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Re-thinking water use in pig diets while accounting for food-feed competition

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ABSTRACT

Livestock feed production is one of the primary users of freshwater and arable land, and it is also in competition with human food production. Therefore, we require reconsideration of the way we use freshwater in livestock feed production. The objective of this study is to assess the impact on freshwater use of pork production by using alternative pig diets based on local feed ingredients, or by-products. We used a lifecycle approach to analyse the freshwater use associated with feed production to produce one kg of pork. We explored three feeding scenarios (STANDARD: diets commercially used in Ireland; LOCAL: diets based on ingredients grown in Ireland; and BY-PRODUCT: diets based on by-products only). We calculated the freshwater use, using the water footprint (WFP) method, and the competition for water use between food and feed production using the water use ratio (WUR) for each scenario. The WUR quantifies the maximum amount of human digestible protein (HDP) derived from food crops that could be produced on the same land, and using the same water resources, that were used to grow the feed ingredients needed to produce 1 kg of pork.

The WFP of the scenarios was 2,470 L/kg pork for STANDARD, 2,492 L/kg pork for LOCAL, and 2,205 L/kg pork for BY-PRODUCT. When we considered the WUR, none of the scenarios had a value < 1 (i.e. in all scenarios, more HDP can be produced from direct cultivation of food crops rather than pork). However, the BY-PRODUCT scenario (1.4) performed better than STANDARD (1.9) and LOCAL (2.9). Beet pulp and bakery by-products had zero WFP and no edibility and were thus considered promising ingredients. Moreover, rapeseed meal had a low WFP and rapeseed meal and sunflower seed meal are not considered human edible and were considered fit for future inclusion in diets. We also concluded that both the WFP and WUR methods have separate strengths and limitations, and should thus be used in conjunction; the ideal diet is one with the minimum WFP and WUR. Consideration of human edibility of feed ingredients is an important approach which should be included in future studies. Moreover, the entire food system including dairy, beef, poultry and other competitive uses should be taken into account when considering which feed ingredients to use in pig diets.

1. Introduction

Livestock production is responsible for about one third of global freshwater withdrawals (i.e. blue water use), primarily for the irrigation of feed crops (Poore and Nemecek, 2018). Furthermore, almost 40% of global arable land, and hence the coupled green water withdrawal (i.e. rainwater that is taken up by plants or evaporates), is used for animal feed production (Mottet et al., 2017). From a food security perspective, using these land and water resources to produce food that can be consumed by humans directly is much more efficient than using it to produce feed (Schlink et al., 2010; Foley et al., 2011). As global population is still rising, the pressure on land and water resources is expected to increase further. We, therefore, need to optimize the utilization of our natural resources to produce food, which implies, among others, rethinking freshwater use in animal production systems.

The pig sector is one of the largest livestock sectors globally (Bellini,

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2021). Pig production in Europe is currently primarily carried out under intensive industrial land-less systems. As a result, it hugely depends on the import of feed from outside the farm (Meul et al., 2012). In pig production chain, feed production is the main contributor to freshwater use (70%), with green water being most important (79%), followed by blue water (21%) (Noya et al., 2016). On-farm processes contribute about 24% (González-García et al., 2015). One method to estimate the green and blue water use of food products (either plant or animal based) is 'water foot-printing (WFP)', which is defined as the volume of freshwater that is used directly or indirectly to produce the product, e.g. a unit (kg) of pork (Ercin et al., 2012).

Water foot-printing does account for the water use for cultivation of animal feed, but it does not explain the effect of redirecting this water, and the associated land, to cultivate crops for human consumption. Thus, although WFP helps us to understand the water resource competition from a blue water use perspective, since green water use is directly connected to land use, competition over the latter remains unclear. Thus, the question arises whether to use our current diminishing resources for production of animal feed (which can be either human edible or inedible) or for production of crops that are to be consumed by humans directly. The tension or trade-offs between uses of edible crops for animal feed or human consumption is defined as food-feed competition (van Zanten et al., 2018).

While pigs are efficient feed convertors, they currently consume high quality feed, and often consume more human edible protein than they produce (Mottet et al., 2017; van Zanten et al., 2018). Major ingredients fed to pigs that could also be used for human consumption include, among others, wheat, soybean, barley, and maize. To improve the sustainability of pig production, it is crucial to account for food-feed competition. To account for food-feed competition and to address the interlinkages between land and water resources, an alternative to the WFP method has been proposed, called the water use ratio (WUR; Ran et al., 2017). The WUR allows us to account for this competition by calculating the ratio between the maximum amount of human digestible protein (HDP) that could have been produced from food crops from all water used to produce one kg of animal product (e.g., pork), and the amount of HDP in that kg of animal product. If the WUR exceeds 1, then it means more HDP can be produced from food crops.

To improve the environmental sustainability of pig diets several researchers have studied the use of alternative feed ingredients to those with a high environmental footprint, such as imported soybeans and soybean meal (Meul et al., 2012). With regard to food-feed competition, there is growing interest in use of feed ingredients that are unsuitable for human consumption. These potentially viable by-products mainly come from grain fermentation, grain milling, bakeries, milk processing, meat processing, vegetable losses, sugar and starch production (Thaler and Holden, 2010). Inclusion of by-products (wheat bran, wheat middlings, dried citrus pulp, potato peels) in pig diets has been studied in relation to their nutritive value as pig feed (Kyriazakis and Emmans, 1995; Rosenfelder et al., 2013; Ncobela et al., 2017), and in relation to various environmental impacts, but not in relation to freshwater use. The environmental impact (i.e., acidification potential, eutrophication potential, global warming potential, nonrenewable energy use and nonrenewable resource use) of including co-products (meat meal, bakery meal, corn DDGS and wheat shorts) in grower/finisher diets, for example, was studied by Mackenzie et al. (2016) and it was found that increased inclusion of bakery meal and wheat shorts reduced all the studied impact categories.

Although by-products and locally grown ingredients have been included in pig diets previously to investigate whether they improve measures of sustainability, no detailed studies exist that calculated the WFP, or the WUR of diets based on locally grown ingredients or a diet completely based on by-products compared to that of a conventional diet. Thus, we hypothesize that alterations in feed composition (e.g., locally grown crops, other crops, residues or food waste) could reduce the freshwater use of pig farms while also reducing food-feed competition and make pig production systems more sustainable.

The objective of this study is to assess the impact on freshwater use of pork production when using alternative pig diets based on local feed ingredients, or by-products unsuitable for human consumption, based on a life cycle approach. To account for food-feed competition, the WUR was calculated in addition to the WFP. We have explored which feeding strategies (scenarios) can reduce the green and blue water use of pig diets including all production phases (gestation, lactation, weaners and finishers) and help in avoiding feed-food competition. For this study the conventional pig diets used in Ireland were used as the benchmark.

2. Material and methods

Our study focused on the Irish pig production chain, so we formulated scenarios representing plausible diets with feed ingredients used in Ireland, including the ones that are imported into the country. We compared the freshwater use, expressed per kg pork, of three scenarios that differed in the types of ingredients used during gestation, lactation, the weaner and the finisher stage. This resulted in 12 diets in total, i.e., three potential scenarios in each of the four production stages (3x4). All the diets were applied to a standard Irish pig farm, which was simulated using the Teagasc Pig Production Model (TPPM; Calderón Díaz et al., 2019). This standard Irish pig farm was based on the performance figures from the National Pig Herd Performance Report for 2020 (Teagasc, 2020), and was defined as a farrow-to-finish system with an average herd size of 799 sows, weekly farrowing batches with a mean of 2.3 litters per sow per year, 14.3 piglets born alive per litter, a piglet mortality rate of 11.1%, a weaner mortality rate of 2.8%, a finisher mortality of 2.7%, and a resulting 27.5 pigs produced per sow per year. Pigs were sent to slaughter once they reach 115.3 kg.

2.1. Considered scenarios

The diets explored represent three scenarios: standard scenario (STANDARD) representing those diets typically and currently used commercially in Ireland; local scenario (LOCAL) considering diets based on ingredients grown in Ireland; and by-product scenario (BY-PRODUCT) consisting of diets formulated using entirely by-products. Diets were composed based on nutritional requirements without considering dietary costs. This allowed us to explore opportunities for reducing

Table 1
Diet composition per scenario and production stage.

	Gestation	Lactation	Weaners	Finishers
STANDARD diet				
Barley	40%	30%	19%	11%
Wheat	30%	40%	33%	43%
Maize			13%	23%
Soyabean meal	11%	21%	21%	18%
Soya hulls	11%			1.8%
Full fat soya			6.2%	
Soya oil	1.0%	3.0%	4.0%	0.4%
LOCAL diet				
Barley	34%	20%	10%	7.9%
Wheat	33%	33%	20%	31%
Field peas	8.0%	19%	31%	21%
Faba beans	18%	23%	30%	25%
Rye				11%
Rapeseed oil		0.4%	4.5%	0.5%
BY-PRODUCT diet				
Wheat middlings	15%	34%	20%	31%
Rapeseed meal	7.5%			
Bakery by-product	30%	30%	45%	32%
Maize DDGS		6.0%		12%
Soyabean meal		10%	19%	8.5%
Whey powder	12%	15%	13%	13%
Sunflower seed meal	14%			
Beet pulp	16%	1.0%		

*Diet details in Appendix A (Table A1).

freshwater use without economic constraints. Table 1 shows the summary of diet composition with percentage of each feed ingredient used in all scenarios and production stages. The production stages considered in the study are gestation, lactation, weaners and finishers. Gilts are included in the gestation stage and they are fed the gestation sow diet. Grower-finisher stages are considered together in this study because in Ireland, these two stages are normally not separated, producers keep pigs in the same group from when they are about 35 kg to slaughter age. The detailed ingredients and diet composition of the studied pig diets can be found in Appendix A (Table A1). Nutritional needs for pigs (FEDNA, 2013) and the nutritional values for all the feed ingredients were taken from Fundación Española para el Desarrollo de la Nutrición Animal (FEDNA, 2019) and NRC feed ingredient tables (NRC, 2012). All the diets were formulated on dry-fed basis and as per the energy and nutritional requirements of the different stages, so animal performance was assumed to remain unchanged. A detailed description of the diets is given below.

Scenario 1: STANDARD.

The standard scenario was based on the pig diets typically used in Ireland with the main ingredients being wheat, barley, maize, soyabean meal, full fat soya, soya hulls and soya oil. These diets were based on the reference diets used in Teagasc pig research facility (a 200 sow farrow to finish farm).

Scenario 2: LOCAL.

The locally grown diets included ingredients which are commonly grown within Ireland and could be used in Irish pig diets instead of sourcing imported feed. The ingredients used were wheat, barley, field peas, rye, faba beans and rapeseed oil. Field peas and faba beans were mainly used to replace the protein rich imported soyabean used in the standard diets, and rapeseed oil was used to replace soya oil.

Scenario 3: BY-PRODUCT.

The by-product diets were formulated using by-products that are commonly produced in or imported to Ireland, and frequently used in pig diets because of their nutritional value. The by-products included were wheat middling, rapeseed meal (RSM), bakery by-product, whey powder, sunflower seed meal (SSM), beet pulp, maize DDGS (distiller's dried grains with solubles) and soyabean meal (SBM).

2.2. Simulated farm data using TPPM

The Teagasc Pig Production Model (TPPM) is a stochastic model that simulates the annual production of a farm using biological (e.g. herd size, number of litters/sow/year, mortality %), physical (e.g. infrastructure) and technical (e.g. feeding practices) inputs to calculate physical (e.g. feed usage and number of pigs slaughtered) and financial outputs. The detailed feed usage and performance parameters of simulated pig farms, generated using the TPPM when provided with each of the three scenario diets for each production stage, are presented in Table 2.

Table 2
Details of the simulated farm (using Teagasc Pig Production Model) for each scenario.

	Scenario		
	STANDARD	LOCAL	BY-PRODUCT
Feed usage, t/year			
Gestation	670	654	675
Lactation	430	448	436
Weaner	1270	1292	1346
Finisher	3762	3977	4773
Sales/year			
Culled sows and finisher pigs	21372	21372	21372
Meat sold, t/year[a]	1856	1856	1856
ADG[b] wean-to-sale, g	775	809	775
ADFI[c] wean-to-sale, g	1705	1783	2060
FCR[d] wean-to-sale	2.20	2.20	2.66

[a] Carcass weight including weight of culled sows and finisher pigs.
[b] Average daily gain.
[c] Average daily feed intake.
[d] Feed conversion ratio.

Table 3
List of feed ingredients in STANDARD and BY-PRODUCT diets and country of origin.

Feed ingredient	Country of Origin
Barley	United Kingdom
Wheat	United Kingdom
Maize	Ukraine, Canada
Soyabean and by-products	Argentina
Wheat middling	United Kingdom
Rapeseed meal	France
Bakery by-product	United Kingdom
Whey powder	Ireland
Sunflower seed meal	Portugal
Beet pulp	Ireland
Maize DDGS	Canada

2.3. Water footprint assessment

2.3.1. Freshwater use for crop cultivation

The WFP of a diet was calculated by weighing the WFP of each feed ingredient by its relative share in the diet. Data on the WFP of added minerals and vitamins are scarce, and as the share of these additives was almost comparable in all diets, we neglected to include the water use of these additives. We used the method described by De Boer et al. (2013) to calculate the green and blue water used for each feed ingredient.

To determine the country of origin of each feed ingredient, we first obtained the national feed import data for ingredients included in the standard and the by-products diet from the Feedingstuffs, Fertilizer, Grain and Poultry Division (FFGPD) of the Department of Agriculture, Food and the Marine (DAFM) of Ireland (Table 3). All ingredients in the LOCAL diet were grown in Ireland.

In each country, the International Food Policy Research Institute (IFPRI) grid data (IFPRI, 2019) were used to identify the regions/locations (coordinates) that are responsible for the highest national production. For the selected region, the predominant soil type was identified from the Harmonized World Soil Database v 1.2 (FAO/IIASA/ISRIC/ISS-CAS/JRC, 2012). The sowing dates of each crop and length of the growing period were either obtained from national databases Teagasc (2021) (personal communication) or, when not available, from global databases (USDA, 2020). The actual yield of the crop in the region with the highest production was calculated using the IFPRI grid data (IFPRI, 2019), and where not available data from FAO (2020) was used.

Second, the AQUASTAT climate information tool (AgERA5 dataset; Boogaard et al., 2020) was used to retrieve the climate data (mean temperature, mean sunshine etc.) and calculate the ET_o (reference evapotranspiration, millimeter/growing period) for the specific location based on the classic Penman-Monteith equation (Allen et al., 1998). These climate inputs and ET_o values were added to the CROPWAT-online, (on AQUASTAT) along with the crop type, sowing dates, cropping days and soil type to calculate the soil water balance and crop water requirements. Subsequently, the crop specific evapotranspiration (ET_p, millimeter) over the entire growing period was calculated, assuming maximum soil water availability. This was calculated by multiplying the crop coefficient (K_c) for the respective growth period with the reference crop evaporation (ET_o) per day, and summing these daily values for the entire crop growing period from sowing to harvest (Eq. (1)).

$$ET_p = \sum Kc \text{ x } ET_o \quad (1)$$

Rain-fed evapotranspiration (ET_{rf}, millimeter), i.e. the volume of the evapotranspired precipitation (green water) of a crop over its growth period, was derived from AQUASTAT. ET_{rf} for the crop growing period was calculated using Eq. (2)

$$ET_{rf} = \sum K_s \text{ x } ET_p \tag{2}$$

Where Ks, the transpiration reduction factor, necessary to consider water stress, was calculated as a function of maximum and actual available soil moisture in the rooting zone derived from AQUASTAT. Also the values for effective root depth and soil water depletion fraction were taken from AQUASTAT. The consumption of rainwater (green) and irrigation (blue) water per kg of crop dry matter was calculated using the actual crop yields. To determine blue water use during crop cultivation, ET_{rf} was compared with the actual evapotranspiration of a crop (ET_a) based on actual yields. Evapotranspiration related to the actual yield (ET_a) (millimeters/year) was computed as follows (3):

$$ET_a = -\left(\left(1-Y_a/Y_{mp}\right) / k_y - 1\right) \times ET_p \tag{3}$$

where Y_a is the actual crop yield per hectare; Y_{mp} is the maximum potential crop yield per hectare; k_y is the yield response factor, which is crop specific and describes the relationship between ET deficit and yield reduction, and ET_p is the crop specific potential evapotranspiration (millimeters) as described above. The potential crop yield Y_{mp} was derived by multiplying the national average yield for the region with a factor of 1.2 (Reynolds et al., 2000).

If $ET_a \leq ET_{rf}$ then irrigation is assumed to be absent. If $ET_a > ET_{rf}$, irrigation volume was computed as follows (4):

$$\text{Irrigation volume} = \left(ET_a - ET_{rf}\right) / Ir_{eff} \tag{4}$$

Where Ir_{eff} is the irrigation efficiency, which was assumed to be 0.7 for all crops, implying that per unit of irrigation water, 70% was taken up by the crop and 30% was lost (Allen et al., 1998). The waterfootprint of all ingredients are mentioned in Appendix B (Table B1).

2.3.2. *Water footprint of diets and per kg of pork*

To compute the green and blue water use of each crop/ingredient the following method was used. Under rain-fed conditions, blue crop water use was zero, whereas green water use of the crop was calculated as follows (5):

$$\text{Green water use} = \left(Et_a \times 10\right) / \text{crop yield} \tag{5}$$

where green water use is expressed in m^3 per tonnes, Et_a is expressed in millimeters per year, and the factor 10 is used to convert mm per year to m^3/ha, and crop yield is expressed in t/ha.

Blue water use of the crop during crop production is estimated by the irrigation volume for a specific crop grown in specific region, as follows (6):

$$\text{Blue water use} = \left(\text{Irrigation volume} \times 10\right) / \text{crop yield} \tag{6}$$

where blue water use is expressed in m^3 per tonnes, irrigation is expressed in millimeters per year, and the factor 10 is used to convert mm per year to m^3/ha and, crop yield is expressed in t/ha.

Based on the consumptive green and blue water use per crop calculated above we computed the green and blue WFP (m^3/t) of each feed ingredient. This was done by multiplying the green and blue water use with the economic allocation factor of each crop/feed ingredient, divided by the amount of ingredient produced per unit of crop (t/t). The economic allocation factor for each feed ingredient was derived from databases (van Middelaar et al., 2011; Vellinga et al., 2013; Colomb et al., 2015; Wernet et al., 2016).

The total input of each diet (t/year) (gestation, lactation, weaner, and finisher) and the relative share of each feed ingredient in the diet (%) was used to calculate the amount of each feed ingredient in the diet (t/year). These values were then multiplied with the green and blue water use (m^3/t) to compute total green and blue water use of each crop ingredient per farm per year.

The WFP of all ingredients was summed up to get the total green and blue WFP of each diet.

To determine the amount of water used per kg of pork produced (associated with feed production) on the farm for each diet (gestation, lactation, weaners and finisher) under the three scenarios (STANDARD, LOCAL and BY-PRODUCT) we divided the green/blue water use (L) by the total amount of pork (kg) i.e. carcass weight, produced on the farm during the year.

2.4. *Water use ratio*

Water use ratio represents the maximum amount of human digestible protein (HDP) derived from food crops that could be produced on the same land and using the same water resources that were used to grow the feed ingredients to produce 1 kg of pig-meat. To determine food-feed competition and water use efficiency of the pig diets in the different scenarios we calculated the WUR according to Eq (7), as described by Ran et al. (2017):

$$\text{WUR} = \frac{\sum_{i=1}^{n}\sum_{j=1}^{m}\left(CWU_{ij\times}\ HDP_j\right)}{HDP\ of\ one\ kg\ pork} \tag{7}$$

where CWU_{ij} is the consumptive water use in m^3, evapotranspired over a land area used to cultivate the amount of feed ingredient i (i = 1,n) in country j (j = 1,m) used to produce 1 kg of pork. HDP_j is the maximum amount of human digestible protein (HDP) that can be produced using the same water resources, by direct cultivation of food crops in country j. HDP values were corrected for protein quality by multiplying the crude protein values with the digestible indispensable amino acid score (DIAAS), which is a measure of protein quality of a food product. It is based on the lowest score of the true ileal digestibility of the indispensable amino acids that are present in product (Rutherfurd et al., 2015). The denominator is the amount of HDP in 1 kg of pork. To determine the direct value of protein in animal feed that is human edible we modified the methodology to include human edible portion (HEP) of feed ingredients and protein quality based on Hennessy et al. (2021).

2.4.1. *Human digestible protein in food crops and pork*

To determine the HDP in food crops, we first quantified the amount of consumptive water resources (CWU_{ij}) required to grow each feed ingredient (i = 1, n) in the different countries of origin (j = 1, m), used to produce 1 kg of pork. This was done by calculating the WFP of each feed ingredient as explained in section 2.3.2. Second, the suitability of the same land area to cultivate food crops using the crop suitability index defined by Global Agro-Ecological Zones (GAEZ) database (IIASA and FAO, 2012). Crop suitability in this database is defined by eight groups (not suitable to very high), depending on the crop requirements, climatic conditions, soil properties and management practices. We evaluated the crop suitability for the current cultivated land based on high input levels, optimal water supply and baseline climatic conditions (1961–1990). Crops falling within the suitability index >55 (i.e. good, high or very high) were considered suitable for cultivation on that land. Based on the suitability of the crops, we selected the crop which had the highest yield and protein content. Then, we determined which crop had the highest HDP by multiplying the amount of food crop produced per hectare for each suitable crop with its dry matter content, HEP, crude protein content and DIAAS (Table 4).

Once the most suitable crop (i.e. the one with the highest HDP) was selected, we determined the WFP of cultivating that food crop in the same region, replacing the feed ingredient. Next, we assessed how much of this food crop (kg) could be produced using the same water resources used to produce the amount of that feed ingredient needed to produce 1 kg of pork. Then we calculated the HDP_j in the selected food crop that replaced the feed ingredient. The sum of all the HDP in all the feeds per scenario form the numerator of the WUR equation. To assess the

Table 4

Crude protein (CP) values, Human Digestible Protein (HEP) and protein digestibility scores (DIAAS) of pork and food crops and by-products.

	kg DM/kg product	g CP/kg DM	Estimated HEP %	DIAAS %
Pork	0.50^{a}	139^{a}	78^{g}	114^{c}
Wheat	0.90^{a}	125^{a}	66^{b}	40^{c}
Barley	0.90^{a}	110^{a}	61^{b}	47^{c}
Maize	0.90^{a}	105^{a}	15^{b}	42^{c}
Soybean	0.99^{a}	399^{a}	61^{b}	100^{c}
Oats	0.92^{a}	184^{a}	80^{d}	57^{e}
Peas	0.21^{a}	54^{a}	74^{b}	65^{c}
Faba beans	0.89^{a}	261^{a}	92^{b}	57^{e}
Rye	0.89^{a}	116^{a}	72^{b}	48^{c}
Wheat middlings	0.88^{f}	143^{f}	90^{b}	70^{f}
Whey powder	0.96^{f}	110^{f}	80^{b}	90^{f}
Soyabean meal	0.90^{f}	470^{f}	60^{b}	86^{f}

[a] USDA, 2015.

[b] Laisse et al., 2019.

[c] Ertl et al. (2016).

[d] Wilkinson (2011).

[e] Hennessy et al. (2021).

[f] Fedna (2013).

[g] Ockerman and Hansen (1988).

denominator, i.e., the amount of HDP in 1 kg edible pork, we multiplied the crude protein content and DIAAS (Table 4).

A ratio larger than 1 indicates that a larger amount of HDP can be produced from food crops rather than pork and a ratio below 1 means that through livestock production we can produce more HDP rather than direct food crop cultivation.

2.4.2. *Water use ratio of the three scenarios*

In the case of the main feed crops which are human edible such as wheat, barley, peas, faba beans etc. we calculated the WUR by directly calculating the HDP of these crops or by replacing them with another crop as described in section 2.4.1. Unlike other (van Zanten et al., 2016; Ran et al., 2017) studies that calculated the land use ratio (LUR) or WUR of animal-sourced food products, we also accounted for food-feed competition in the case of the by-products which was not considered in these studies. To do so, we followed two approaches. In the first approach, for by-products that are human edible or have a human edible portion (e.g., wheat middlings, whey powder and soybean meal), we calculated the HDP, as if humans could have consumed these by-products directly. By-products that do not have a human edible portion were assigned a value of zero. In the second approach, we used economic allocation, to calculate how much HDP could have been produced by cultivating food crops based on the same procedure as for the main ingredients.

Sugar beet pulp and bakery by-products do not have a human edible portion so have a HDP of zero, and they also have an economic value close to zero. Rapeseed meal, sunflower seed meal and maize DDGS also do not have any human edible portion (i.e. HEP = 0), but because of their economic value they were replaced by another food crop with higher HDP. In the case of whey powder, the maximum HDP was based on the HEP of whey powder (so no alternative application of water resources). Economic allocation factors of all ingredients are listed in Appendix B (Table B2) (van Middelaar et al., 2011; Vellinga et al., 2013; Colomb et al., 2015; Wernet et al., 2016).

3. Results

3.1. *Water footprint of the three scenarios*

Table 5 shows the WFP of pork associated with feed production (i.e. partial WFP) in each of the three scenarios, broken down into green and blue water, and the contribution per production stage, expressed in liters per kg of pork. The total WFP was 2470 L/kg pork for STANDARD, 2492 L/kg pork for LOCAL, and 2205 L/kg pork for BY-PRODUCT. The WFP for the STANDARD scenario consisted entirely of green water, whereas that of LOCAL and BY-PRODUCT included blue water (227 L/kg pork in case of LOCAL and 5.0 L/kg pork in case of BY-PRODUCT) arising from the peas, faba beans and whey powder added to the diets.

Table 5

The water footprint of pork associated with feed production, divided between green and blue water, and the contribution per production stage (L/kg pork) per scenario.

Stage/ Diet	STANDARD	LOCAL		BY-PRODUCT	
	Green WFP (L/kg pork)	Green WFP (L/kg pork)	Blue WFP (L/kg pork)	Green WFP (L/kg pork)	Blue WFP (L/kg pork)
Gestation	226	198	10	463	0.41
Lactation	181	149	14	112	0.35
Weaner	640	512	64	342	0.92
Finisher	1424	1403	138	1284	3.3
Total	2470	2265	227	2200	5.0

Among all the scenarios and production stages, the finisher stage (58–66%) contributed most to the WFP (green and blue water), followed by weaners (16–28%), gestation (5–21%) and lactation stages (5–7%).

The diet composition and distribution of water use per feed ingredient per kg pork is presented in Fig. 1 (Appendix B; Table B3 also provides a list of diet composition and water use per feed ingredient). In the STANDARD scenario the highest contribution to the WFP of pork was from soyabean meal followed by wheat, maize and barley. In the LOCAL scenario, the highest contribution was from peas and faba beans. These crops also contributed to the blue WFP for the LOCAL scenario. In the BY-PRODUCT scenario, almost half of the WFP of pork was related to water use for the production of whey powder and soyabean meal, being by-products from cheese and soyabean production, although they only constituted 14% and 16% of the diet on a dry matter basis (Table 1). Beet pulp and bakery by-products are wastes arising from human food industry and are commonly used in the manufacture of compound feeds. They have no economic value so all of the water used is allocated to production of the main product and the respective products have a WFP of zero when using economic allocation.

3.2. *Water use ratio*

The water use ratios (WUR) of pork for the three scenarios are presented in Fig. 2. The WUR accounts for food-feed competition and the fact that water resources used for animal feed production can potentially support food crops for humans. The BY-PRODUCT scenario resulted in the lowest WUR, followed by the STANDARD and LOCAL scenarios. In the STANDARD and LOCAL scenarios, the two approaches used to calculate the WUR resulted in similar values. The WUR values show that per kg HDP in pork, we could potentially produce approximately 2 kg HDP (STANDARD) and approximately 3 kg HDP (LOCAL) from food crops directly, using the same water resources. In the BY-PRODUCT scenario, the two approaches to calculate WUR did result in slightly different outcomes. The first approach (only edible by-products contribute to food-feed competition) resulted in a WUR of 1.3, while the second approach (all by-products with an economic value contribute to food-feed competition) resulted in a WUR of 1.6. The second approach results in a slightly higher WUR as this approach accounts for the potential alternative use of water resources in case human inedible by-products do have an economic value, while the first approach does not include an alternative water use if the byproduct is human inedible. For example, rapeseed meal and sunflower seed meal have no human edible portion but an economic value of 23% and 20% respectively. Thus, using the second approach, the water use allocated to those products could potentially be used to produce a food crop. The fact that

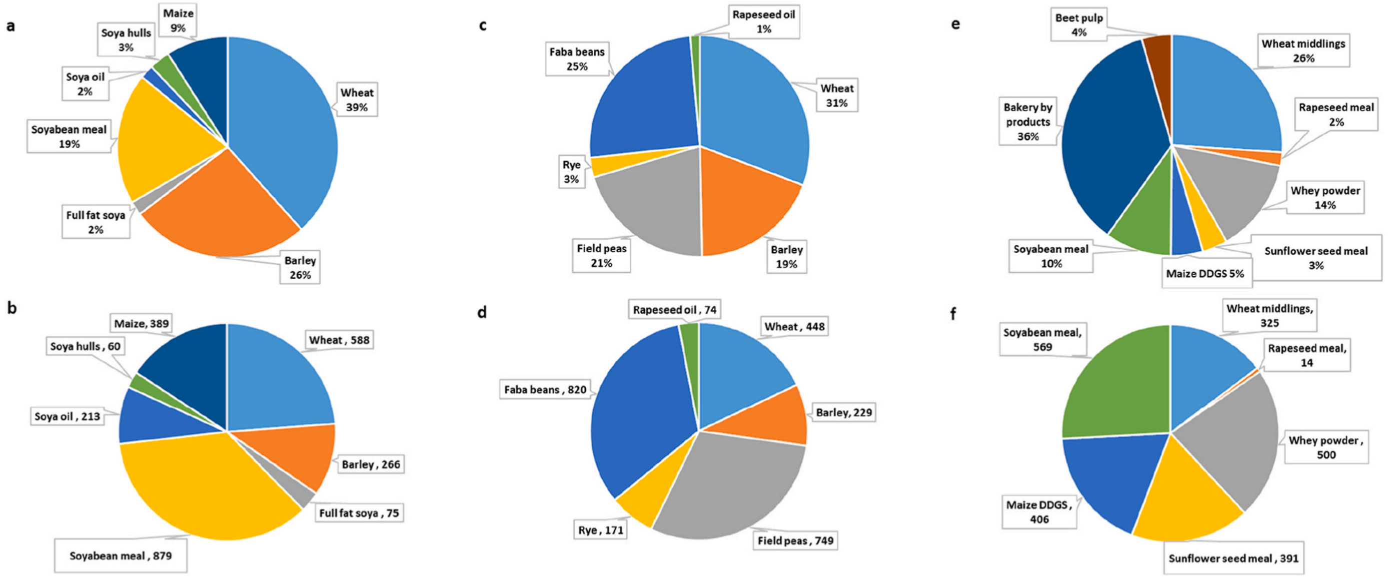

Fig. 1. Diet composition (% of ingredients per kg DM) by scenario: STANDARD (a), LOCAL (c) and BY-PRODUCT (e) and consumptive water use (CWU in liters/kg pork) per ingredient by scenario: STANDARD (b), LOCAL (d) and BY-PRODUCT (f) (Appendix B; Table B3 provides the tabulated data for the diet composition and consumptive water use).

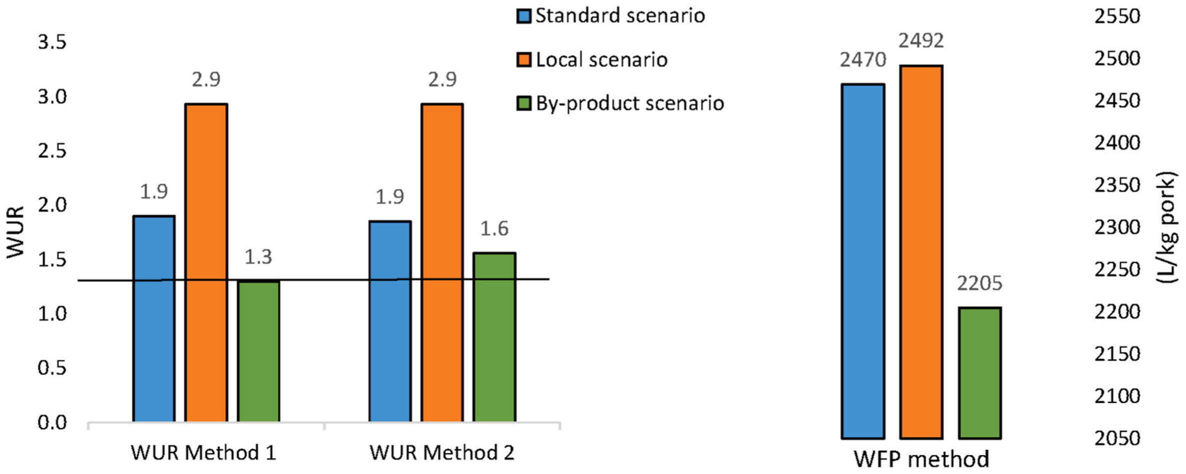

Fig. 2. Water use ratio (WUR) and the WFP (associated with feed production) L per kg pork of the three scenarios.

even the first approach results in a WUR >1 shows that even though by-products were the only ingredients, the proportion of human edible products used in the BY-PRODUCT scenario is still high. Because the results were so similar, the different WUR approaches did not affect the comparison between scenarios.

When we compare the results of WFP and WUR (Fig. 2), it is evident that while for the WFP method results for the STANDARD and LOCAL scenarios are comparable, the WUR of the STANDARD scenario is lower than that of the LOCAL scenario. Regardless of the method used, the BY-PRODUCT scenario has the lowest water use.

4. Discussion

This study aimed to investigate the impact of alternative pig diets based either on locally grown feed ingredients, or food crop by-products, on the freshwater use of pork production. We used a life cycle approach to calculate the WFP of pork, focusing on freshwater use related to feed production only. The Irish pig production system was taken as a starting point and feed ingredients grown in Ireland and imported into Ireland were included. This study also considered competition for water resources between food and feed production for both the local and by-product scenarios relative to a typical commercially used pig diet by calculating the WUR of pork for each scenario. Below, we will discuss the results from both analyses (WFP and WUR), and suggest options for altering feed composition to shift to a more sustainable use of water resources.

4.1. Significance of WFP and WUR results

4.1.1. WFP of the three scenarios

The WFP calculations showed that the STANDARD and LOCAL scenario result in similar WFP values (liters per kg pork), while in case of the BY-PRODUCT scenario, the WFP was about 12% lower. The factors that influence this partial WFP of pork are the composition of the diet (i.e., the share of each ingredients in the diet), the feed requirements per kg pork produced, and the WFP of each feed ingredient. In practice, diet composition is affected by the price, the availability, and the nutritional value of the single ingredients.

In the STANDARD scenario three ingredients contributed 75% of the total WFP of pork; soyabean meal (1498 m^3/t meal), maize (977 m^3/t maize from Ukraine; 520 m^3/t maize from Canada) and wheat (451 m^3/t wheat). Previous researchers (Mekonnen and Hoekstra, 2010) have also concluded that, wheat, maize and soyabean have the largest share in the total WFP. The high WFP of the LOCAL diet is mainly driven by field peas (green WFP 777 m^3/t peas; blue WFP 245 m^3/t peas) and faba beans (green WFP 895 m^3/t beans; blue WFP 55 m^3/t), as they explain 63% of the WFP of pork and constitute 46% of the dry matter of the diet. Beans and peas have a high WFP due to their lower yield, which means that more water is used per kg of beans and peas (Mekonnen and Hoekstra, 2010). Although in Ireland peas and beans are not irrigated, our results show a small blue WFP for both products. This can be explained by a divergence between the yield data and the climate data in case of those two crops. As field peas and beans are only recently grown in Ireland, yield data was derived from FAO (2020) and based on the years 2016–2019 for peas and 2018–2019 for beans, while the climate dataset (AgERA5) we used for the WFP calculations was from 1979 to present. For all other crops, yield data was based on IFPRI (2019) and therefore in line with the climate data. Conversely, although wheat constitutes 31% of the dry matter of diets used in the LOCAL scenario, it has a lower contribution to the total WFP of pork due to its lower WFP (448 m^3/t wheat).

In the BY-PRODUCT scenario, soyabean meal contributes 26% to the WFP but constitutes only 10% of the dry matter of the diet. Another by-product, whey powder, a by-product of cheese production from milk, contributes 23% to the WFP even though it forms only 14% of the dry matter of the diet. Similarly, maize DDGS and sunflower seed meal in the BY-PRODUCT scenario is only 5% of the dry matter, but the WFP contribution is 18%. Thus, the high WFPs of each of the four diets in this scenario can be attributed to the input of these four ingredients. Sunflower seed meal contributes most to green water use (7971 m^3/t meal) followed by soyabean meal (1498 m^3/t meal), maize DDGS (1258 m^3/t DDGS) and whey powder (983 m^3/t powder). Moreover, whey powder is the only ingredient in the BY-PRODUCT scenario with a small proportion of blue water use (9.9 m^3/t powder), in addition to the green water use. In case of the BY-PRODUCT scenario, by-products used in the diet such as whey powder, maize DDGS and wheat middlings, all have a high WFP mainly because of the high ratio between inputs- and outputs (i.e. to produce small quantities of whey powder, relatively large volumes of milk are required), and therefore these ingredients have an important influence on the WFP of pork. To reduce the contribution to the WFP by soyabean meal and sunflower seed meal, we considered replacing it with alternatives such as rapeseed meal (507 m^3/t meal), which is produced in Europe and has a lower WFP. Indeed, a recent review by Lannuzel et al. (2022), concluded that rapeseed meal is a promising ingredients in terms of reducing reliance on imported soya and have competitive prices. However, the protein and lysine contents are lower and fiber contents are higher than soyabean meal which limits its inclusion in monogastric diets. The finisher stage is the main contributor to the total WFP. So that our results would be commercially relevant we formulated all three scenario diets so that the animals would have similar growth-rates, consistent with those typically found on Irish pig farms. As such, the inclusion of these identified alternatives to soyabean meal was not feasible.

Nevertheless, the WFP results show that by-products with a WFP of zero (in this case bakery by-products and beet pulp) or low WFP rapeseed meal (507 m^3/t) hold promise as ingredients that can reduce the total diet WFP. Reconsidering current growth rates might be required to enable the inclusion of ingredients of lower qualities, contributing to lowering the WFP of pork.

4.1.2. WUR results

Comparison of the WUR of the various diets allows us to compare how the competition between food and feed production varies across the scenarios. Our findings that the WUR of the BY-PRODUCT scenario was lower than both the standard and local ones clearly demonstrated the benefits of this diet over the others, using this metric. For both the LOCAL and STANDARD scenarios most of the ingredients used in the diets were human edible, and the WURs were the same whether the edibility or economic value of the ingredients was used in the calculations. However, in the BY-PRODUCT scenario there was a slight difference in the WUR, whereby WUR based on edibility was lower than when based on the economic value of ingredients.

According to a recent study on LUR (Hennessy et al., 2021), all the feed used in standard pig diets originates from arable crop production, therefore resulting in food-feed competition. However, in our study we formulated diets including crop by-products or waste, considered feasible based on expert judgement. We used the optimum growth performance approach for pigs, which meant that diets needed to meet the required energy demand. Thus, we ended up including some energy and nutrient rich human edible by-products in the diets such as whey powder, wheat middlings and soyabean meal. From the perspective of food-feed competition inedible by-products like bakery by-products, beet pulp, rapeseed meal and sunflower seed meal are preferred. Consequently, if we allow for a lower growth performance, the selection of by-products could shift to those not edible and with less energy and protein, potentially resulting in lower WUR.

Apart from the WFP approach that was used in this study, literature also categorizes other methods commonly used to quantify freshwater use in livestock production (Ran et al., 2016). These methods include water productivity assessment and other LCA based methods. While water productivity assessment doesn't differentiate between green and blue water use, LCA methods normally only focus on blue water use. Thus, for our study we chose to use the WFP assessment to quantify both green and blue water use of pig feeding scenarios and to combine this assessment with a WUR method to determine the impact on food-feed competition.

4.2. Water use assessment methods

Green water constitutes a major part of pig diets (Mekonnen and Hoekstra, 2012), and indeed in the current study STANDARD scenario has 100% green water use. Even though the LOCAL and BY-PRODUCT scenarios incorporated some blue water use, the vast majority was green water use (91% and 99.8%). Inclusion of green water in water use assessment studies has historically been controversial since it is not associated with water stress; nevertheless, its inclusion can help in reducing the total water use of food production (Ran et al., 2017). Moreover, green water also plays a crucial role in food-feed competition since most of the feed ingredients used in the pig diets are human edible. Green water use is associated with arable land and therefore, human edible feed crops grown on this land are in direct competition with human food and by-products have an indirect competition for resources.

The benefit of using both the WFP and WUR methods is that they provide insights that are complementary to each other: while WFP accounts only for the water use for cultivation of animal feed, the WUR explains the effect of redirecting this water and the connected land use to cultivate crops for human consumption. Both methods are needed and should be used in conjunction because WFP helps us to identify the crops which are not water intensive and therefore more suited for animal feed, but it does not show alternatives where this water can be diverted and it does not reflect the increased pressure on arable land use. On the other hand, the WUR helps us to compare livestock systems and food crop production, and determine which systems use water most efficiently to produce human edible protein while accounting for food-feed competition. The WUR shows us that by using crop residues/by-products it is possible to convert human non-edible feed products into food (pork).

When calculating food-feed competition based on the WUR we used two methods, edibility and economic value of the product. Previous studies that calculated food-feed competition using either or both LUR or WUR assumed the economic value of by-products to be zero and did not consider their edibility. This approach does not reflect the true competition for resources and overestimates the resource use of the entire system (van Zanten et al., 2018). Therefore, economic value and human edibility are additional criteria which should be used when calculating the WUR. However, in our study we saw that economic allocation alone did not make any difference to the WUR, because most of the feed ingredients were human edible. Thus, using more inedible by-products in the diets might lead to less arable land use for animal feed production, and the unused land can be used for growing food crops. However, selecting by-products should be done carefully based on their palatability and nutritional profiles as both can impact on overall pig performance. Moreover, to optimize the use of by-products in the diets and lower the overall WFP, we should follow an entire food system approach, thus considering other production systems like dairy, beef and poultry which pose competitive uses.

To verify our results, a sensitivity analysis was carried out to assess the impact of changing some of the main parameters to calculate the WFP and WUR values. For the WFP values, we changed the evapotranspiration values and maximum potential yields of crops by 10%. These changes did not alter the conclusion that the WFPs of pork were similar for the STANDARD and LOCAL scenarios, while that for the BY-PRODUCT scenario was lower. For the WUR values, we adapted the HEP values based on the *potential* human edible protein values reported by Laisse et al. (2019). The final conclusion of our study did not change and the WUR of pork was lower for the BY-PRODUCT scenario than for the other two scenarios. The final graphs of the sensitivity analysis are added to Appendix C.

4.3. Future research and feeding systems

Future water use assessments should focus on valorizing only the inedible food wastes and crop by-products for inclusion in pig diets. A wide range of by-products are available from the grain milling, baking, brewing, fruit and vegetable processing and other industries, some of which are already used in the present system. A recent study (van Hal et al., 2019) also concluded that feeding livestock only with low-opportunity cost feed such as food waste and food processing by-products can provide some nutritious animal source food while reducing competition for land resources. Future feeding systems should consider the exact inclusion levels of different by-products so that they have minimal impact on growth performance. It is also important to consider that by-product-based diets could be cheaper than traditional diets, and the savings could offset costs associated with reduced growth rates. Detailed cost: benefit analysis should be carried out in tandem with investigation of water use assessment. Apart from use in animal feed, there are many other competitive uses of by-products such as for fuel and fibre production. Thus, availability of by-products should also be considered and making all conclusions based on WFP and WUR is not entirely correct.

Our data demonstrate that based upon both WFP and WUR calculations, by-product-based diets hold promise to promote sustainable water use. However, increasing the proportion of by-products used in pig diets will require a change in farming practices and moving from a more profit based to a more circular and sustainable approach. Crop by-products generally have large variability in nutritional value and physical characteristics and thus more knowledge is required about the best handling and processing methods to include these as feed ingredients (Boumans et al., 2022). To include crop by-products in pig diets we need more insight into their nutritional value, palatability, intake and digestibility, as well as into the impact on pig performance and well-being. Indeed, future research should also focus on understanding consumer perception of diverting from the current consumption pattern of a high animal source food diet to a moderate animal source food diet. Therefore, feedback from livestock producers and consumers is critical if we want to move towards a circular livestock production system.

5. Conclusion

When we compared three scenarios STANDARD, LOCAL and BY-PRODUCT based on the WFP and WUR methods, the BY-PRODUCT scenario used the least water and had the lowest impact on food-feed competition. The results of the WFP assessment show that the most promising ingredients are rapeseed meal, bakery by-products and beet pulp as they have a lower or no water use. The results of the WUR assessment suggest that all the human inedible by-products i.e. bakery by-products, rape seed meal, beet pulp and sunflower seed meal are best suited for reducing food-feed competition. In conclusion, water use assessment should focus on both WFP and WUR in conjunction, and human edibility of the feed ingredients is an important criteria to determine which ingredients will reduce the competition over water resources between food and feed production in the future.

CRediT authorship contribution statement

Shilpi Misra: Conceptualization, Methodology, Data curation, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. **John Upton:** Conceptualization, Methodology, Supervision, Writing – review & editing. **Edgar G. Manzanilla:** Methodology, Writing – review & editing. **Keelin O'Driscoll:** Methodology, Supervision, Writing – review & editing. **Amy J. Quinn:** Writing – review & editing. **Imke J.M. de Boer:** Conceptualization, Supervision, Writing – review & editing. **Corina E. van Middelaar:** Conceptualization, Methodology, Supervision, Writing – review & editing.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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Appendix A

Table A.1
Composition of all the diets belonging to the three scenarios
Ingredients and nutritional composition of the three scenarios for all the production stages. All ingredient inclusions shown in g/kg as fed, all nutrient levels shown as % as fed unless otherwise stated.

Ingredients	Standard	Local	By-product

(*continued on next page*)

Table A.1 (*continued*)

Ingredients	Standard				Local				By-product			
	Gestation	Lactation	Weaners	Finishers	Gestation	Lactation	Weaners	Finishers	Gestation	Lactation	Weaners	Finishers
	Gestation	Lactation	Weaners	Finishers	Gestation	Lactation	Weaners	Finishers	Gestation	Lactation	Weaners	Finishers
Barley	400.0	300.0	188.5	105.0	340.0	200.00	100.0	79.1				
Wheat	300.0	400.0	327.3	433.5	330.0	325.00	200.0	310.0				
Maize	0.00	0.00	132.0	225.3								
Soyabean meal (SBM)	110.0	214.0	206.0	176.0					0.00	100.0	190.0	85.0
Full fat soya	0.00	0.00	61.6	0.0								
Soya hulls	110.9	0.00	0.00	18.0								
Soya oil	10.0	30.0	40.0	4.00	0.00	3.50	45.0	4.50				
Field peas					80.0	190.00	310.0	207.1				
Faba beans					180.0	230.00	300.0	250.0				
Rye					0.00	0.00	0.00	110.0				
Wheat middlings									150.0	340.0	200.0	305.0
Bakery byproduct									300.0	300.0	450.0	319.0
Rapeseed meal (RSM)									75.0	0.00	0.00	0.00
Wheypowder									115.0	150.0	128.0	130.0
Sunflower seed meal (SSM)									135.0	0.00	0.00	0.00
Beet pulp									160.0	10.0	0.00	0.00
Maize DDGS									0.00	60.0	0.00	120.0
CaCO3	13.0	14.0	6.00	11.0	14.2	11.0	5.00	9.50	12.5	18.0	10.1	10.6
Di calcium phosphate	16.8	15.5	15.7	10.0	15.8	20.0	18.5	12.0	2.00	2.50	3.90	0.00
HCl Lys	0.00	0.70	5.80	2.60	0.00	0.70	4.40	0.45	0.00	1.60	5.90	2.98
DL- Methionine	0.00	0.00	1.40	0.40	0.10	0.90	3.60	1.29	0.00	0.01	1.70	0.20
L-Threonine	0.00	0.00	2.30	0.30	0.00	0.60	3.00	0.50	0.00	0.00	1.90	0.00
L-Tryptophan	0.00	0.00	0.40	0.00	0.00	0.20	1.10	0.30	0.00	0.00	0.40	0.00
Salt	3.94	4.50	4.00	3.80	4.00	4.00	4.00	4.00				
Vit/Min	35.4	21.3	9.00	10.1	35.9	14.1	5.40	11.4	50.5	17.9	8.10	27.2
Nutrients												
ME (MJ/kg)	12.2	13.5	14.3	13.3	12.5	12.9	14.0	13.1	12.1	13.2	13.9	13.1
NE (MJ/kg)	8.92	10.1	10.7	9.94	9.35	9.56	10.4	9.71	8.55	9.60	10.2	9.61
Dig Lys	0.53	0.81	1.29	0.85	0.55	0.77	1.24	0.79	0.51	0.79	1.27	0.83
Trp min	0.17	0.23	0.28	0.20	0.15	0.18	0.28	0.19	0.19	0.20	0.27	0.19
Met total min	0.22	0.27	0.42	0.29	0.19	0.27	0.54	0.31	0.29	0.27	0.44	0.29
Thr total min	0.49	0.63	0.91	0.59	0.46	0.60	0.92	0.61	0.59	0.64	0.88	0.61
Crude protein	14.2	18.0	19.6	16.4	14.2	16.4	19.1	16.8	15.3	17.1	19.2	16.9
Ca	1.04	1.02	0.73	0.77	1.00	0.98	0.73	0.73	1.00	0.99	0.72	0.71
P	0.60	0.63	0.64	0.52	0.60	0.69	0.67	0.55	0.63	0.70	0.62	0.67
Dig P	0.32	0.32	0.33	0.24	0.31	0.38	0.37	0.28	0.26	0.33	0.30	0.32

Appendix B

Table B.1
Water footprint of all feed ingredients

Feed ingredients (Origin)	GreenWFP (m^3/ton)	BlueWFP (m^3/ton)
Wheat (UK)	451	0
Wheat (Ireland)	448	0
Barley (UK)	479	0
Barley (Ireland)	563	0
Maize (Ukraine)	977	0
Maize (Canada)	520	0
Soyabean meal (Argentina)	1498	0
Full fat soya (Argentina)	1898	0
Soya hulls (Argentina)	779	0
Soya oil (Argentina)	4621	0
Faba beans (Ireland)	895	55
Peas (Ireland)	777	245
Rye (Ireland)	726	0
Rapeseed oil (Ireland)	1780	0
Wheat middlings (UK)	306	0
Bakery by-products (UK)	0	0
Whey powder (Ireland)	983	9.93
Beet pulp (Ireland)	0	0
Rapeseed meal (France)	507	0
Sunflower seed meal (Portugal)	7971	0
Maize DDGS (Canada)	1258	0

Table B.2
Economic allocation factors of all feed ingredients

Feed ingredients	Economic allocation factor
Wheat	0.78
Barley	0.75
Maize	1
Soyabean meal	0.556
Soya hulls	0.031
Soya oil	0.341
Faba beans	1
Peas	1
Rye	0.70
Rapeseed oil	0.756
Wheat middlings	0.066
Bakery by-products	0
Whey powder	0.079
Beet pulp	0
Rapeseed meal	0.234
Sunflower seed meal	0.203
Maize DDGS	0.1935

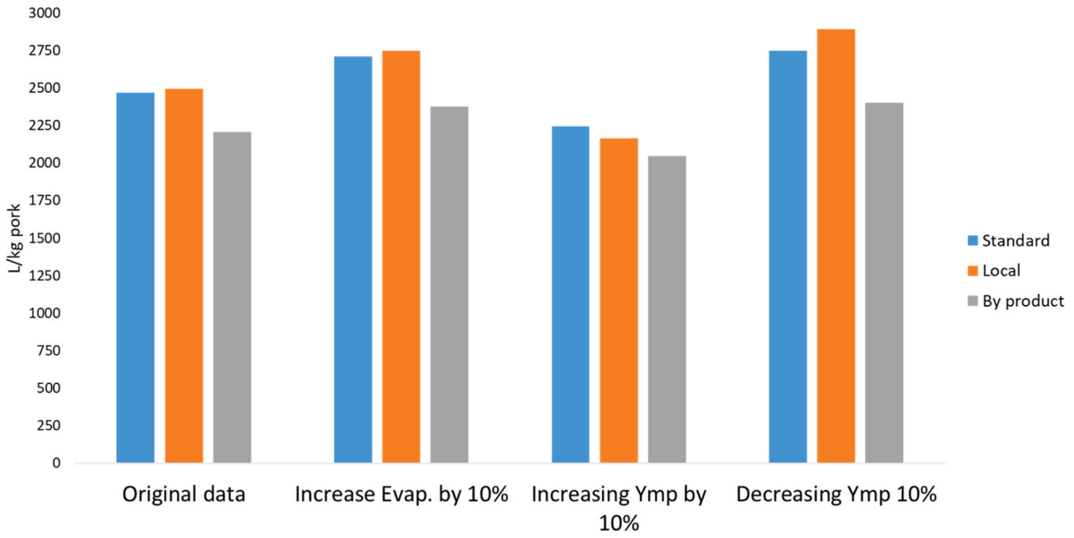
Table B.3
Dry matter (%) and Consumptive water use (CWU in liters/kg pork) of ingredients by scenario: STANDARD, LOCAL and BY-PRODUCT

Feed ingredients	STANDARD		LOCAL		BY-PRODUCT	
	Dry matter %	CWU L/kg pork	Dry matter %	CWU L/kg pork	Dry matter %	CWU L/kg pork
Wheat	38%	588				
Barley	26%	266				
Full fat soya	2%	75				
Soyabean meal	19%	879				
Soya oil	2%	213				
Soya hulls	3%	60				
Maize	9%	389				
Wheat			31%	448		
Barley			19%	229		
Field peas			21%	749		
Rye			3%	171		
Faba beans			25%	820		
Rapeseed oil			1%	74		
Wheat middlings					26%	325
Rapeseed meal					2%	14
Whey powder					14%	500
Sunflower seed meal					4%	391
Maize DDGS					5%	406
Soyabean meal					10%	569
Bakery by products					36%	0
Beet pulp					4%	0

Appendix C. Sensitivity analysis of HEP and WFP values. Results of WUR and WFP are presented in the graphs below

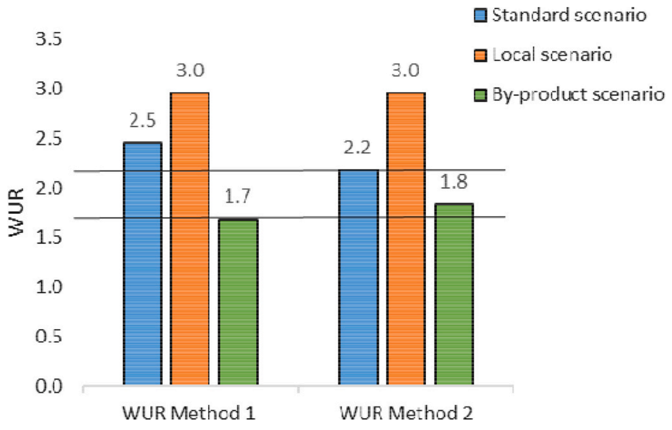
STANDARD scenario- Reference pig diets from Ireland, LOCAL scenario-all feed ingredients grown in Ireland, BY-PRODUCT scenario-only by-product based diet.

WFP results



Original data are our main results presented in the paper, Increase Evapotranspiration values 10% -we increased all the Eto, Etp and Etrf values by 10%, Increased and decreased the maximum potential yields (Ymp) by 10%

WUR ratio results



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