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Published in:
Sustainability

DOI:
10.3390/su10051473

First published: 08/05/2018

Document Version
Peer reviewed version

Link to publication

Citation for pulished version (APA):
Leinonen, I., MacLeod, M., & Bell, J. (2018). Effects of alternative uses of distillery by-products on the greenhouse gas emissions of Scottish malt whisky production: a system expansion approach. *Sustainability*, *10*(5), 1 - 18. [1473]. https://doi.org/10.3390/su10051473

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Effects of Alternative Uses of Distillery By-Products on the Greenhouse Gas Emissions of Scottish Malt Whisky Production: A System Expansion Approach

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Received: 6 April 2018; Accepted: 4 May 2018; Published: 8 May 2018

Abstract: Agricultural by-products are an important component of livestock feed. In Scotland, distillery by-products are protein rich and traditionally cost competitive feed ingredients in cattle production. However, during recent years, distilleries in the UK (including Scotch whisky producers) have started to use the by-products also as a source of renewable energy, in order to reduce the carbon footprint of alcohol production. In this study, a systems-based material and energy flow analysis was performed to calculate the life-cycle greenhouse gas (GHG) emissions of whisky production for two scenarios where distillery by-products were used either (1) as beef cattle feed to replace other protein sources (namely soya bean meal and rapeseed meal); or (2) as anaerobic digester (AD) feedstock in order to generate renewable energy (heat and electricity). System expansion was used to quantitatively handle the by-products in the analysis. The results show that considerable reductions in GHG emissions could be achieved by either replacing feed crops with by-products or by using the by-products in AD plants to generate bio-energy. The biggest reductions in the GHG emissions were achieved when by-products were used to replace soya meal in animal feed. However, the results are highly sensitive to methodological choices, including the accounting method of the land use change emissions arising from soya production.

Keywords: agricultural by-products; whisky production; cattle; beef; livestock feed; renewable energy; greenhouse gas emissions

1. Introduction

Various agricultural by-products (i.e., products originating from food and drink production but not normally used for human consumption) are widely used as part of livestock feed. They can form an important source of protein and metabolizable energy needed for animal production [1–4] and are currently used in production of a wide variety of livestock species [5]. For example, brewery, spirit distillery and bio-ethanol production by-products, such as brewers' grains, usually made from barley, wheat, maize or rice, can form a significant part of the animal diet especially in ruminant production. These products are generally favoured due to their high protein and fibre content [6–10] and inclusion of them in ruminant feed has been found to have positive effects on the animal performance [11,12]. Brewers' grains, or further processed distillery by-product "distillers dark grains with solubles" or "dried distillers grains with solubles" (DDGS), can be also used in non-ruminant production, for example, as part of pig feed [13–17]. According to recent studies, relative high proportions of DDGS can be applied in pig diets while still maintaining acceptable level of growth performance [15,16,18].

Further application of brewery and distillery by-products such as DDGS and yeast products can also be found in chicken industry [19–23], or even in fish production [24,25]. However, high variability in the nutritional value of these by-products, depending for example on the variety of the cereal, harvest time and the malting and mashing processes [10,26,27] may limit their use in non-ruminant livestock production where the content of certain nutrients, especially the balance of essential amino acids, can have major impact on animal performance [28]. Despite such limitations, brewery and distillery by-products can be potentially seen as a partial replacement of soya as a protein source in livestock production [20,29,30]. Reducing the dependency on soya is an increasing trend in livestock systems due to environmental concerns related to its production. The cultivation of this crop is generally associated with recent land use changes, causing greenhouse gas emissions from deforestation and conversion of other land uses to arable production, resulting in loss of carbon previously stored in soil and biomass [31]. Other environmental issues associated with soya production include the loss of biodiversity and freshwater and groundwater contamination [32,33].

The availability and usability of agricultural by-products or co-products can vary strongly depending on the location of production and this can also affect the distribution and profitability of livestock industries. In agricultural production in Scotland, barley is by far the most important arable crop species, in terms of area of cultivation, the total mass of grain production and the amount of crop protein produced [34]. The barley grown in Scotland is used either directly for animal feed, or as a raw material of alcohol (including whisky) production. The whisky distillation process utilizes only the carbohydrates of the barley grains, so therefore the use of the remaining compounds (including protein) in livestock production has been seen as a useful way to fully utilize this important crop. As a result, the main by-products of Scottish malt whisky production, namely "draff" (unprocessed by-product of the mashing process), "pot ale" (liquid by-product of distillation) and "distillers dark grains with solubles" (DDGS, dried and pelletized product made of draff and pot ale) are widely used as protein rich and low-cost ingredients of livestock feed, particularly in beef and dairy cattle production. In 2012, it was estimated that a total of 346,000 t (on a dried product basis) of distillery by-products from the whisky industry in Scotland were potentially available for use in animal feed [35]. About 60% of this amount was consumed in Scotland. Therefore, in this specific region, whisky industry and the feed that it provides for livestock can be considered as a significant part of the beef and dairy production chains.

Distillery by-products used as feed have been considered to have low environmental impacts and especially low embedded greenhouse gas (GHG) emissions, compared to alternative protein sources such as rapeseed meal and imported soya [35,36]. One of the reasons for this finding is that in agricultural life cycle assessment (LCA) studies, economic allocation of the environmental burdens is generally applied to distribute the burdens between various co-products originating from the same production process [37–39]. In this specific method, the burdens are allocated to different co-products proportionally to their economic value [3,36]. Therefore, due to a relatively low price of the distillery by-products such as draff, the produced alcohol is considered to be the main product with the highest share of the environmental burdens and only a small proportion of the overall environmental impacts associated with whisky production is allocated to by-products [35].

In addition to the traditional use of distillery by-products as livestock feed, distilleries in Scotland (and other alcohol producers in the UK) have during recent years started to use these products as a source of renewable energy. This development is partly motivated by the government subsidies for such energy sources due to their low embedded GHG emissions. Furthermore, the reduction of the use of fossil fuels in the production process can also provide a greener image for the whisky industry through reducing its carbon footprint [40]. A recent trend in this area has been to increase the use of by-products as a feedstock of anaerobic digestion and utilize the produced biogas to generate electricity and heat that can be directly used in the distillation process. This strategy is expected to have multiple benefits in terms of reduction of GHG emission. For example, in addition to the renewable energy generated in digestion, the digestate (material remaining after the anaerobic digestion process) contains nutrients that can be utilized by crops and therefore can replace the use of synthetic fertilisers and reduce the greenhouse gas emissions related to production of the fertilisers [41,42].

The proposed alternative use of distillery by-products has raised some concerns amongst livestock farmers in Scotland and elsewhere in the UK [43]. As the use as renewable energy increases, the farmers are getting worried about the future availability and cost of by-products as animal feed. However, it should be noted that also the feed use of these by-products can be expected to have beneficial effects on greenhouse gas emissions due to reduction of the use of carbon-intensive feed ingredients. For this reason, a systematic comparison of GHG emissions associated with alternative uses of by-products is needed to quantify these possible effects.

The aim of this study was to carry out a systems-based analysis of the material and energy flows within the whisky production chain, in order to quantitatively analyse the processes associated with distillery by-products and assess the life-cycle greenhouse gas emissions arising from the entire whisky production chain, including the end use of by-products. Instead of applying an economic allocation approach for the outputs of the distillery processes, we selected to use a system expansion method for the by-products, specified as "expanding the product system to include the additional functions related to the co-products" in the ISO [44] LCA standards. Those standards also prefer the system expansion approach over any allocation methods and suggest that allocation between co-products should be avoided when possible. The system expansion approach makes it possible to directly compare the changes in greenhouse gas emissions when using the by-products for alternative purposes (livestock feed, bioenergy generation) and replacing alternative commodities (protein crops grown for cattle feed, fossil fuels used in distillation process, synthetic fertilisers used in crop production). As an outcome, the greenhouse gas emissions can be calculated for a unit of produced alcohol while taking into account both the burdens and benefits achieved through the end use of the by-products.

2. Materials and Methods

A systems-based material flow analysis linking the Scottish malt whisky production and the end use of its by-products either in a cattle production system or in energy generation processes was carried out (Figure 1) to quantify the life-cycle GHG emissions arising from whisky production. The analysis applied a system expansion approach, that is, whisky was considered as the main product of distilleries, the by-products of the process were used to replace alternative commodities and the changes in greenhouse gas emissions as a result of this replacement were accounted for when quantifying the overall emissions of whisky production. In order to achieve this, the whisky production system was linked to other systems affected by the by-product use, namely beef cattle production system, crop production system and energy generation system (see detailed system diagram in Supplementary Materials). The changes in the material and energy flows within these connected systems were analysed and the associated GHG emissions quantified as detailed below. This approach was used to calculate the greenhouse gas emissions for two baseline scenarios: Scenario 1: distillery by-products were used as cattle feed to replace either soya bean meal or rapeseed meal as a protein source (while maintaining the nutritional quality of the feed) and Scenario 2: distillery by-products were used as anaerobic digester (AD) feedstock in order to generate renewable energy (heat and electricity). For both of these scenarios, the functional unit was 1 litre of pure alcohol (LPA) and the system boundary was from cradle to the end of the distillation process. However, instead of the whisky production chain itself (which remained the same in both baseline scenarios), the main focus of this study was in the effects of alternative uses of the by-products on GHG emissions in other, connected systems, analysed through the system expansion approach.

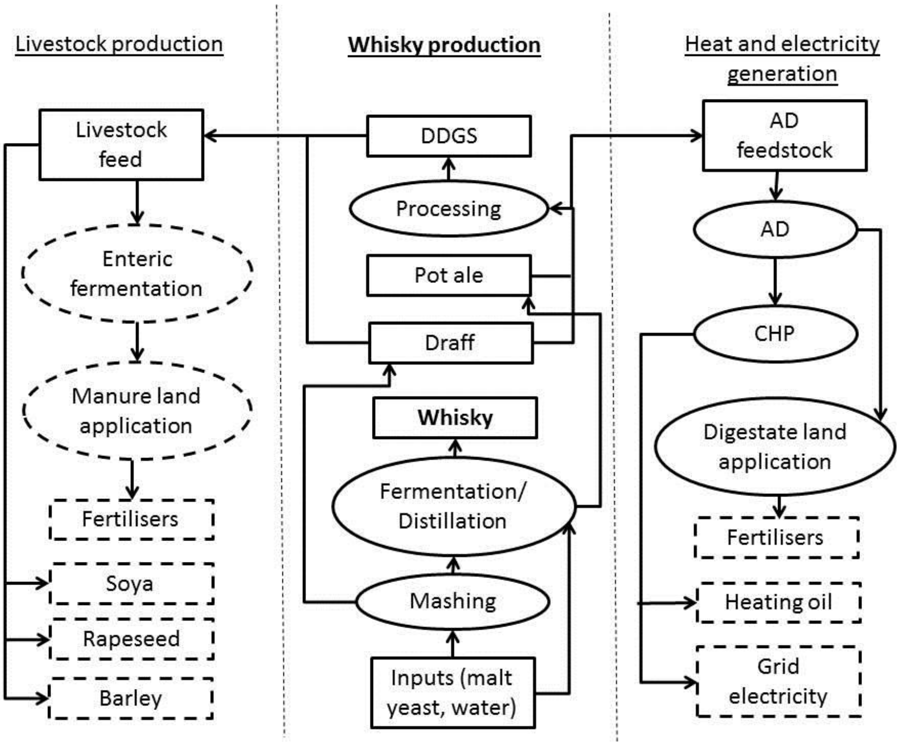

Figure 1. A simplified diagram of the production systems analysed in this study and processes affecting the greenhouse gas (GHG) emissions. The rectangles indicate inputs or outputs and the ovals indicate processes. The objects with broken lines indicate replaced products or processes partly affected by the replacement.

The greenhouse gas emissions associated with whisky production (including production, processing and transport the raw materials but excluding the by-product processing and their end use) were quantified based on data from an earlier study [35] and the changes of these emissions, as affected by the alternative uses of the by-products, were included in the calculations. Details of the data and the calculated GHG emissions associated with different processes within the whisky production chain can be found in the Supplementary Materials. Following this analysis, the processing and end use of the by-products was analysed in different scenarios, the changes in the material and energy flows within connected systems were quantified and the resulting increases or reductions of GHG emissions were included in the total emissions of the whisky production chain. For this analysis, the quantities of the primary by-products produced per one litre of pure alcohol were obtained from the calculations by Bell et al. [35] and were estimated to be 0.56 kg DM of draff and 0.36 kg DM of pot ale. In all the systems included in the calculations, the changes in the emissions of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) were quantified and the overall greenhouse gas emissions were expressed in terms of CO_2 equivalent: with a 100-year timescale, where 1 kg CH_4 and N_2O are equivalent to 25 and 298 kg CO_2 respectively [45].

2.1. Scenario 1: Distillery By-Products as Livestock Feed

In this scenario, the amounts of replaced feed ingredients in livestock production were quantified, together with the resulting changes in GHG emissions associated with feed production, enteric fermentation, manure management and fertiliser use in crop production. Two alternative by-products of malt whisky distilleries were used as a protein source in cattle feed, namely draff and DDGS. Draff was used fresh, without further processing, while DDGS was produced as a combination of draff and pot ale and additional processing (drying and pelletizing) was needed in its production. The use of distillery by-products was assumed to replace two alternative protein sources widely used in Scottish cattle industry, namely soya bean meal and rapeseed meal. As a result, four different options in the feed use of the by-products were considered separately:

- Scenario 1a: draff is used to replace soya bean meal (and pot ale is disposed)
- Scenario 1b: draff is used to replace rapeseed meal (and pot ale is disposed)
- Scenario 1c: draff and pot ale are used to produce DDGS, which is used to replace soya bean meal, and
- Scenario 1d: draff and pot ale are used to produce DDGS, which is used to replace rapeseed meal

The amounts of the replaced alternative ingredients in animal feed were quantified based on a feeding strategy according to which the digestible protein and metabolizable energy contents of the feed were kept unchanged for all scenarios, although the intakes of the total combustible "gross" energy and the total (digestible + non-digestible) protein (and therefore also the total nitrogen intake) could vary between feeding options. Using this approach, also the animal performance was assumed to remain unchanged (for example, the same amount of meat was always produced per unit of energy or protein fed into the beef production system) and would therefore have no effect on the greenhouse gas emissions when compared between the scenarios. Because the protein content of the distillery by-products is lower than that of the replaced soya meal or rapeseed meal, on dry matter (DM) basis higher quantities of the by-products were needed, compared to the replaced ingredients. The higher DM quantity of the by-products brought also additional energy to the feed. Therefore, other changes in the feed were also needed to achieve equal energy content. This was done in this study by reducing the inclusion of barley grains (which are a typical source of energy in cattle feed in Scotland) when the distillery by-products were used in the feed. Linear optimization was used (with the constraints of equal protein and energy content) to determine the quantities of the replaced ingredients to equal 1 kg DM of the by-product for both draff and DDGS feeding scenarios.

The nutrient contents of different feed ingredients were based on the Feedipedia [46] database. Assuming unchanged digestible protein and energy intake, the nutritional data were used to quantify the differences in the animal intake of dry matter and nutrients when either distillery by-products or alternative ingredients were used in the feed and this information was used to quantify the changes of the greenhouse gas emissions arising from the livestock production system (see below).

The greenhouse gas emissions of the production of the replaced feed ingredients (soya bean meal, rapeseed meal, barley) were calculated using the Scottish Agricultural Emission Model (SAEM) [47], which is based on the FAO GLEAM livestock model [48,49]. Details of SAEM can be found in the Supplementary Materials. The emissions related to land use changes (LUC) arising from South American soya production were also included in the calculations following the FAO [48] approach and emission factors [47]. However, since there are plenty of uncertainties in the LUC emissions and differences in the methods for accounting for those in the context of agricultural production chains, alternative estimates of those emissions were evaluated in the sensitivity analysis (see below). The other replaced feed crops apart from soya, that is, rapeseed and barley, were assumed to be originated from "mature" agricultural land in the UK and therefore no LUC emissions were associated with those feed ingredients [50,51].

The changes in the greenhouse gas emissions arising from enteric fermentation and manure management, resulting from the changes in the feed composition, were also quantified and taken into account in the analysis. The calculation of these emissions was based on the intake of nitrogen and gross energy by the animal, applying the IPCC [45] Tier 2 approach and SAEM [47] emission factors (Table 1, Supplementary Materials). In this approach, the emissions of CH_4 are proportional to the feed gross energy intake of the animal and the N_2O and NH_3 emissions are proportional to the amount of nitrogen excretion (affected by the protein content of the animal feed intake).

Table 1. Emission factors and other constants used in the life cycle assessment (LCA) model.

Factor	Value	Source
GHG emissions from rapeseed production, kg CO_2e per kg DM	0.86	[47]
GHG from barley production, kg CO_2e per kg DM	0.325	[47]
LUC emissions from soya meal production, kg CO_2e per kg DM	3.25	[47,48]
Other GHG emissions from soya meal production, kg CO_2e per kg DM	0.83	[47]
GHG emissions from N fertiliser production, kg CO_2e per kg N	6.8	[53]
GHG emissions from P fertiliser production, kg CO_2e per kg P	3.3	[53]
GHG emissions from K fertiliser production, kg CO_2e per kg K	1.0	[53]
GHG emissions from UK grid electricity, kg CO_2e per kWh	0.465	[54]
GHG emissions from heating oil, kg CO_2e per kWh	0.267	[54]
Volatile solids of DM of distillery by-products	91%	[55]
CH_4 yield, m^3 per kg VS	0.385	[55]
Biogas CO_2 content	40%	[56]
AD/digestate CH_4 leakage	3%	[56]
Other digestate C losses	10%	[57]
Feed/AD feedstock DM carbon content	47.5%	[58]
Long-term (20 years) soil C storage of all soil C input	15%	[59]
CHP electricity yield of total CH_4 energy	36%	[56]
CHP heat yield of total CH_4 energy	40%	[56]
Electricity fed back to AD	12%	[56]
Heat fed back to AD	9%	[56]
Proportion of net heat utilized	60%	[56]
Digestate/manure N fertiliser replacement value	65%	[52]
Digestate/manure P fertiliser replacement value	100%	[52]
Digestate/manure K fertiliser replacement value	100%	[52]
CH_4 from enteric fermentation, kg CH_4 per MJ GE	0.0012	[45,47]
Direct manure management N_2O emissions, % N_2O-N of total N	0.2%	[45,47]
Indirect manure management N_2O emissions, % N_2O-N of total N	0.13%	[45,47]
Total manure management N losses: volatilized	12.5%	[47]
Total manure management N losses: leached	1.7%	[47]

The differences in the contents of main available plant nutrients, namely nitrogen (N), phosphorus (P) and potassium (K) in the manure, as affected by alternative scenarios, were calculated on the basis of nutrient intake and subsequent losses (assuming that the nutrient retention in animal body remained unchanged regardless of the feed ingredients used) and their benefits in reducing the greenhouse gas emissions by replacing synthetic fertilisers were quantified. The replacement rates of synthetic fertilisers applied in this study were based on the study by DeVries et al. [52]. The greenhouse gas emissions from the replaced synthetic fertiliser production were quantified by using the emission factors of the SAEM beef model [47,53].

Changes in the soil carbon (C) content (carbon sequestration) as a result of manure fertiliser use were not considered in the baseline calculations. However, the possible effects of changes of the carbon input to soil are evaluated in the sensitivity analysis (see below).

2.2. Scenario 2: Distillery By-Products as a Source of Renewable Energy

In this scenario, the amounts of replaced commodities were quantified when the by-products were used as an energy source. These commodities include grid electricity, fossil fuels used for heating and fertilisers used in crop production. The changes in GHG emissions associated with energy generation, management of the digestate and production of the fertiliser were then quantified as detailed below. Two by-products of whisky production, namely draff only (Scenario 2a) and a combination of draff and pot ale (Scenario 2b), were used as feedstock of anaerobic digestion (AD) to produce biogas. These scenarios were selected so that in terms of the input material, Scenario 2a was comparable to the feed use scenarios 1a and 1b (using draff directly as a feed ingredient) and Scenario 2b comparable to Scenarios 1c and 1d (using draff and pot ale to produce DDGS for feed). Unlike in Scenarios 1c and

1d, no further processing of by-products (needed to produce DDGS) was applied in Scenario 2b, as such processing would have no value in biogas production.

The produced biogas was assumed to be subsequently used to generate heat needed in mashing, fermentation and distillation processes and electricity to be fed to electrical grid, using the combined heat and power (CHP) technology.

The yield of CH_4 per kg of DM of distillery by-products was obtained from Luna-del Risco et al. [55] and the same value was used for both Scenario 2a and 2b (Table 1). The yields of electricity and heat generated in the CHP process, the proportions of the generated electricity and heat needed in the AD process and efficiency of the utilization of the net heat were obtained from an earlier study carried out at SRUC [56]. The heat obtained from the use of the biogas was assumed to replace part of the use of fuel oil, which is a commonly used fuel in Scottish malt whisky production as many distilleries are remote and not on the natural gas grid. Finally, the replacement of the grid electricity (i.e., the electricity fed to the grid minus the electricity used in the AD process) and the utilizable heat (net heat production minus the heat used in the AD process) were quantified, the associated greenhouse gas emissions were calculated based on the UK Department for Business, Energy & Industrial Strategy emission factors [54] and these avoided emissions were subtracted from the total greenhouse gas emissions of whisky production.

The direct and indirect greenhouse gas emissions arising from the AD and CHP processes and from the management of the digestate were also quantified and added to the emissions of whisky production. The methane leakage was based on values from an earlier study carried out at SRUC [56] and the N_2O and NH_3 emissions where based on the nutrient content of the feedstock, obtained from the Feedipedia [46] database and calculated in a same way as the emissions from manure management.

Similarly, as in the use of the by-products as feed, the fertiliser value of the nutrients obtained as an output of the AD process was quantified. All phosphorus and potassium of the feedstock were assumed to remain in the digestate and the nitrogen emissions described above were subtracted from the total nitrogen content of the digestate. The remaining nutrients could then be expected to replace synthetic fertilisers. It should be noted that part of the grid electricity is also generated from biomass (in 2016, this was estimated to be 7.6%, according to Ofgem [60] data) and was therefore assumed to replace a similar amount of fertiliser per kWh of generated electricity as the AD system considered here. To avoid double counting, a proportion equal to this share was subtracted from the applicable organic fertilisers produced in the AD. Similarly, as in Scenario 1, the changes in soil carbon content were not included in this baseline but they are evaluated in the sensitivity analysis.

A summary of the emission factors and other constants used in the calculations for different scenarios can be found in Table 1.

2.3. Sensitivity Analysis

2.3.1. LUC Emissions

In the baseline analyses, the emissions arising from the land use changes associated with the soya production were based on the FAO [48] default calculations methods, resulting in an emission factor of 3.25 kg CO_2 equivalent per kg DM soya bean meal [47]. However, alternative estimates of this value exist, so two alternatives were used here for comparison. First, recent calculations by Williams et al. [59] estimated the direct LUC emissions to be 1.46 kg CO_2e per kg DM soya bean meal (based on weighted average of the origins of soya used in the UK). Second, assuming that the soya would originate from sustainable sources, (i.e., no LUC associated with its production) and following the methods of PAS 2050 carbon footprinting guidelines [50,51], the LUC emissions would be zero.

2.3.2. Carbon Sequestration

Although soil carbon content is not normally considered in agricultural LCA, changes in the ecosystem carbon stock are included in the IPCC [45] guidelines for calculating GHG emissions.

For this reason, alternative calculations were carried out where the changes of soil carbon content in different scenarios were estimated. First, the amount of carbon in the digestate was determined based on the carbon content of the AD feedstock [58] and the carbon losses as CO_2 and CH_4 during the digestion process. For the animal feed, it was assumed that the dry matter excretion rate is inversely proportional to the organic matter digestibility, obtained from the Feedipedia [46] database and a constant carbon content of the excreted organic matter was used in the calculations [58]. Then, the changes of the carbon input entering soil (in the fertiliser use of digestate or manure) were quantified in each scenario. Finally, following the method introduced by Williams et al. [59] and assuming the same decomposition rate of organic matter as in their study, the proportion of the carbon remaining in the soil within a 20-year time scale (consistent with the IPCC [45] guidelines) was determined to be 15% of the total addition of carbon to soil. This was then converted to avoided CO_2 emissions and subtracted from the greenhouse gas emissions of whisky.

3. Results and Discussion

The potential of the distillery by-products to replace different feed ingredients in either soya meal based (Scenarios 1a and 1c) or rapeseed meal based (Scenarios 1b and 1c) feed is presented in Table 2. The results show that using an equal amount of the by-product, generally a bigger amount of rapeseed meal could be replaced than soya bean meal, due to the lower protein content of the former. It can be also seen that on the dry matter basis, DDGS is more efficient than draff in replacing alternative protein sources.

Table 2. The amounts of different feed ingredients in cattle feed replaced by the distillery by-products (Draff or dried distillers grains with solubles (DDGS)) in different scenarios. The quantities are based on equal content of metabolizable energy and digestible protein.

By-Product (1 kg DM)	Replaced Soya Meal, kg DM	Replaced Rapeseed Meal, kg DM	Replaced Barley, kg DM
Draff: Scenario 1a	0.28		0.41
Draff: Scenario 1b		0.44	0.32
DDGS: Scenario 1c	0.39		0.54
DDGS: Scenario 1d		0.60	0.42

Replacement of alternative feed ingredients resulted in considerable reductions in greenhouse gas emissions arising from feed production (Table 3). When comparing different alternative protein sources (soya and rapeseed), higher reductions could be achieved when soya bean meal was removed from the feed, due to avoided emissions that would arise from land use changes associated with soya production.

Table 3. Effects of replacing soya bean meal or rapeseed meal in cattle feed by distillery by-products (Draff or DDGS) on GHG emissions arising from different sources (kg CO_2 equivalent per 1 kg DM of by-product). Negative signs indicate reduction of emissions and positive signs increase of emissions.

Source of GHG Emission	Draff Replacing Soya (Scenario 1a)	Draff Replacing Rapeseed (Scenario 1b)	DDGS Replacing Soya (Scenario 1c)	DDGS Replacing Rapeseed (Scenario 1d)
Feed production	−1.288	−0.480	−1.773	−0.655
Manure N_2O	0.002	−0.001	0.003	−0.001
CH_4 enteric fermentation	0.063	0.049	0.14	0.066
N fertiliser replacement	−0.005	0.001	−0.007	0.001
P fertiliser replacement	0.001	−0.005	−0.016	−0.024
K fertiliser replacement	0.009	0.002	0.002	−0.007
Processing (DDGS)	0	0	0.518	0.518
Total	−1.219	−0.433	−1.133	−0.101

There were only minor changes in emissions directly related to livestock production, other than those arising from feed production, when distillery by-products were replaced with alternative feed ingredients (Table 3). The reason for that is that the inputs (gross energy intake, nutrient intake) affecting those emissions in the calculations based on IPCC Tier 2 method remained very similar in all feeding scenarios. This is expected, as the quantities of the feed ingredients consumed by the animals were specified so that the metabolizable energy intake and the digestible protein intake (affecting N emissions) remained constant in all scenarios. The differences in those emissions were thus a result of small differences in the contents of nutrients in the feed and different digestibility of energy and protein in different feed ingredients. These factors affected the avoided emissions related to the production of replaced fertilisers but the differences in those emissions were also rather small between the feeding scenarios with different feed ingredients.

The outputs of the scenario where the distillery by-products were used to generate renewable energy are presented in Table 4. In addition to the generated electricity and heat (replacing grid electricity and heating oil used in whisky production), considerable amounts of synthetic fertilisers could also be replaced when the digestate obtained from the anaerobic digestion would be used as a fertiliser in crop production.

Table 4. Outputs of use of distillery by-products as a source of renewable energy by applying a combination of anaerobic digester (AD) and combined heat and power (CHP) (per 1 kg of dry matter (DM) of the by-product).

Outputs per 1 kg DM by-Product	Draff (Scenario 2a)	Draff + Pot Ale (Scenario 2b)
Methane, m^3	0.351	0.351
Electricity to grid, kWh	1.146	1.146
Utilized heat, kWh (replacing oil)	0.790	0.790
Replaced N as fertiliser, kg	0.018	0.024
Replaced P as fertiliser, kg	0.003	0.009
Replaced K as fertiliser, kg	0.0003	0.009

Since the same conversion factor for methane yield was used for different types of distillery by-products when used as AD feedstock [55], there were no differences in the amount of energy generated per unit of DM between the options where draff only or a combination of draff and pot ale were used in AD. However, there were differences in the amount of fertiliser that could be replaced by the digestate, depending on the feedstock used. This was due to the high nutrient content of pot ale and for this reason, the digestate from the combination of draff and pot ale had a higher capacity to replace fertilisers than the digestate originating from draff only.

The biggest part of the reductions in the greenhouse gas emissions, when distillery by-products were used as AD feedstock, was associated with the replaced grid electricity (Table 5). However, considerable reductions were achieved also by using the digestate to replace synthetic fertilisers, most notably nitrogen fertilisers. Unlike in the Scenario 1, most of the nutrients entering to the AD process as part of the feedstock could actually be credited to whisky production. In contrast, in the feed use, the difference in the nutrient output between the by-products and the alternative feed ingredients was rather small. The reduction of the GHG emissions was also affected by the emissions of methane and nitrous oxide arising from the digestion process and storage of the digestate (Table 5).

Table 5. Effects of using distillery by-products as a source of renewable energy (by applying a combination of AD and CHP) on GHG emissions arising from different sources (kg CO_2 equivalent per 1 kg DM of by-product). Negative signs indicate reduction of emissions and positive signs increase of emissions.

Source of GHG Emission	Draff (Scenario 2a)	Draff + Pot Ale (Scenario 2b)
Electricity replacement	−0.549	−0.549
Oil replacement	−0.25	−0.25
N fertiliser replacement	−0.12	−0.159
P fertiliser replacement	−0.011	−0.03
K fertiliser replacement	−0.000	−0.009
N_2O emissions	0.051	0.063
CH_4 emissions	0.176	0.176
Total	−0.703	−0.759

Total GHG emissions per volume unit of produced alcohol were 2.6 kg CO_2 when the end use of the by-products was excluded from the calculations [35]. The changes in these emissions when the draff obtained from the mashing process was used either as animal feed or as AD feedstock are presented in Table 6 and Figure 2. It can be seen that the highest overall reductions were achieved when draff was used to replace soya in animal feed. However, nearly as high reduction could be achieved when draff was used to generate renewable energy.

Table 6. Effects of the alternative uses of draff on the GHG emissions of Scottish malt whisky production. The following scenarios are compared: Scenario 1a: draff replacing soya bean meal and barley, Scenario 1b: draff replacing rapeseed meal and barley and Scenario 2a: draff replacing grid electricity and oil.

	Amount of Draff Produced, kg DM per Litre of Alcohol	Effect on GHG Emissions, kg CO_2e per Litre of Alcohol (Relative Change in Parentheses)	Final GHG Emissions per Litre of Alcohol, kg CO_2e
Scenario 1a: Replacing soya	0.56	−0.68 (−26%)	1.92
Scenario 1b: Replacing rapeseed	0.56	−0.24 (−9%)	2.36
Scenario 2a: Renewable energy	0.56	−0.39 (−15%)	2.21

When comparing the alternative uses of DDGS (or a combination of draff and pot ale), the patterns were somewhat different (Table 7, Figure 2). Compared to draff, the combination of draff and pot ale was able to produce higher reductions in GHG emissions when used either to replace soya in animal feed, or to generate renewable energy. The reason for this is partly in the larger amount of the by-product utilised per unit of produced alcohol and also in the high nutrient content of pot ale. This enabled the combination of draff and pot ale to replace higher amount of alternative protein sources in animal production, or replace more fertilisers when the digestate is used in crop production. In contrast, only minimal reductions in the GHG emissions were achieved when DDGS was used to replace rapeseed meal in animal feed. This is due to the fact that the benefits achieved by reducing the amount of rapeseed in feed are counteracted by the high energy use of producing DDGS from the primary by-products draff and pot ale.

Table 7. Effects of the alternative uses of combination of draff and pot ale on the GHG emissions of Scottish malt whisky production. The following scenarios are compared: Scenario 1c: DDGS replacing soya bean meal and barley, Scenario 1d: DDGS replacing rapeseed meal and barley and Scenario 2b: draff + pot ale replacing grid electricity and oil.

	Amount of Draff + Pot Ale Produced, kg DM per Litre of alcohol	Effect on GHG Emissions, kg CO_2e per Litre of Alcohol (Relative Change in Parentheses)	Final GHG Emissions per Litre of Alcohol, kg CO_2e
Scenario 1c: Replacing soya	0.92	−1.04 (−40%)	1.57
Scenario 1d: Replacing rapeseed	0.92	−0.09 (−3%)	2.51
Scenario 2b: Renewable energy	0.92	−0.70 (−27%)	1.91

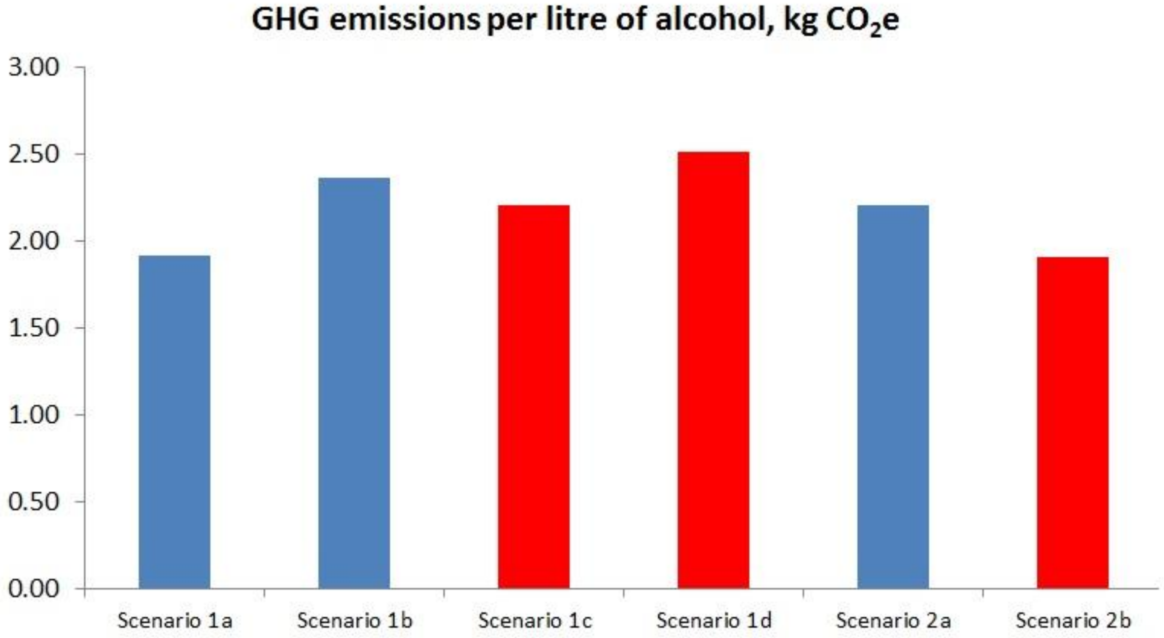

Figure 2. GHG emissions of Scottish malt whisky production with different end uses of by-products. Scenarios applying draff only are presented in blue colour and scenarios applying both draff and pot ale in red colour. Scenario 1a: draff replacing soya bean meal and barley, Scenario 1b: draff replacing rapeseed meal and barley, Scenario 1c: DDGS replacing soya bean meal and barley, Scenario 1d: DDGS replacing rapeseed meal and barley, Scenario 2a: draff replacing grid electricity and oil and Scenario 2b: draff + pot ale replacing grid electricity and oil.

The sensitivity analysis shows that the method used for quantifying the GHG emissions associated with the land use changes has a major effect on the comparison between different uses of the by-products and on conclusions drawn from this comparison. It can be seen in Table 8 that when lower LUC emissions are applied for soya, the benefits of by-product feed use in reduction of the GHG emissions are largely lost and the use of the by-products for heat and electricity generation becomes the most efficient option. In fact, in the option where zero LUC emissions were assigned to soya production, the use of DDGS to replace soya became the least efficient way to reduce the GHG emissions of whisky production, while in the baseline scenario it resulted in the highest reductions.

Including the carbon sequestration (i.e., changes in soil carbon content as a result of the alternative uses of the by-products) also affected the results. In general, when such changes were accounted for, the efficiency of energy generation option in reducing the GHG emissions increased. This is because the net input of C to soil increases when digestate is used as a fertiliser. However, an increase in soil carbon was also observed when the by-products were used as animal feed. This increase was a result of the lower digestibility (i.e., higher proportion of non-digestible carbon compounds per unit of digestible energy) of the by-products and hence higher dry matter excretion when the by-products were used as feed, compared to the alternative feed ingredients barley and soya/rapeseed.

Table 8. The results of the sensitivity analysis showing the GHG emissions (kg CO_2e per litre of alcohol) with different assumptions of land use changes (LUC)-related emissions and carbon sequestration. Scenario 1a: draff is used to replace soya; Scenario 1b: draff is used to replace rapeseed; Scenario 1c: DDGS is used to replace soya; Scenario 1d: DDGS is used to replace rapeseed meal; Scenario 2a: draff is used to replace grid electricity and oil; Scenario 2b: draff and pot ale are used to replace grid electricity and oil.

	Scenario 1a	**Scenario 1b**	**Scenario 1c**	**Scenario 1d**	**Scenario 2a**	**Scenario 2b**
Baseline	1.92	2.36	1.57	2.51	2.21	1.91
Alternative LUC emissions (Williams et al. 2016)	2.21	2.36	2.21	2.51	2.21	1.91
No LUC emissions	2.44	2.36	2.73	2.51	2.21	1.91
Including carbon sequestration	1.88	2.33	1.53	2.50	2.16	1.83

General Discussion

Overall, the results confirm the expectations of the whisky industry that the carbon footprint of whisky production can be reduced considerably when the by-products are used to generate heat and electricity and therefore the use of fossil fuels in the distillation process can be reduced. However, the by-products can also have other, indirect effects outside the distillery system, affecting greenhouse gas emissions. To understand and quantify such effects, other systems, in addition to whisky production itself, need to be included in the analysis and this can be done by applying a systems-based modelling approach.

In general, when the greenhouse gas emissions related to agricultural by-products (or co-products) are considered using LCA or other environmental assessment methods, the methodological choices related to allocation of the environmental burdens between those products often become a central issue of the analysis. Unfortunately, such choices can be very much subjective and they can also strongly affect the outcomes of the study in question. In studies related to livestock production and especially animal feeding, the use of various by-products as feed ingredients has often been found as an environmentally friendly option [3,36]. The reason for this that amongst different potential approaches to handling the co-products in environmental impact assessment, economic allocation has been widely used in agricultural LCA studies [38,39,61]. As an outcome of such analyses, smaller proportions of the environmental impacts are allocated to low value by-products, compared to the "main" product. In many cases, such an approach is justified and preferred, keeping in mind that the main product, not the by-products, is actually the driving force of the production.

Despite the general applicability of the economic allocation, alternative allocation methods have also been suggested for agricultural LCA. The idea behind this is that the ISO [44] standards prefer the use of a "causal" or "physical" allocation method, in cases where allocation cannot be avoided altogether for example through system separation. Another reason for avoiding economic allocation is the potentially varying prices of the co-products, which has sometimes been considered problematic and causing inconsistencies in LCA studies. However, alternative methods, such as system separation, or so called "biophysical allocation", where the aim is to link the inputs to outputs through actual physical flows or causalities [61–65] are problematic due to the unique nature of agricultural LCA. The fact is that agricultural products are always an outcome of complicated biological processes with various interactions. Therefore, attempts to physically separate the processes behind each co-product are not meaningful as such an approach would necessarily be based on arbitrary, subjective decisions [66]. In addition to attempts to model the physical flows, other "physical" allocation methods, used to avoid economic allocation, can be based for example on mass (fresh or dry matter) or protein or energy content of the products. Again, using such methods in agricultural LCA in a systematic way can be very difficult, due to potentially varying end uses of the by-products and possible difficulties in distinguishing between actual products and waste materials, for example, in case of manure [66].

To avoid allocation, in cases where system separation is not possible, the ISO [44] standards recommend using a system expansion approach. System expansion is also preferred over co-product allocation in various carbon footprinting guidelines such as PAS 2050 [50]. Over recent years, this approach has been widely applied for example in LCA studies on livestock production [67,68]. However, as pointed out by Mackenzie et al. [66], the use of this approach cannot be considered as becoming a general practice in agricultural LCA, for example due to possible difficulties in identifying the main product and by-products. Another difficulty with this approach is that it could require large amount of additional data from other sub-processes or systems [66,69,70]. Despite possible shortcomings, the use this method can be considered to be justified in many cases and especially when 1) the process in question is clearly targeted to produce one specific main product and 2) the focus of the analysis is in alternative uses of the emerging by-products, not in the production process itself. This was the case in this study and in fact, it would be difficult to systematically compare the very different uses of whisky by-products by applying any other of those alternative methods mentioned above.

The system expansion (usually as part of so called "consequential LCA" approach [71]) has been earlier used in other studies evaluating the environmental consequences of alternative uses of agricultural by-products, including the use of those products in generating renewable energy. For example, Styles et al. [57] used a consequential approach to quantify the reduction of the GHG emissions when manure and food waste are used in AD in a dairy farm. Their conclusion was that the achieved benefits were dependent on how much crops were used as co-digestate in addition to the manure, as this would determine the need for animal feed imported to the farm, which had its own effect on the feed-related GHG emissions. In another study, van Zanten et al. [72] applied consequential LCA to compare uses of two by-products, namely wheat middlings and beet tails. In the case of the beet tails, the alternative use also in their study was bioenergy generation using AD, as opposed to using them as cattle feed.

Williams et al. [59] assessed the effects of alternative end uses of turkey litter on the environmental impacts of turkey meat production. Also in that study, a system expansion approach was used in order to compare the use of litter either as a biofuel (used for electricity generation in a large-scale power plant) or directly as a fertiliser through land spreading. Similarly, as in the current study, the availability of nutrients for crop production, obtained from the litter, was quantified for both scenarios and the displacement of the synthetic fertilisers (and the grid energy in the case of bioenergy use) was taken into account when calculating the total emissions related to turkey production. That study also demonstrated the potentially significant effect of carbon sequestration on the overall GHG emissions arising from agricultural production.

4. Conclusions

The most notable reductions of greenhouse gas emissions of whisky production were achieved when the distillery by-products replaced soya meal, the production of which is associated with land use changes. When using the by-products to replace alternative feed ingredients, there were changes also in emissions from enteric fermentation, manure management and the end use of manure and its potential to replace synthetic fertilisers but these had only minor effect on the overall greenhouse gas emissions, compared to effect achieved by changes in the production of the feed and related LUC emissions. Different by-products had different environmental effects when used as livestock feed. Compared to draff, DDGS could reduce more greenhouse gas emissions related to production of the replaced feed ingredients but on the other hand, it had higher emissions arising from processing, especially from drying and pelletizing.

The use of by-products as a source of renewable energy, that is, production and combustion of biogas, reduced the greenhouse gas emissions by replacing grid electricity and fossil fuels used for heating. Additional benefits were achieved by using the digestate as a fertiliser and thus replacing the production of synthetic nitrogen fertilisers. Overall, the energy use of by-products could produce reduction of greenhouse gas emissions with similar magnitude as the use of the by-products as feed.

It should be also noted that in the case of this study, similarly as in earlier studies on agricultural by-products discussed above, the outcome is largely dependent on methodological choices. The sensitivity analysis demonstrates that the calculated reductions in the GHG emissions are strongly affected by the method how the emissions associated with land use changes and land management are accounted for in the calculations. Currently, there is no generally accepted approach to this process and this is causing difficulties in comparing the results of agricultural LCAs, especially in cases where the products are strongly associated with LUC. In assessment of greenhouse gas emissions in agricultural production, probably the most important single product where direct LUC is involved is soya bean meal imported from South America. This has been demonstrated for example by Leinonen et al. [51], who applied LCA modelling to quantify the environmental impacts of UK poultry production systems with alternative scenarios using different protein crops as a basis of diet formulations for broilers and laying hens. The general conclusion of their study was that inclusion of alternative protein sources (e.g., beans or peas) to replace soya bean meal could slightly reduce the Global Warming Potential of broiler and egg production but also in that study, this observed reduction was highly dependent on the LUC emission accounting method.

A high sensitivity to the LUC emissions was also found by van Zanten et al. [72]. According to their findings, higher reductions in GHG emissions could be achieved with the feed use of beet tails, through displaced emissions related to barley production, when compared to the bioenergy use. However, this was only the case when indirect LUC emissions were accounted for in barley productions, which is not a common practice in agricultural LCA studies [73]. If these emissions were excluded, higher reductions in the emissions could be achieved through the bioenergy option [72]. To avoid these methodological problems, some attempts have been made to harmonize the LUC accounting methods in agricultural LCA [73,74]. Despite this, current inconsistencies in the methods will necessarily remain a challenge in interpretation of the results of studies on environmental sustainability of agricultural products, especially in the context of livestock systems.

In addition to carbon losses due to land use changes, agricultural systems can also contribute to carbon sequestration. Although a large proportion of the carbon in the UK soils has been lost during recent decades, partly as a result of agricultural practices [75,76], this trend can be partially reversed for example, by the use of organic fertilisers. Although the changes in soil carbon (other than those related to land use changes) are not usually considered in agricultural LCA, we explored this process in the sensitive analysis of this study, using a similar approach as Williams et al. [59]. In general, soil carbon balance is potentially an important component of the overall effect of agricultural and bioenergy systems on global GHG emissions and therefore should not be ignored in such studies.

Supplementary Materials: The following supplementary materials are available online at http://www.mdpi.com/2071-1050/10/5/1473/s1, 1. Diagram of the production systems and material flows, 2. Quantifying GHG emissions from malt whisky production and 3. Outline of the Scottish Agricultural Emission Model (SAEM).

Author Contributions: All authors contributed to the design of the study, analysis of the data and writing the paper. I.L. led the writing process and data analysis, M.M. led the development of the livestock modelling tool and J.B. provided unpublished data for the analysis.

Acknowledgments: This research was undertaken within the Scottish Government Rural Affairs and the Environment Portfolio Strategic Research Programme 2016–2021, WP 1.4 “Integrated and Sustainable Management of Natural Assets” and 2.4 “Rural Industries.”

Conflicts of Interest: The authors declare no conflict of interest.

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