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Accounting for feed-food competition in environmental impact assessment: Towards a resource efficient food-system

O. van Hal*,[1], A.A.A. Weijenberg [1], I.J.M. de Boer, H.H.E. van Zanten

Animal Production Systems Group, Wageningen University & Research, PO Box 338, 6700, AH, Wageningen, the Netherlands

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A B S T R A C T

This study demonstrates the effect of better accounting for feed-food competition in life cycle assessment (LCA) to derive mitigation strategies that contribute to efficiently feeding the growing world population. Economic allocation, commonly used in LCA, falls short in accounting for feed-food competition as it does not consider interlinkages in the food system. The authors hypothesise that an alternative "food-based" allocation better accounts for food-feed competition by assigning no environmental impact to feed products unfit for human consumption. To evaluate the impact of accounting for feed-food competition on LCA results, economic and food-based allocation were compared in an LCA of a novel egg production system that feeds only products unsuitable or undesired for human consumption. Using economic allocation, the global warming potential (GWP) of 1.30 kg CO_2-eq, energy use (EU) of 10.49 MJ, land use (LU) of 2.90 m^2, and land use ratio (LUR) of 1.56 per kg egg of the case study farm were all lower than that of free range or organic eggs. Avoiding feed-food competition on this farm reduced the environmental impact per kg egg by 56–65% for GWP, 46–54% for EU, 35–48% for LU and 88% for LUR, compared to free-range laying hens fed a conventional diet. Accounting for feed-food competition with food-based allocation further reduced impacts per kg egg by 44% for GWP to 0.57 kg CO_2-eq, 38% for EU to 4.05 MJ, 90% for LU to 2.59 m^2, and 83% for LUR to 1.29. This improved LCA better captures the complexity of the food system.

1. Introduction

Animal-source food (ASF) supplies humans with high quality protein and essential micro-nutrients (Craig and Mangels, 2009), but it's production has significant negative environmental impacts (Steinfeld et al., 2006). These impacts include climate change (Vermeulen et al., 2012), ecosystem pollution (Gerber et al., 2013), biodiversity loss (Newbold et al., 2016) and use of scarce resources such as land, water, and fossil-energy (Steinfeld et al., 2006). Globally, the livestock sector is responsible for ~15% of anthropogenic greenhouse gas (GHG) emissions (Gerber et al., 2013), and uses ~80% of farmed land (Poore and Nemecek, 2018).

Feed cultivation is responsible for the majority of greenhouse gas (GHG) emissions and almost all land use (LU) of livestock production (De Vries and de Boer, 2010). Globally, it occupies ~40% of all arable land (Mottet et al., 2017) on which food crop cultivation is more efficient (Garnett, 2011) as nutrients are lost when converting plant into animal biomass (Godfray et al., 2010). To address arable land availability, a major limitation to sustainably feeding the world's future population (Lambin and Meyfroidt, 2011), recent studies propose to avoid this inefficiency by feeding livestock only with products that humans cannot or do not want to eat (Van Zanten et al., 2018). These 'low-opportunity-cost feedstuffs' (LCF) include crop residues, e.g. wheat straw or beet tails, and by-products, e.g. wheat middlings or sugar beet pulp, of food crops grown on arable land, food waste, and grazing resources from non-arable land (Schader et al., 2015). Livestock fed with only LCF upcycle nutrients that would otherwise be lost to the food system into ASF (Bowles et al., 2019), without using additional arable land (Garnett et al., 2015). By avoiding competition between feed and food crop production (Röös et al., 2017), they contribute to a more efficient food supply (Van Kernebeek et al., 2016).

Despite this scientific acknowledgement of the relevance of

Abbreviations/concepts: ASF, Animal-source food; LUR, Land use ratio; LCA, Life cycle assessment; LU, Land use; EU, Energy use; GWP, Global warming potential; GHG, Greenhouse gas; LCF, Low-opportunity-cost feedstuffs.

* Corresponding author.
E-mail address: Ollie.vanhal@wur.nl (O. van Hal).

[1] Authors contributed equally.

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avoiding feed-food competition, the state of the art life cycle assessment (LCA) used to assess environmental impacts of ASF production falls short in addressing this issue as it is not designed to include interlinkages in the food system (Van Zanten et al., 2018). Producing oil from sunflower seed, for example, also yields meal and hulls (see Fig. 1). In an LCA of ASF, the environmental impact of this multifunctional process is allocated to its multiple outputs (e.g. oil, meal and hulls) based on their relative economic value (De Vries and de Boer, 2010), a method defined as economic allocation (Guinée, 2002). Of the impact of cultivating and processing one kg of sunflower seed, 80% is allocated to the resulting 285 g sunflower oil as this oil represents 80% (€0.25/€0.32) of the economic value of the process outputs (Fig. 1). The economic value of a product, however, does not reflect their (un)suitability for direct human consumption (Van Zanten et al., 2016).

By not considering whether used feeds are fit for human consumption or compete for land with food crop production, mitigation strategies proposed by LCA studies may increase the resource use of the entire food system (Van Zanten et al., 2018). LCA studies by Herrero et al. (2016), for example, propose to reduce the environmental impact per kg ASF by increasing animal productivity, defined as animal output over feed input (Balmford et al., 2018). This productivity increase requires high quality feeds (De Vries et al., 2015), typically including food crops or feed crops grown on arable land, thereby increasing competition with food production (Wilkinson and Lee, 2018). Negative implications of such strategies, i.e. increased pressure on arable land, are overlooked as the state of the art LCA ignores their consequences on interlinked production systems (Van Zanten et al., 2018).

To move towards a resource efficient food system, LCA's shortcoming in considering food system interactions such as feed-food competition should be addressed. This study presents a first step towards achieving this by introducing a novel allocation method that reflects the (un)suitability of feed products for human consumption. This food-based allocation assigns zero environmental impact to by-products unsuitable or undesired for human consumption whereas the determining (food) product is given full allocation. Of the environmental impact of cultivating and processing one kg of sunflower seed, 100% is now allocated to the resulting 285 g sunflower oil as this is the only edible end-product which drives sunflower seeds production (Fig. 1).

This study evaluates the impact of explicitly accounting for feed-food competition on LCA results. A conventional LCA with economic allocation was compared with an alternative LCA with "food-based" allocation that explicitly accounts for feed-food competition (Fig. 1). Both LCAs were extended with the land-use ratio (LUR) indicator which provides insights into the land use efficiency of the entire food system (Van Zanten et al., 2016). The limitations of economic allocation, illustrated by the impact of accounting for feed-food competition in LCA, were assessed in a case study of an innovative egg production system that avoids feed-food competition.

2. Material and methods

The impact of explicitly accounting for feed-food competition in LCA was explored. LCA is a holistic approach to evaluate the environmental impact throughout a product's entire life cycle (Baumann and Tillman, 2004). Following the LCA protocol (Guinée, 2002), the goal and scope definition and inventory analysis are described in the material and methods, the impact assessment in the results and interpretation of the results in the discussion.

2.1. Goal and scope definition

LCA was applied to a case study of 'Kipster', an innovative egg production system designed to produce eggs with respect for animals, farmer, and planet. The system avoids feed-food competition, produces and uses solar energy, and rears the male chicks associated with egg production for meat (Kipster, 2017). First, the environmental impacts of this system were benchmarked against free range and organic egg production, using traditional LCA with economic allocation. Subsequently, the impact of accounting for feed-food competition in LCA was illustrated by comparing economic with food-based allocation (Fig. 1). How each allocation method applies to the feed used by Kipster is described in section 2.2.4, i.e. the inventory assessment of feed production.

The indicators LU (m^2) and GWP (CO_2-eq) were selected as livestock production contributes significantly to land use and climate change (Steinfeld et al., 2006), and EU (MJ) for its inherent

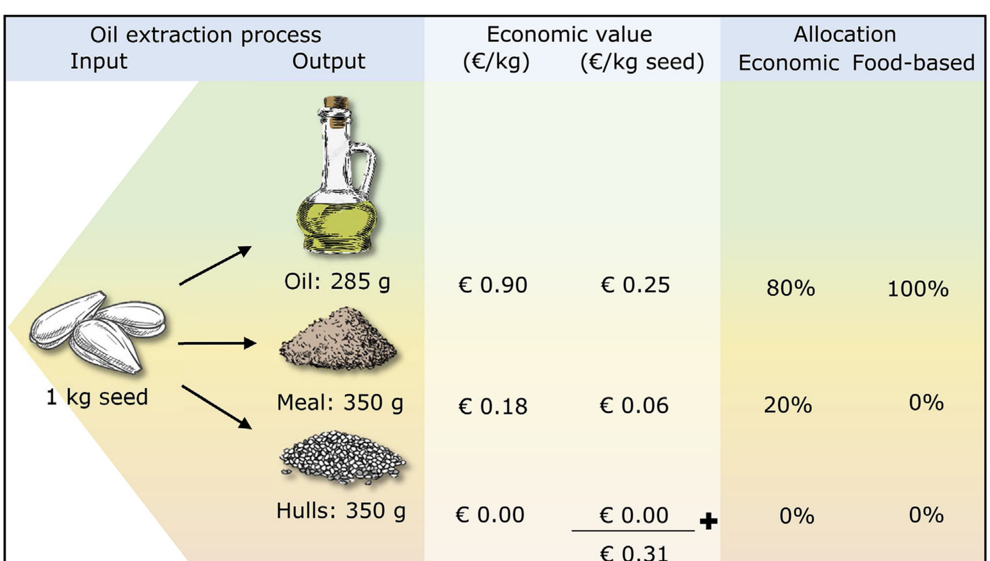

Fig. 1. Environmental impact allocation over the co-products resulting from the multifunctional process sunflower seed crushing under traditional economic and food-based allocation as introduced in this paper (mass distribution of outputs & price of outputs (FeedPrint, 2019)).

relation with GWP. To calculate GWP, the three main GHGs related to agriculture, CO_2, CH_4 and N_2O, were summed using their CO_2-eq weighting factors for 100-year time horizon: 1 for CO_2, 28 for biogenic CH_4, 30 for fossil CH_4 and 265 for N_2O (Myhre et al., 2013). Where LU quantifies the amount of land needed to produce one kg egg, the land use ratio (LUR) was included to indicate whether this land could have been used more efficiently to produce plant-source food (Van Zanten et al., 2016), for more detail see section 2.3.

The LCA, performed from cradle-to-farm-gate, included the following processes: rearing female and male chicks, egg production, solar energy production, manure management, feed production, and other off farm processes such as bedding material and energy production (Fig. 2). The hatching phase and parent stock were excluded.

2.2. Inventory analysis

The following section quantifies the inputs and outputs related to each farm process (Table 1): chick rearing (2.2.1), egg production (2.2.2), and solar energy production (2.2.3). The environmental impacts per unit of these inputs and outputs are then quantified for the off-farm processes: feed production (2.2.4), bedding material and energy production (2.2.5), and manure management (2.2.6).

2.2.1. Rearing female and male chicks

Female chicks were reared from hatch to the egg productive stage, whereas male chicks were reared as slow-growing broilers. Kipster rears male chicks in response to societal concerns about the conventional culling of day-old male chicks. In the European union only 16% of these chicks is used as feed for zoo animals or reptiles while the rest is wasted (Bokma and Leenstra, 2010). Production data and inputs and outputs related to female chicks reared for Kipster (Table 1) are in line with the Dutch average production (Vermeij, 2017). Male chicks are reared under similar circumstances (Table 1) and reach a slaughter weight of 1.5 kg in 119 days (Zanders and Claessens, 2018), resulting in a meat yield of 580 g per chick (Loetscher et al., 2015; USDA, 2018). Based on the principles of system expansion, this valuable meat output, is expected to replace free range broiler meat with an average GWP of 7.01 kg CO_2-eq, EU of 41.2 MJ and LU of 9.96 m^2 per kg (Appendix A).

Table 1
Production data, inputs and outputs of rearing male and female laying hen chicks and the laying phase.

		Female chicks	Male chicks	Laying hens
Production data				
Round size	# animals	24,840	24,930	24,000
Round duration	days	119	119	470
Mortality	%	3.5	4.75	7.81
Housing density	animals/m^2	10.50	10.50	6.70
Farm input	*(/animal/round)*			
Feed	kg	5.6	7.3	55.33
Bedding material	kg	0.015	0.015	0.088
Diesel	l	30	-	-
Gas	m^3	0.15	0.15	-
Electricity	kWh	2.35	2.35	8.36
Farm output	*(/animal/round)*			
Eggs	kg	-	-	23.17
Meat	kg	-	0.58	0.58
Manure	kg	2.48	3.14	13.12
Solar energy	kWh	-	-	16.71

2.2.2. Egg production

Inputs and outputs related to the egg production phase (Table 1) were based on technical results of Kipster. The DeKalb white laying hens produce eggs for 64 weeks after a 3 week adaptation period, and are kept at a density of 6.7 animals per m^2 (Zanders and Claessens, 2018). At the end of the egg production phase, hens of 1.5 kg are slaughtered. The resulting 580 g meat per hen (Loetscher et al., 2015) was accounted for using similar system expansion assumptions as reported for rooster meat.

2.2.3. Solar energy production

The Kipster laying hen barn is covered with 1,097 solar panels, producing ~385,479 kWh solar energy per laying round, covering the energy requirement of both the rearing and the laying phases (Appendix E; Table E5). The surplus solar energy sold to the grid is assumed to replace average Dutch grid electricity which has a higher environmental impact (Table 3).

2.2.4. Feed production

In the rearing phase, both female and male chicks were fed a conventional diet (Appendix B). Laying hens were fed a diet

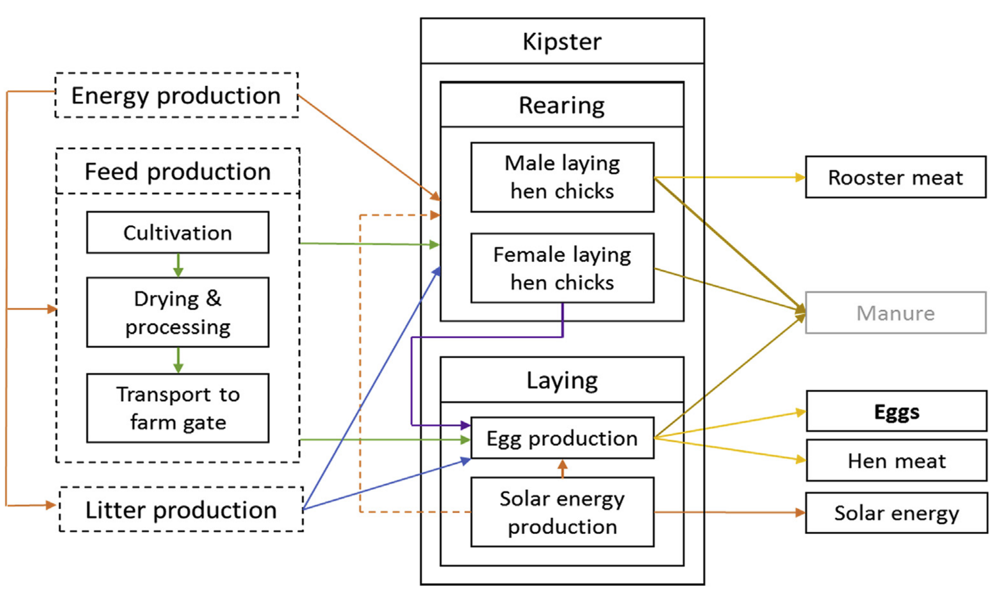

Fig. 2. Production chain of the Kipster egg production system.

consisting of LCF specifically designed for Kipster to avoid feed-food competition. Energy providing LCF included bakery rest streams (e.g. bread crumbs, biscuit sand, crispbread, dough melange, rice waffle, rusk) and candy rest streams (e.g. candy syrup, waffle syrup), while European sunflower and rapeseed meal provided protein (Appendix B; S1). The environmental benefits of two potential future protein-rich LCF were explored in two diet scenarios (Appendix B; S2−S3) with the same nutritional value of 11.8 MJ metabolisable energy, 6 g digestible lysine and 3 g digestible methionine per kg. The alternative protein source in the oilseed scenario (S2) was soybean meal. As the demand for soybean meal drives soybean production, it's considered a feed crop that competes for arable land with food crop production (Van der Werf et al., 2005). In a future circular food system where soybean cultivation is limited to the demand for soybean oil, soybean meal is a by-product unsuitable for human consumption. In the insect scenario (S3), the alternative protein source was meal from larvae fed on food waste and manure, both being unsuitable as livestock feed (Van Zanten et al., 2015). Feeding insects to livestock is not permitted in the EU (Veldkamp et al., 2012), but has the potential to reduce the environmental impact of livestock production (Sánchez-Muros et al., 2014).

The impact of each feed ingredient (Appendix B) was derived from Feedprint (Vellinga et al., 2013), supplemented for larvae meal (Van Zanten et al., 2015), additives (Garcia-Launay et al., 2014), soybean oil and lecithin (Ecoinvent, 2013), and fish oil (AgriBalyse, 2017). Feed production impacts include those related to feed cultivation, drying/processing and transport to the farm but exclude those related to land use change. The environmental impact per kg feed, for each allocation method (Table 2), was calculated by multiplying the impact per kg feed ingredient with its relative use in the diet.

Using economic allocation, impacts related to cultivation and processing were allocated to the resulting co-products based on their relative economic value (Fig. 1). This implies that of the impact of cultivating and processing 1 kg sunflower seed, 80% was allocated to the resulting sunflower oil, and 20% to sunflower meal (Vellinga et al., 2013). Food industry wastes such as dough melange were assumed to have no economic value according to LCA regulations (FEFAC, 2018). Using food-based allocation, all cultivation and processing impacts were allocated to the determining (food) product (Fig. 1). This implies that the impact of cultivating and processing 1 kg sunflower seed was fully allocated to the sunflower oil driving these processes, and none to the associated sunflower meal, as it is unfit for human consumption. Environmental impacts related to the processing of a by-product, for example, drying sunflower meal, were allocated to this by-product. Although soybean meal drives soybean production, under food-based allocation no impact related to cultivation or processing of soybeans was allocated to it, assuming that in a future circular food system soybean production will be limited to oil demand.

Table 2
Global warming potential (GWP), energy use (EU) and land use (LU) per kg feed for each phase/scenario, under economic and food-based allocation.

	Economic allocation			Food-based allocation		
	GWP	EU	LU	GWP	EU	LU
Feed	(kg CO_2-eq)	(MJ)	(m^2)	(kg CO_2-eq)	(MJ)	(m^2)
Rearing female	0.65	5.84	1.96	0.54	6.16	1.34
Rearing male	0.65	6.53	1.65	0.46	4.95	0.91
Laying hen S1	0.37	3.44	1.02	0.13	1.75	0.01
Laying hen S2	0.30	3.75	0.85	0.20	2.79	0.27
Laying hen S3	0.40	4.39	0.09	0.30	3.66	0.02

Table 3
Global warming potential (GWP), energy use (EU) and land use (LU) related to the production of farm inputs (Ecoinvent, 2013).

	GWP [a]	EU	LU
Farm input	(kg CO_2-eq)	(MJ)	(m^b)
Diesel (l)	0.22	3.39	0.004
Gas (m^c)	2.10	38.95	0.002
Electricity[b] (kWh)	0.74	2.98	0.014
Solar power (kWh)	0.11	1.31	0.010
Bedding material[c] (kg)	0.07	0.76	0.005

[a] GWP includes production and combustion of energy sources.
[b] Dutch average grid electricity.
[c] Wood chips.

2.2.5. Bedding material and energy production

Other off-farm processes include the production of animal bedding material and energy sources used on the farm and for transport. The environmental impact of each of these inputs (Table 3) was derived from Ecoinvent (2013).

2.2.6. Manure management

CH_4 and N_2O emissions from manure handling and storage were computed using a tier 2 approach (IPCC, 2006), country specific data from Van Bruggen et al. (2014), and IPCC default values (IPCC, 2006), (Appendix C). Laying hen manure was dried before storage and no leaching or volatilisation was assumed to occur (Oenema et al., 2000).

2.3. Land use ratio

The LUR, an indicator of land use efficiency, is defined as the maximum amount of plant-based human digestible protein (HDP) that can be derived from the land used to cultivate the feed to produce 1 kg HDP from ASF (Van Zanten et al., 2016). A LUR below one implies that livestock produce more HDP per m^2 than food crops could on the same land. As described in detail in Appendix D, the LUR is calculated with Equation (1).

$$LUR = \frac{\sum_{i=1}^{n} \sum_{j=1}^{m} (LO_{ij} \times HDP_j)}{HDP \ of \ one \ kg \ ASF}$$

where LO_{ij} is the land area (m^2) occupied for a year to cultivate the amount of feed ingredient i ($i = 1,n$) in country j ($j = 1,m$) needed to produce 1 kg ASF, in this case eggs and chicken meat, including rearing young stock. HDP_j is the maximum amount of HDP that can be produced per m^2/year by direct cultivation of food-crops in country j. The denominator contains the amount of HDP in 1 kg ASF (Van Zanten et al., 2016).

3. Results

Using economic allocation, the GWP per kg Kipster egg was 1.13 kg CO_2-eq, the EU was 11.86 MJ, and the LU was 2.99 m^2 of which 61−73% resulted from the laying phase (Fig. 3). These results consider the impacts avoided by replacing grid energy with surplus solar energy, and replacing broiler meat with rooster and laying hen meat (Appendix E; Table E1). The solar energy surplus of 80,476 kWh reduced egg production phase GWP by 0.095 kg CO_2-eq, EU by 1.42 MJ, and LU by 0.002 m^2 per kg eggs (Appendix E, Table E5). The 12,900 kg meat produced from culled laying hens further reduced GWP by 0.17 kg CO_2-eq, EU by 0.99 MJ and LU by 0.24 m^2 per kg egg. The 13,750 kg meat produced from male chicks reduced GWP of rearing male chicks by 0.18 kg CO_2-eq, EU by 1.06 MJ, and LU by 0.26 m^2 per kg egg.

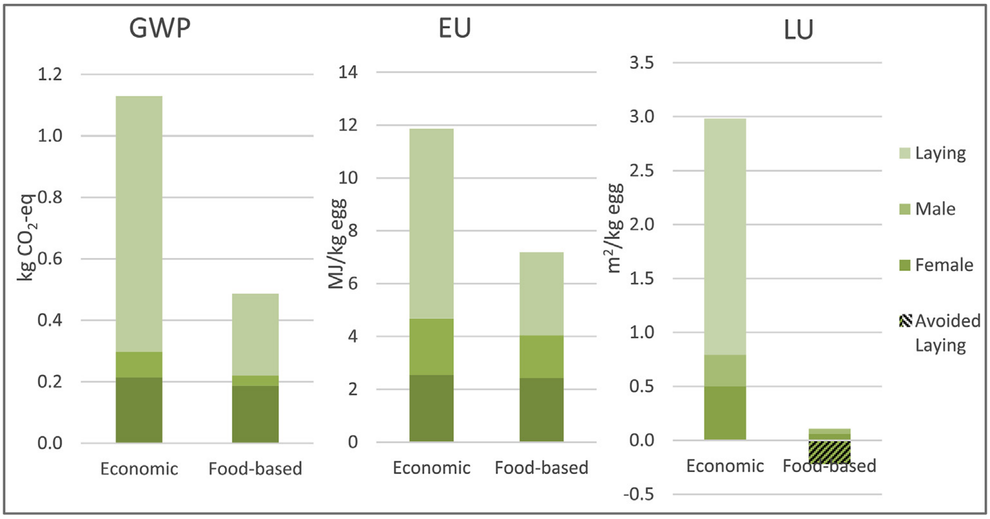

Fig. 3. Global warming potential (GWP), energy use (EU), and land use (LU)/kg egg of Kipster as a whole using economic and food-based allocation, and the contribution of rearing of female and male chicks and egg production.

3.1. Food-based versus economic allocation

Food-based allocation reduced the GWP per kg Kipster egg to 0.49 kg CO_2-eq, EU to 7.19 MJ, and LU to 0.11 m^2 (Fig. 3). The majority of this reduction occurred in the laying phase, as only laying hens were fed an LCF-based diet. The contribution of the laying phase to the total impact per kg egg was reduced to 55% for GWP, 44% for EU, and −206% for LU. The negative LU of the laying phase, the hatched area in Fig. 3, resulted from the LU avoided by replacing broiler meat with laying hen meat (0.24 m^2/kg egg), being higher than the LU in the laying hen phase (0.02 m^2/kg egg). The reduction in GWP (26%) and EU (13%) in the rearing phase was relatively small, while the reduction of LU was 59%.

Using economic allocation, the majority of the GWP, EU, and LU per kg Kipster egg was related to feed production (Table 4). For GWP, a relatively large share (14.5%) of the impact originated from manure management. For EU, the use and production of farm energy sources accounted for 22.5%. While feed production remained the dominant impact source, food-based allocation reduced its contribution to all indicators (Table 4).

3.2. Diet scenarios

With economic allocation, neither of the alternative diets (S2−S3) reduced the impact per kg egg for all indicators simultaneously, compared to the baseline diet (S1) (red dashed line, Fig. 4). The insect meal diet (S3) greatly reduces LU while slightly increasing EU and GWP. Food-based allocation results in a lower environmental impact on all indicators for all diets, most pronouncedly for LU. The difference between allocation methods is less pronounced for the insect meal diet (S3) due to the high EU of insect rearing and the low economic value of the insect feed. With food-based allocation, the lowest impact on all indicators is achieved using the baseline diet (S1) (black dashed line, Fig. 4).

Table 4
Percentage of Kipster's global warming potential (GWP), energy use (EU) and land use (LU) resulting from energy use/production, feed production, bedding production, and manure management under economic and food-based allocation.

	Economic			Food-based		
Input	GWP (%)	EU (%)	LU (%)	GWP (%)	EU (%)	LU (%)
Energy	5.8	22.5	0.0	9.9	32.4	0.0
Feed	79.7	77.5	99.9	65.3	67.6	99.8
Bedding material	0.0	0.0	0.0	0.0	0.0	0.0
Manure	14.5	0.0	0.0	24.8	0.0	0.0

3.3. Land use ratio

Using economic allocation, the LUR of the laying phase alone is ≥ 1 for both S1 (1.14) and S2 (1.06). This implies that the land used to produce laying hen feed could yield more HDP if used to produce human food crops (Fig. 5a). The LUR of S3 was 0, implying an absence of competition for land between feed and food production. Adding the 0.57 LUR of the rearing phase to consider the entire Kipster system resulted in an LUR of 1.70 for S1, 1.63 for S2, and 0.57 for S3 (Fig. 5b). Using food-based allocation, the LUR of the laying phase is 0 for S1 and S3. The LUR of 0.36 for S2 implies that some feed-food competition occurs. Adding the 0.30 LUR of the rearing phase results in an LUR of 0.66 for S2 and 0.30 for S1 and S3 (Fig. 5b). These <1 LUR's imply that Kipster produces protein more efficiently than achievable with food crops grown on the same land, thereby contributing to food system efficiency.

4. Discussion

Before discussing the impact of allocation methods on LCA results, LCA results based on economic allocation are benchmarked against those found in literature. For this comparison, GWP results were recalculated using previously assumed equivalence weighing factors: 1 for CO2, 25 for CH4 and 298 for N2O (Forster P., 2007). The environmental impact per kg Kipster egg was lower than that of commercial free range or organic eggs (Table 4) due to avoided feed-food competition, on-farm solar energy use, supply of surplus solar energy to the grid, and rearing male chicks. While use and supply of solar energy reduced Kipster's environmental impacts, rearing male chicks resulted in a net impact increase; the impacts of growing male chicks were higher than impacts avoided by their meat output (Appendix E; Table E1). This is a clear example of a sustainability trade-off, where addressing a social sustainability issue, namely culling of day-old chicks (Kipster, 2017), results in an environmental cost. Excluding the benefits of solar energy use and supply and the costs of rearing male chicks (Appendix E, Table E1 & E6), resulted in a GWP of 1.43 kg CO_2-eq, EU of 14.77 MJ, and LU of

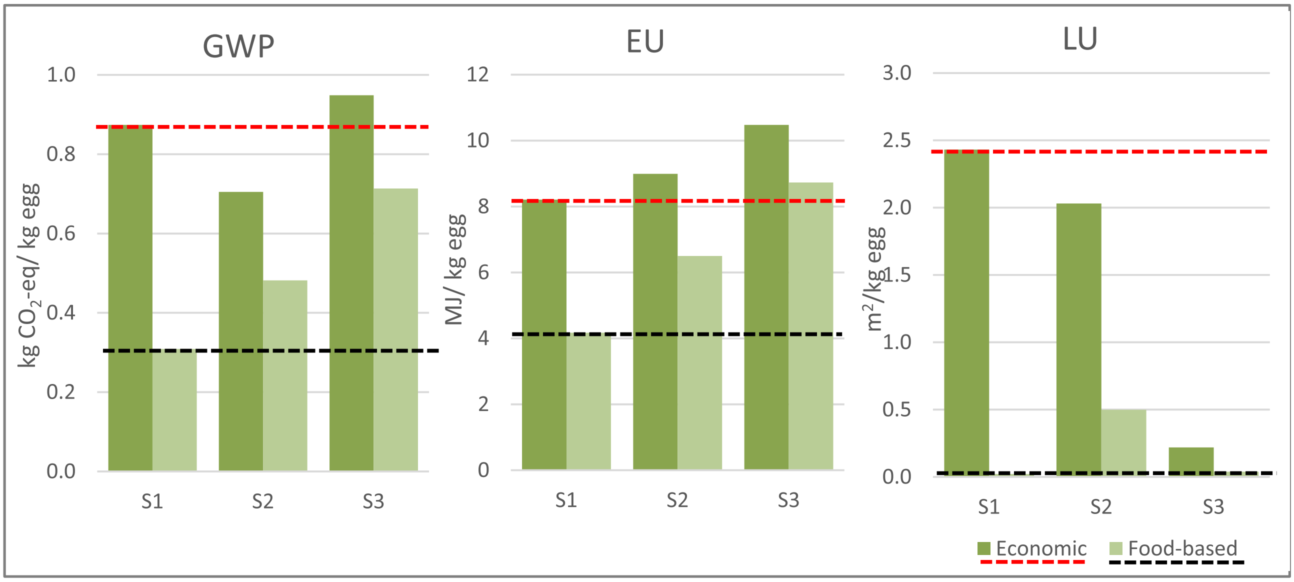

Figure 4. the environmental impact (GWP, EU, LU)/kg egg from the Kipster system using alternative diets (S2 soy bean meal, S3 insect meal), compared to the current diet (S1) using economic and food-based allocation.

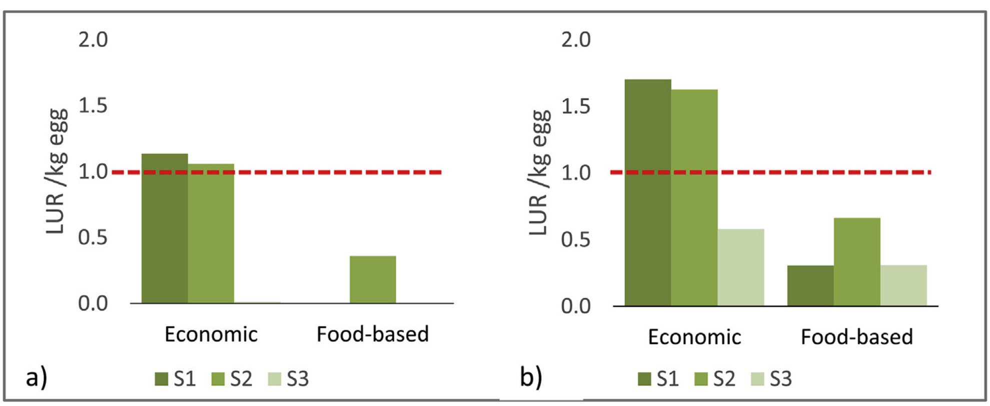

Fig. 5. Land use ratio (LUR) of a) Kipster laying phase and b) Kipster as a whole under the current (S1) and alternative (S2-3) diets, using economic and food-based allocation.

2.70 m^2 per kg egg, and an LUR of 1.42. Compared to free range laying hens fed a conventional diet (Table 5), feeding only LCF to laying hens reduced GWP by 48–58%, EU by 21–37%, LU by 34–47%, and LUR by 32%. This was due to the small environmental impact allocated to LCF due to their relatively low economic value, and is in line with findings from studies assessing the impact of feeding specific LCF such as rape seed meal (Van Zanten et al., 2015a), waste fed insects (Van Zanten et al., 2015b), and food waste (Zu Ermgassen et al., 2016).

Accounting for feed-food competition with *food-based allocation* further reduced the environmental impact per kg egg by 57% for GWP, 40% for EU, 96% for LU (Fig. 3), and 88% for LUR (Fig. 4). As to date, Kipster only avoids feed-food competition in the laying phase, the main impact reductions are achieved there. The reduction is most pronounced for LU, while the limited reduction in EU and GWP is due to the smaller contribution of feed production on these impacts (Table 4) and the energy needed to process LCF into compound feed, such as animal fat refinery, drying and additive production. GWP and EU can be further reduced by avoiding heavily-processed co-products, improving production processes, or using renewable energy sources. The second law of thermodynamics determines that recycling materials in a circular food

Table 5
Global warming potential (GWP), energy use (EU), and land use (LU) per kg egg from free range and organic systems found in literature and of Kipster found in this study.

	GWP		EU		LU		LUR
Study	Free range	Organic	Free range	Organic	Free range	Organic	Free range
Dekker et al. (2011)	2.75	2.54	23.45	20.55	4.08	6.76	-
Leinonen et al. (2012)	3.38	3.42	18.78	26.41	5.10	-	-
Van Zanten et al. (2016)	-	-	-	-	-	-	2.08
Kipster (current study)	**1.14**	**-**	**11.86**	**-**	**2.98**	**-**	**1.70**

system always requires energy which, by definition should be obtained from renewable sources (Korhonen et al., 2018).

A conventional LCA with economic allocation not only underestimates the mitigation potential of strategies directed at avoiding feed-food competition, it even promotes the use of food crops as livestock feed (Van Zanten et al., 2018). This has been demonstrated in studies aiming to reduce the environmental impact of livestock production, as well as in studies aiming to reduce the impact of human diet. The latter typically recommend replacing grass-based beef with meat from fast-growing livestock such as broilers (Hallström et al., 2015) which are fed high quality feed-like cereals.

Accounting for feed-food competition in LCA is essential to promoting the circular food system and economy strived for by the Dutch government (Dijksma and Kamp, 2016) and the European Union (European Commision, 2015). This study illustrates the potential of food-based allocation to account for feed-food competition. Food-based allocation is simplified and binary; a product is allocated all the impact of cultivation and processing when suitable for human consumption, and none when unsuitable. This simplistic allocation – assuming products are either food or not – is applicable in the case study, where only products unfit for human consumption are fed to livestock. When assessing conventional systems with a high-quality feed diet, the impact allocated to each product should reflect its value for human nutrition. Developing this type of allocation method is complex, as it requires implementing a measure expressing nutritional value including multiple nutritional aspects such as the nutrient density score (Van Kernebeek et al., 2014). This score considers the nutrient content per 100 g of a product relative to the daily recommended nutrient intake, and averages the score per nutrient into one final score (Drewnowski and Fulgoni, 2014). Besides the complexity of implementing this score in an allocation method, it does not fully account for the nutritional benefits of ASF, for example, essential vitamin B12 is only available in animal products, and the amino acid composition matches daily requirements better than plant-source foods (Ertl et al., 2016).

Food system modelling (Van Kernebeek et al., 2016) or scenario studies (Schader et al., 2015) are the most promising methods for capturing the complexity of the food system. Although these methods are unsuited to assessing or monitoring the impact of an individual product or production system, they provide valuable insights into how much ASF can be consumed when feeding only LCF. Van Zanten et al. (2018) reviewed these food system studies and showed that feeding livestock LCF only, globally provides about 9–23 g of animal protein per capita per day. Per capita availability of ASF when feeding only LCF can be further increased by optimally using LCF (van Hal et al., 2019) and exploring alternative LCF ingredients such as insect meal, as in S3 in this study. The insect meal diet (S3) showed reductions of LU at the cost of an increase in EU and GWP. The high EU and GWP relate to the assumed high EU from larvae rearing and processing, based on an experimental trial of rearing larvae on food waste and manure conducted by a Dutch waste processor (Van Zanten et al., 2015). Both can be reduced by using renewable energy and developing industry-scale larvae rearing systems (Van Zanten et al., 2015), which can only occur when European legislation no longer prohibits the use of waste-fed insects in animal feed (Van Zanten et al., 2015).

Avoiding feed-food competition assumes that the ultimate goal of the food system is to feed humans efficiently, thereby neglecting other purposes served by agricultural production. In reality, the debate around competition for agricultural resources should not only consider the production of food and feed, but also the production of fibre (e.g. cotton), fuel (e.g. wood, biofuels), and the provision of other ecosystem services. This competition framework is complex and has not been comprehensively studied (Muscat et al., 2018). In the larger perspective of the battle for biomass, leftovers from the agricultural sector should be considered for other purposes than feeding livestock, keeping in mind that livestock feeding is seen as the most valuable use of food waste and by-products (Papargyropoulou et al., 2014). Including feed-food competition in the environmental impact assessment of food is an important first step towards a more efficient agricultural system.

5. Conclusion

Compared to free range laying hens fed a conventional diet, feeding only low-opportunity-cost feeds (LCF) reduced GWP by 48–58%, EU by 21–37%, LU by 34–47% and LUR by 32% in case of economic allocation. This was caused by the small environmental impact allocated to LCF due to their relatively low economic value. Using food-based allocation, the impact per kg egg was further reduced by 54% for GWP, 38% for EU, 94% for LU, and 88% for LUR. An LCA with economic allocation underestimates the environmental benefits of avoiding feed-food competition. Although food-based allocation illustrates the inadequacy of LCA in accounting for the complexity of the food system, it is as yet simplistic, and should be further developed to reflect the nutritional value of co-products for human nutrition. To promote mitigation measures that improve the resource use efficiency of the entire food system, improved LCAs that capture the complexity of the food system are needed.

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Appendix A. Supplementary data

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