	181.2	198.3	−17.0
	United States	37.7	0.8	38.5	38.0	0.5
	EU-27	31.8	55.9	87.7	68.7	19.0
	Total	161.7	145.7	307.5	305.0	2.5
BLUE WATER (km^3)	China	16.7	3.5	20.2	28.6	−8.4
	United States	1.8	0.0	1.9	2.6	−0.7
	EU-27	1.5	1.5	3.0	14.8	−11.7
	Total	20.1	5.0	25.1	45.9	−20.8

of feed crops, with soybean covering at least 60% of the traded feed (tables S4–S6). China is the largest net importer, to which over 50% of the feed is directed. The EU-27 countries are oilseed importers from Brazil and the United States and of cereals from Ukraine (figure 3). Spain and Germany are the largest producers of pigmeat in the EU-27 and are the largest importers of both virtual land and water associated to pig feed cultivation. Australia and Asian countries such as Thailand and Vietnam are net exporters to China of cassava and rice and of the associated virtual natural resources.

As for co-products, the results change slightly between the two scenarios, mainly due to different amount of co-products included in the diverse diets (region specific and country-specific) (figure 2). These co-products are assumed to be produced locally in both the cases.

4. Discussion

In 2018, pig farming in China, EU-27, and the United States, the three largest producers, required 64.1 Mha of land, 307.5 km^3 of GW, and 25.1 km^3 of BW (table 1, figure 2). In terms of land, pig feed crops in China, EU-27 and the US account for 5% of total global cropland area, the 5% of cereal harvested area and more than 18% of soybean harvested area (FAOSTAT 2018). Concerning water for pig farming requires 6% and 2% of global GW and BW global agricultural water use calculated by Chiarelli *et al* (2020).

4.1. Comparison with other studies

As for the estimated croplands, the results can be compared with those of Mottet *et al* (2017). The latter authors calculated 45 Mha of land for cereals (52 Mha, DS) and 39 Mha for oilseed crops (45 Mha, DS). The difference between ours and their estimates seems to be mainly related to four factors that is adjustments to feed ratio in the diets (see section 2), rise in animal numbers between 2010–2018, up-to-date (and greater) agricultural yields (FAOSTAT 2018), and feed trade. Different estimates for cereals depend mainly on the different adjustments to feed ratio used by the authors and also on the rise in pig numbers. For oilseeds, all four factors interact. In particular, Mottet *et al* included a global trade matrix on soybean cakes, while we obtained a total global estimate only under the hypothesis of domestic feed production.

Focusing on the EU-27, Sporchia *et al* (2021) estimated that total EU pigmeat production in 2017 need 14.5 Mha of land, slightly less than our estimate (17.7 Mha), 51.9 km^3 GW that is lower than ours (87.7 km^3), and 3.9 km^3 BW that is higher than ours (3 km^3). These differences can be attributed to a smaller soybean content in animal diets used by the authors, implying smaller imports from South America of low-yield crop as soybean. The local use of a higher BW and a lower GW is due the domestic cultivation of other irrigated oilseeds. In addition, the different methods and periods to which the climate data refer to for GW and BW calculation make difficult the comparison of water use.

4.2. Feed-food debate and alternative solutions

Excluding co-products, which account for 21% of feed, 12% of land and 9% of water, the remaining feed demand is met by human-edible products (cereals) or crops that could be consumed by humans (soybean instead of cake). The inclusion of these crops reaches even higher levels in industrial systems (more than 90% of competition). Maize and wheat are the main ingredients since they are the main source of energy in pig diets, as with broilers and layers (Govoni *et al* 2021) (figure 1, table S2). For this reason, the production of ASFs has attracted considerable attention in recent years aiming to mitigate environmental impacts and find solutions to the growing consumption of natural resources and the increasing competition in the sector. The soybean supply issue has

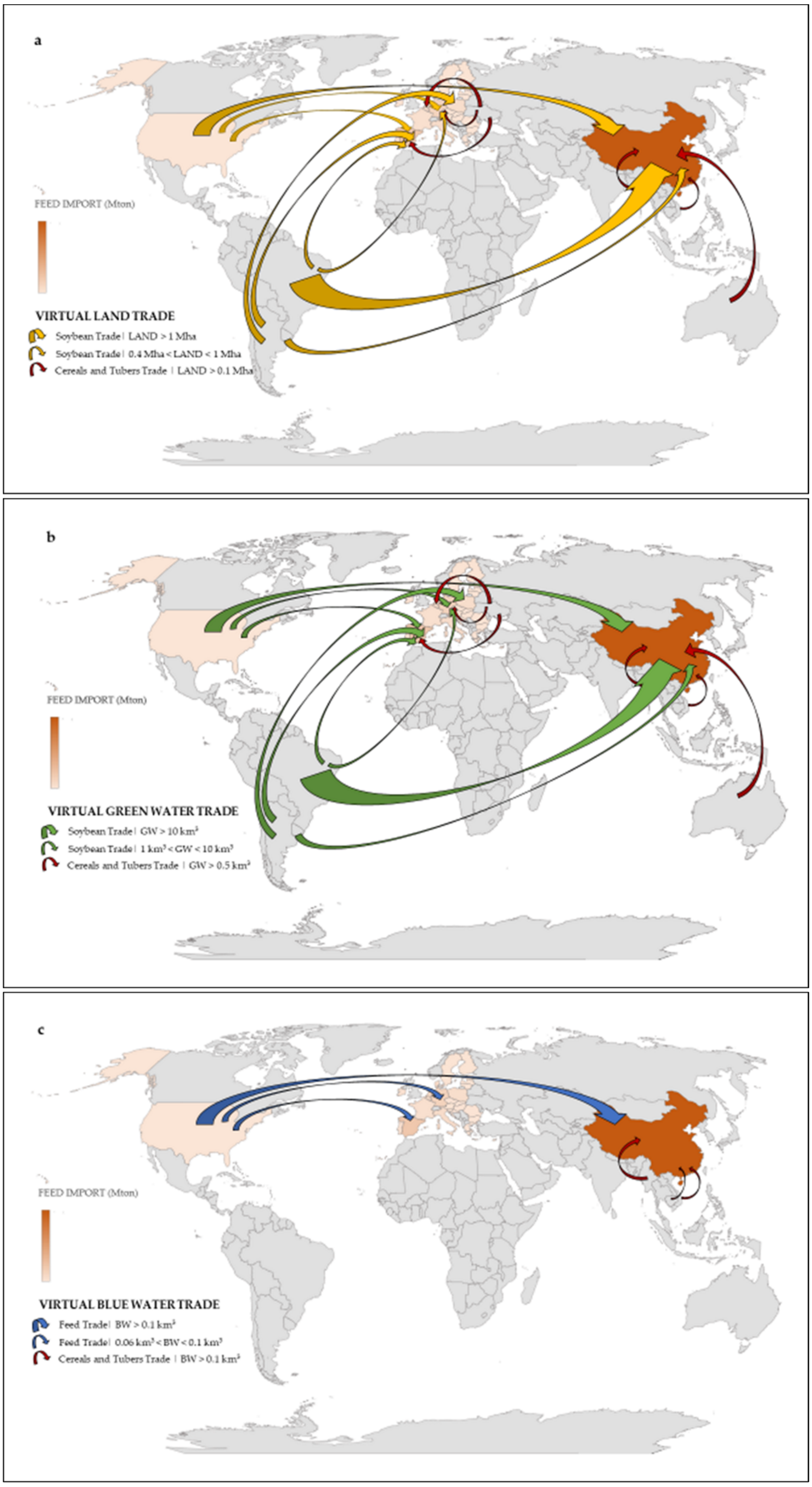

Figure 3. Virtual trade of natural resources associated with pig feed crops in China, EU-27, and the United States. (a) Virtual land trade, (b) virtual green water trade, (c) virtual blue water trade.

been addressed by the feed industry which now promotes responsible sourcing practices (FEFAC 2021). Several innovative strategies have recently been proposed to stem the problem. Among these, the use of alternative ingredients as animal feed stands out due to its environmental benefits (Luciano *et al* 2020, 2021, Pinotti *et al* 2020, 2021). Exploiting ex-food and food waste in the feed production chain can not only save resources but also ensure the effective disposal of these products, thus fully meeting the needs of the circular economy (Kummu *et al* 2012). The target species of these kinds of solutions are omnivores, e.g. pigs and poultry, although recent studies did not exclude the possibility of their use also in ruminant diets. In this context, Zu Ermgassen *et al* (2016) estimated a potential land saving of 21.5% in EU pork production with the use of swill feeding in pig diets, although not yet allowed its use by the European legislation. While ex-food and swill could be used especially to replace cereals as the energy source, insects are one of the most promising alternatives as a protein source in animal nutrition (Pinotti *et al* 2019, Gasco *et al* 2020). The use of all these kinds of alternative ingredients, however, needs to be in full compliance with the countries' food laws to ensure their safety when used as feed (Pinotti and Dell'Orto 2011, Tretola *et al* 2017, Pinotti *et al* 2021).

4.3. Pros and cons of international feed trade

We show the required feed input, and, in turn, the related resources used originated partly from the countries' own crop production and the remainder from international feed trade. The inclusion of trade in the livestock feed production sector, in particular, could lead to domestic feed savings, and/or natural resources savings (Govoni *et al* 2021). This last is the case when crops are exported from countries with higher agricultural yields and/or higher water-use efficiency, to countries where the domestic crop cultivation would be less profitable and/or more resource-demanding (D'Odorico *et al* 2014, Zhang *et al* 2016, Qiang *et al* 2020). China and EU-27 are the largest feed importers, mainly of oilseed crops. Accounting of imported oilseed crops results in agricultural land (11 Mha) and BW (20.1 km^3) saving if compared to DS (table 1). However, this save can have negative effects on the environment. The expansion of cropland areas and tree plantations in the tropics, where the main crop exporting countries are located, takes place at the expense of forests and other ecosystems (Elferink 2009, Balogh and Jámbor 2020). Pendrill *et al* (2019) estimated that in China and Europe, but also many other developed countries, emissions from deforestation embodied in traded agricultural goods equal or even exceed emissions from the domestic agricultural sector. Land-use changes, biodiversity losses, soil erosion, changes in nitrogen and carbon cycles, greenhouse gas emissions, and water scarcity are just some of the effects caused by international trade which subsequently create water and food security issues (Rulli *et al* 2019).

Further analyses could therefore consider the use of resources, not only in the meat producer country (where the animal is fed) but also in the meat consumer country, where the supply chain ends, and where the meat demand originate from. This will be crucial in light of the projected increase in meat consumption in developing countries, where marginalized small-scale farmers started to have access to previously unreachable global markets (Lundström 2019). In our case, the live pig trade is negligible, amounting to less than 3% of the global herd. However, the trade of processed pigmeat and derivative products is significant, covering 14% of the production (FAOSTAT 2018). The latter share changes dramatically from country to country. China consumes its entire pigmeat production domestically, unlike the United States and the EU-27 where exports cover 22% and 45% of the production, respectively. In EU-27, however, exports are partially offset by a share of pigmeat imports from extra-EU countries (41% of domestic consumption).

4.4. Dietary patterns implications

Another significant driver affecting meat consumption, particularly pigmeat, is religion. Religion has a significant impact on food patterns and may even impose restrictions on individual dietary choices (Hong 2013). Since meat and all ASFs have a strong environmental impact, the correlation between religion and diets may therefore have implications on the use of natural resources (Westhoek *et al* 2016). In this context, the low pigmeat consumption and production in some countries results in less pressure on natural resources. This happens in all predominantly Muslim countries, located above all in the Near East and North Africa, and South Asia. Jews, like Muslims, are forbidden to eat pork, which is why even in Israel the consumption of this type of meat compared to the total meat is less than 2% (FAOSTAT 2018; figure 4). Christianity does not put tight restrictions on dietary habits, however, the Eritrean and the Ethiopian Orthodox Church do not permit pork consumption (Seleshe *et al* 2014). In other countries, religious traditions (Hinduism, Buddhism, and others) are intertwined with the spread of vegetarianism, as in India (Arora *et al* 2020). Most Indians are not vegetarians (only 39% define themselves as vegetarians), however more than 80% do follow at least some limitations on meat in their diet and thus India is one of the least meat-consuming countries (FAOSTAT 2018, Corichi 2021). A different situation arises in Africa, in particular in the Sub-Saharan region. Here the consumption of pigmeat is negligible in the diet of most countries due to poverty. In some countries such as Mali, Sudan, Niger, Djibouti, the religious restriction is relevant due to the strong Muslim component. However, the main driver of low pork intake is the low income, to the extent that not only pork but meat consumption, in general, is very low (Szűcs and Vida 2017). These countries are still faced with severe burdens of undernutrition and malnutrition associated with the low consumption of animal sources and other protein-rich foods (Willett *et al* 2019). An important role is played in these countries by poultry meat from backyard systems, which are mainly subsistence driven or oriented at local markets (Govoni *et al* 2021). Although difficult to estimate, 'bushmeat' consumption is widespread in Central

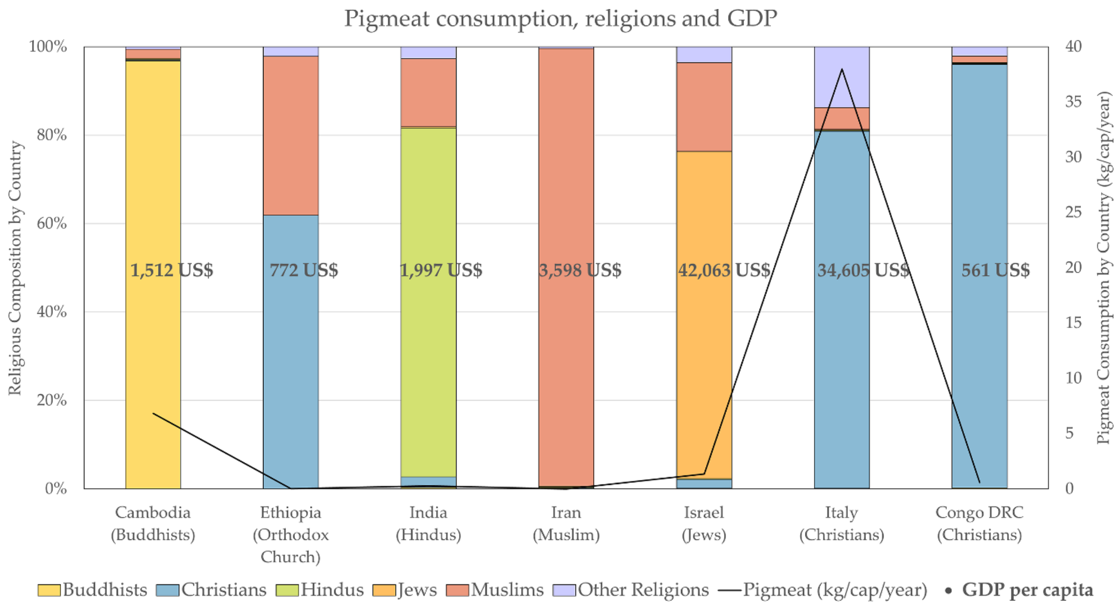

Figure 4. Combination of religious composition, GDP per capita and trend in pigmeat in consumption in some representative countries.

Africa (Ziegler 2010) so it is often not included in the reported country meat consumption. Examples of these interconnections between pigmeat consumption, religions, and GDP are presented in figure 4 for some representative countries.

5. Conclusions

This study has shown that in 2018, the demand for pig feed of China, the EU-27, and the United States, required 39.4 Mha, 17.7 Mha, and 6.9 Mha of agricultural land, respectively, where 6.3 Mha needed for co-products production. In addition to agricultural land, pig feed production required 332.6 of water, subdivided in 25.1 km^3 BW and 307.5 km^3 GW. Among the three largest producers mentioned, China uses the largest share of water which is 80% BW and 60% GW (20.2 km^3 and 181.2 km^3, respectively). These natural resources represent 5% of global cropland area (17% of cropland harvested for livestock) and 5% of total agricultural water use.

Pig feed composition is mostly represented by cereals usually covering more than 60% of the total, whose demand is generally met by the countries' own production, meaning domestic natural resources consumption. The remaining part of feed consists of the protein source represented by oilseed crops, including mostly soybean and related by-products. These crops are highly traded, causing a virtual trade of resources between countries even across large distances. Exceptions are countries such as the United States, which is fully able to domestically meet its demand for pig feed (both in terms of cereals and proteins).

The international trade in animal feed is still highly controversial from the point of view of sustainability due to the negative environmental impact it can produce. On one hand, it represents a potential resource-saving strategy for countries affected by natural resources (e.g. land and/or water) scarcity or uses inefficiency. On the other hand, it could be one of the main drivers of global changes such as land-use change, biodiversity losses, food insecurity, and water scarcity. We have shown the trade of natural resources associated with international feed trade is not negligible and should be considered by countries in the context of sustainable development.

Our results show that pig feed is made up of a significant amount of human-edible ingredients, such as grains and soybeans. This demand for edible feed crops and the associated use of natural resources could make pig farming unsustainable, especially in light of population growth projections. For this reason, the relentless research in the field of animal nutrition remains essential to make the livestock sector more sustainable and to stem the growing pressure on natural resources with new strategies, in a world that is expected to be increasingly populated in the coming decades.

Data availability statement

Any data that support the findings of this study are included within the article.

Acknowledgments

The authors are funded by Cariplo Foundation (SUSFEED Project 0887 CUP D49H170000300007) and by Regione Lombardia (ASSO 14 Project CUP D44I20002000002).

Conflict of 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.

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