Supplementary material for the article:

"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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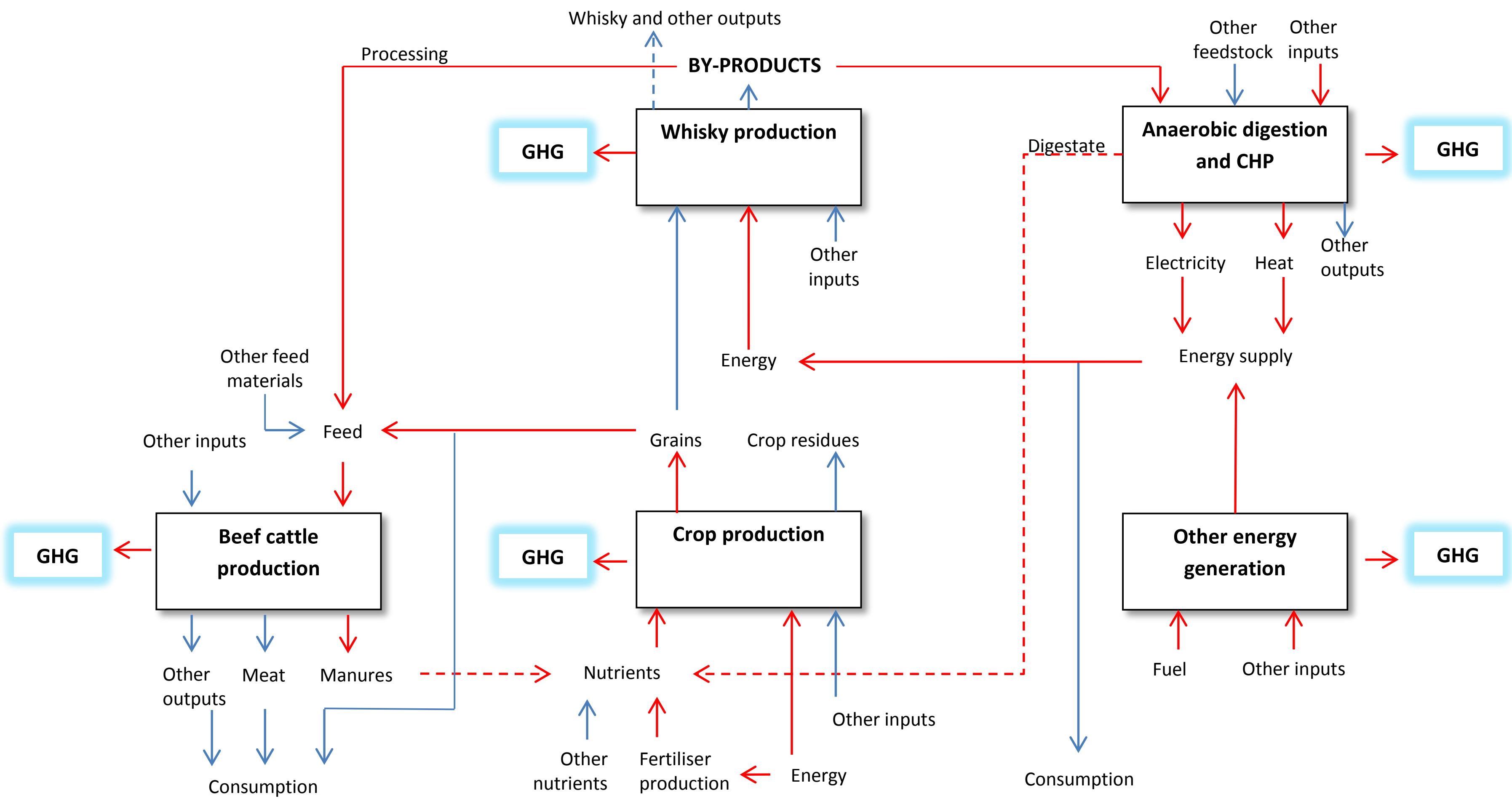
1. Diagram of the production systems and material flows

The production systems included in the analysis in this study are shown in Figure 1, together with the material and energy flows between them. The following systems were considered here:

1. Malt whisky production
2. Beef cattle production
3. Crop production
4. Anaerobic digestion and CHP at the distillery, and
5. Other energy production

In Figure 1, the flows affected by the alternative use of whisky by-products and therefore included in the calculations in this study are shown in red colour.

Figure 1. Schematic diagram showing the relationships between the production systems and material and energy flows between them. The flows affected by the alternative use of whisky by-products and therefore included in the calculations in this study are shown in red colour



2. Quantifying GHG emissions from malt whisky production

The following data are based on the report: Bell, J; Morgan, C; Dick, G; Reid G. Distillery feed by-products briefing, An AA211 Special Economic Study for the Scottish Government, 2012. Available online: http://www.sruc.ac.uk/download/downloads/id/1057/distillery_feed_by-products_briefing

Table 1. Inputs and outputs of a typical malt whisky production chain and GHG emissions arising from different processes (excluding by-product processing and end use):

Factor	Unit	Quantity	GHGE kg CO_2e/unit	GHGE kg CO_2e total
Malting: inputs				
Barley production	t	4.2[a]	350[d]	1457.40
Transport: farm – malting	t km	416[b]	0.04[e]	17.38
Heating (mains gas)	kWh	3123[a]	0.23[e]	708.11
Electricity	kWh	541[a]	0.59[e]	319.28
Malting: output				
Malt	t	3.33[b]		
Mashing/fermentation/distillation : inputs				
Transport: malting – distillery	t km	333[b]	0.04[e]	13.90
Heating (mains gas)	kWh	2548[c]	0.23[e]	577.79
Electricity	kWh	345[c]	0.59[e]	203.49
Mashing/fermentation/distillation : output				
Alcohol	litres	1266[c]		
Total GHG emissions				**3297.35**

Sources:
[a]SAC Consulting + FAO Agribusiness Handbook, Barley, Malt, Beer (2009)
[b]SAC Consulting
[c]SAC Consulting + Chematur Engineering AB, Economic Evaluation of Bioethanol Production, prepared for ITI Life Sciences, (2005)
[d]Carbon Trust Footprint Expert 3.1
[e]SAC Consulting + 2012 Guidelines to Defra/DECC's Greenhouse Gas Conversion Factors for Company Reporting

3. Outline of the Scottish Agricultural Emission Model (SAEM)

The following model description is adapted from: MacLeod, M.; Sykes, A.; Leinonen, I.; Eory, V. Quantifying the greenhouse gas emission intensity of Scottish agricultural commodities: CXC Project, Technical Report, 2017.

SAEM is based on GLEAM, the Global Livestock Environmental Assessment Module, which was developed by the UN-FAO (http://www.fao.org/gleam/en/). It uses a herd model coupled with an IPCC (2006) primarily tier 2 approach to computing emissions, thereby enabling key characteristics of the livestock populations (e.g. herd structures, animal performance, rations and manure management) to be captured in the calculations. The current version of SAEM calculates and reports the greenhouse gas Emission Intensity (EI) for nine agricultural commodities: cattle meat and milk, sheep meat, pig meat, broiler meat, hens eggs, wheat, barley and potatoes. Three (excel-based) versions of the model has been created:

1. SAEM-R (beef cattle, dairy cattle and sheep)
2. SAEM-P (pigs)
3. SAEM-C (broilers and laying hens)

These models are used to quantify the GHG emissions arising from cradle to farm-gate, i.e. they include the emissions arising on-farm, and the emissions arising pre-farm from the production of inputs such as feed, fertiliser and electricity. Post-farm emissions arising from the distribution, processing and consumption of commodities are not included. The GHG categories included are summarised in Table 2.

The structure of SAEM is illustrated in Figure 2. The emissions are quantified using the methods established by the Intergovernmental Panel on Climate Change (IPCC). The IPCC guidance provides a choice of methods for quantifying emissions, from the relatively simple Tier 1 approach to more complex Tier 2 or 3 approaches. SAEM adopts a Tier 2 approach for livestock, i.e. key processes such as feed consumption and excretion rates are calculated bottom-up based on the livestock characteristics (e.g. weight, growth rates, milk yields, ration composition) within a particular production system. This approach enables the model to make emission estimates that reflect the particular features of Scottish systems, which is a significant advantage over the Tier 1 approach, which uses regional default emission factors (e.g. a single emission factor for enteric methane is provided for dairy cattle in Western Europe). While the Tier 2 approach is more informative it is also more demanding and requires values for a wide range of input parameters.

Table 2. GHG categories included in the analysis

Description	Category name
CH_4 from enteric fermentation	Enteric CH_4
CH_4 from manure management	Manure CH_4
N_2O from manure management	Manure N_2O
Direct and indirect N_2O from (a) application of (synthetic and manure) N to crops, (b) crop residues management and (c) direct deposition of manure by grazing animals.	Feed N_2O
CO_2 from energy use in field operations, feed transport and processing, and fertiliser production.	CO_2 (feed energy)

CO_2 from energy use in the production of non-crop feeds (fishmeal, lime and synthetic amino acids)	
CO_2 from direct on-farm energy use for livestock, e.g. cooling, ventilation and heating	CO_2 (on-farm energy)
CO_2 from land use change related to soybean cultivation.	Soy LUC
CO2 from land use change related to cultivation of crops in Scotland	Domestic LUC

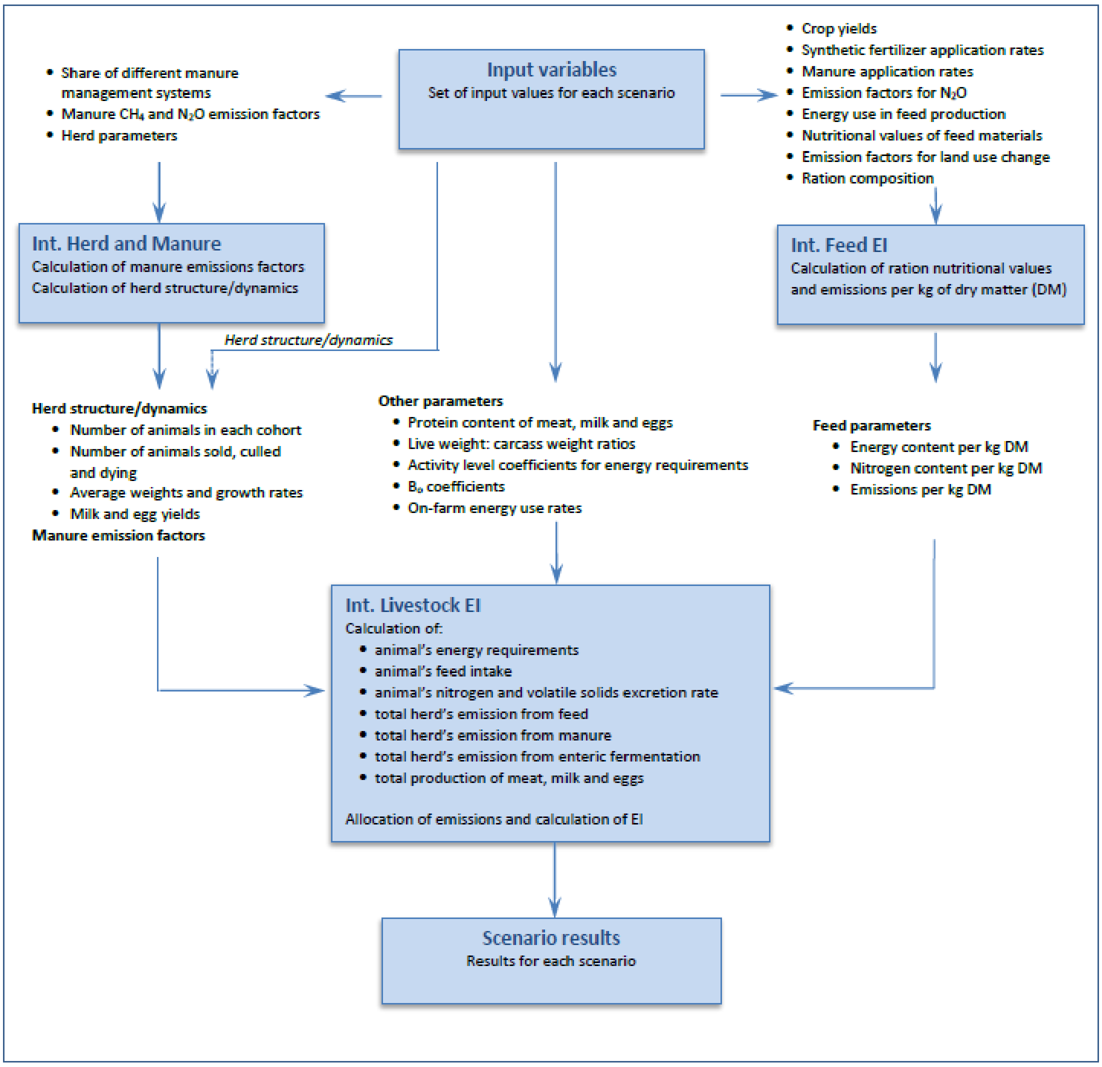


Figure 2 Schematic diagram of SAEM

The Tier 2 approach (illustrated in Figure 3) means that EFs reflect differences in many parameters and therefore enable variation in these parameters to be captured. They also enable estimates to be revised in light of new evidence, for example, the assumptions about how manure is managed in the UK were revised in 2014, leading to significant changes in the manure management EFs.

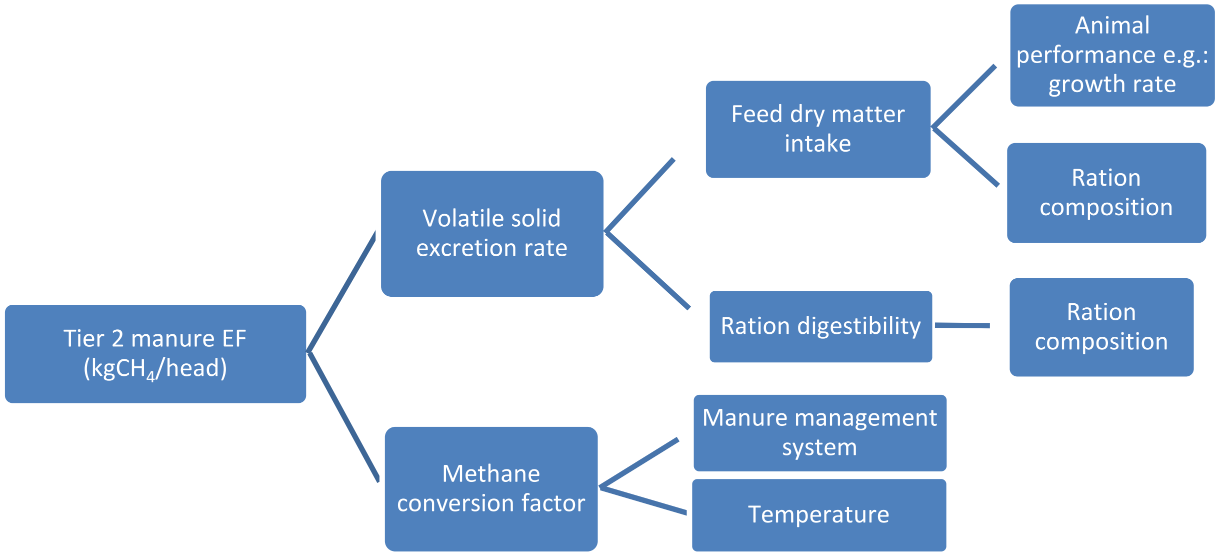


Figure 3 Simplified schematic representation of the IPCC (2006a) Tier 2 approach to determining manure management methane emissions.

The steps performed in order to calculate the EI are summarised in Table 3, and further detail is provided below.

Table 3 Overview of the steps in calculating livestock commodity EI

Pre-farm emissions Determination of emission factors (EFs) for pre-farm inputs (energy, fertiliser). Determination of the rate of consumption of pre-farm inputs.
Determination of herd dynamics Calculation of the herd structure, i.e. the proportion of animals in each cohort*, and the rate at which animals move between cohorts. Calculation of the characteristics of the animals in each cohort, i.e. the average weights and growth rates.
Feed parameters and emissions Determination of the composition of the ration for each species, cohort and system. Calculation of the nutritional values of the ration per kg of feed dry matter (DM). Calculation of the GHG emissions per kg of feed, which involves: • determination of the rates at which organic and synthetic N is applied to crops; • determination of rates of energy use in fieldwork, processing and transport; • calculation of land use change; • determination of crops yields; • allocation of emissions between crop co-products, i.e. grains, crop-residues and crop by-products (brans, meals etc.); • EFs for non-crop feed materials (e.g. lime, synthetic additives, fishmeal).
Feed intake, enteric and manure emissions Calculation of the average energy requirement and feed intake of each animal cohort. Calculation of volatile solid and N excretion rates.

Calculation of the total emissions and arising from the production, processing and transport of the feed. Calculation of the CH_4 and N_2O emissions arising during the management of manure; Calculation of enteric CH_4 emissions.
Allocation and calculation of EI Calculation of the production of commodities (meat, milk, eggs and crops). Allocation of the emissions to the edible outputs Calculation of EI of each commodity.

**e.g. cows, heifers, bulls and calves*

Pre-farm emissions

EFs for energy are based on UK BEIS (2016), IEA (2013) and GLEAM defaults. Rates of on-farm energy use associated with livestock production are based on Scottish Government (2011) (dairy), GLEAM defaults (pigs and chickens). On-farm energy is not determined for beef and sheep, as it is likely to be a minor source of emissions.

Determination of herd dynamics

The herd structure and dynamics are determined using the GLEAM herd module and inserted into the Input variables. The Herd Module is explained in FAO (2017, chapter 2). The calculated values could be replaced with empirical data, if available.

Feed parameters and emissions

Details of how the ration compositions are defined are given in the specific details section. Key elements of the general method used to quantify feed emissions are given In Table 4.

Table 4 Summary of the methods used to quantify feed emissions

Source of emissions	**Approach to quantifying**
Direct and indirect N_2O from crop cultivation;	• Synthetic and manure N application rates are defined for domestic crops based on DEFRA (2016a,b). For non-domestic crops GLEAM defaults are used, which are primarily based on FAO's Fertilizer use statistics. • Crop residue N is calculated using the crop yields and the IPCC (2006, p. 11.17) crop residue formulae. • N_2O emissions calculated using IPCC (2006) Tier 1 methodology
CO_2 arising from land use change (LUC) for pasture and soybean expansion	• Rates of LUC are based on FAOSTAT average LUC rates 1990-2006. • Emissions arising from LUC calculated using IPCC (2006) Tier 1 (Opio et al. 2013, Appendix C).
CO_2 from the on-farm energy use associated with crop production	• GLEAM defaults are used for the rates of energy use in crop production, which are then multiplied by the emissions factor for that energy source. (FAO 2017, section 6.1.2)
CO_2 arising from the manufacture of fertilizer;	• The average European fertilizer EF of 6.8 kg CO_2-eq per kg of ammonium nitrate N is used (based on Jenssen & Kongshaug, 2003).
CO_2 arising from crop transport and processing;	• Roughages are transported minimal distances and are allocated zero emissions for transport. Other feeds are assumed to be transported between 100 km and 700 km by road. In countries where more of the feed is consumed than is produced (i.e. net importers), feeds that are known to be transported globally (e.g. soymeal) also receive emissions that reflect typical sea transport distances (FAO 2017, section 6.1.3). • Emissions from processing (e.g. milling, crushing and heating) are calculated for by-product feeds based on default rates of energy

		consumption (FAO 2017, section 6.1.3).
	•	The energy used in feed mills for blending non-local feed materials to produce compound feed and to transport it to its point of sale, are calculated based on the assumptions that 186 MJ of electricity and 188 MJ of gas are required to blend 1000 kg of DM (FAO 2017, section 6.1.4).
Production of non-crop feed materials	•	Default values are used for fishmeal and synthetic amino acids (from Berglund *et al*. 2009) and for lime (from Kool *et al*. 2012)

Feed intake, enteric and manure emissions

The IPCC (2006) tier 2 approach is used throughout. For cattle, sheep and pigs, the animals energy requirement and feed intake are quantified using the formulae set out in FAO (2017, p53-64). For chickens, new formulae were derived, which better reflect current chicken performance. Enteric and manure emissions are determined using the formulae described in FAO (2017, section 4).

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