Science of the Total Environment 637–638 (2018) 120–131

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Environmental impacts of alternative agricultural uses of poorly drained farm land in Ireland

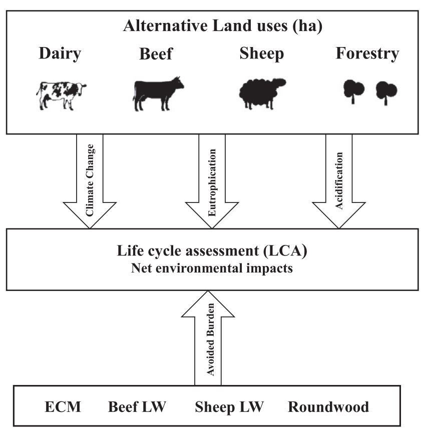
Pooja Sharma [a,*], James Humphreys [b], Nicholas M. Holden [a]

[a] UCD School of Biosystems and Food Engineering, University College Dublin, Belfield, Dublin 4, Ireland
[b] Animal & Grassland Research and Innovation Centre, Teagasc, Moorepark, Fermoy, Co., Cork, Ireland

HIGHLIGHTS

- Environmental impacts of alternative land uses were compared using life cycle assessment with system expansion.
- Grass based dairy and sheep would have least net global impacts for agricultural production on poorly drained soils.
- Grass based suckler beef production system would be best if climate change is prioritised.
- Choice of market substitution will affect the net environmental results.
- Detailed consumption modelling is needed to better understand market substitution.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 16 March 2018
Received in revised form 21 April 2018
Accepted 23 April 2018
Available online 8 May 2018

Editor: D. Barcelo

Keywords:
Life cycle assessment
Land use
Livestock
Forestry
Avoided burden

ABSTRACT

Abolition of the milk quota in the European Union and favourable market conditions have stimulated the expansion of the dairy sector in Ireland, causing more milk to be produced from poorly drained land. This work evaluated the environmental impacts of alternative agricultural uses for poorly drained farm land in Ireland using life cycle assessment (LCA). The avoided burden of the displaced product was used to calculate the net environmental consequences in the context of regional or global markets. The impact categories evaluated were climate change, eutrophication and acidification, all expressed per hectare of land for the alternative land uses, which were pasture-based milk, suckler beef and lowland sheep production and coniferous forestry. Beef had the lowest net climate change impact with global marginal and average product substitution while sheep had the lowest net climate change impact with European displaced product. For net eutrophication and acidification, dairy had the lowest impacts with European and global average displaced product. With global marginal displaced product, forestry had the lowest net eutrophication impact and sheep had the lowest net acidification impact. From an Irish perspective, forestry would generate the lowest environmental impacts and would also increase soil carbon stock, but this was not the best land use option from global perspective. Overall it can be concluded that a pasture based dairy or sheep system would have the greatest net global impact reduction (i.e. greatest global benefit) as land use options for farms with poorly drained soils. Prioritizing climate change, suckler beef system would perhaps be more favourable. It is clear that the choice of the displaced regional or global co-product from the market

* Corresponding author.
E-mail address: pooja.sharma@ucdconnect.ie (P. Sharma).

https://doi.org/10.1016/j.scitotenv.2018.04.315

has a great influence on the results and there is a need to consider more detailed consumption modelling to better understand the substitution process.

1. Introduction

A substantial increase in global food demand is anticipated because of increasing world population. In addition to food and feed production, land is starting to be used to provide other materials and energy in the context of bioeconomy (Brandão et al., 2010). Land use and its associated impacts are both a local and global environmental issue (Foley et al., 2005), so along with achieving primary production goals, land must be managed to ensure that soils can facilitate reaching defined environmental targets (Coyle et al., 2016). Approximately half of the total land area of Ireland has natural limitations for agricultural production, and around half of Irish farms are classified as limited for agricultural use because of poor drainage causing excessive wetness (Tuohy et al., 2014). Such land is considered "marginal" for dairy production. Up to one third of milk production and the vast majority of beef and sheep output are generated by farms that are on poorly drained soils (Crosson, 2016). Poor soil drainage may be due to a combination of rainfall, geology, glacial history and landscape position (Tuohy et al., 2015). Farms dominated by poorly drained soil typically have relatively low productivity and lower economic returns than those on well-drained soil (Kang et al., 2013), and in extreme cases are considered insufficient for food production unless efforts are made to improve land quality (Shahid and Al-Shankiti, 2013). Poorly drained lands can be easily damaged by animals and traffic and can pose additional risk for the wider environment due to runoff and erosion losses (Wiegmann et al., 2008). Concerns about sustainable use of marginal land have been raised (Kang et al., 2013), but with increasing food demand and limited land resources, such land is being bought into production (Kang et al., 2013).

Irish agricultural policy is to increase milk production by 50% by 2020 (DAFF, 2010) and abolition of milk quotas and favourable market conditions have provided opportunities for the Irish dairy industry to expand. The increase in milk production is being realised through displacement of other enterprises (farm transition), typically specialist beef production, an increase in the land area used by existing dairy farms and productivity improvement on existing dairy farms (Dillon, 2011). Theoretically implementation of production policy transition should not be undertaken at the expense of the environment and natural resources (DAFM, 2015). Similar expansion polices exist for beef and sheep production (DAFM, 2015). A growth of 20% in the value of output of the beef sector is targeted by 2020 (DAFF, 2010) with around 90% of beef produced being exported (Clarke et al., 2013). There are currently 2.5 million breeding ewes in the Irish sheep flock and 75% of them are lowland (Bohan et al., 2016). The national policy aims to increase the flock numbers to 3.5 million and to drive a higher retail price for sheep meat (DAFF, 2010). Livestock production activities in Ireland have caused large agricultural greenhouse gas (GHG) emissions representing around 32% of national emissions (Duffy et al., 2015). To reduce GHG emissions for meeting national obligations forestry is also expanding (Upton et al., 2014), with a target of 1.2 million ha (a 17% increase) by 2030 (DAFF, 2008). This means land use competition for food and fibre is starting to occur, and there is a clear need to understand the environmental and economic objectives for land use policy (Brandão et al., 2010). Previous land management studies in Ireland have focused on managing soil-based ecosystems (Schulte et al., 2014), assessing installation of drainage systems on primary productivity and carbon sequestration (O'Sullivan et al., 2015), and on different land uses, soil drainage and the key functions of soil (Coyle et al., 2016). Styles and Jones (2007), compared the environmental impacts of replacing dominant agricultural land uses with energy crops to generate electricity in Ireland. There is a need for quantification of environmental impacts of alternative land uses for sustainable land use planning (Kang et al., 2013). Life cycle assessment (LCA) has been widely used to estimate environmental impacts of livestock systems (Casey and Holden, 2006b; O'Brien et al., 2016; Sharma et al., 2018) and forestry (Murphy et al., 2014). Brandão et al. (2010) and Styles and Jones (2007) have used LCA to compare different land uses. It is now a recognised tool that can be used to evaluate the environmental aspects of agricultural sustainability (it can also be used for social and economic assessment with appropriate methodological modification and impact indicators).

The objective of the study was to explore which agricultural land use, for what can be considered marginal land for dairy production, would cause least contribution to environmental impact. Few such studies have been published. LCA was used to estimate the environmental impacts for four competing land uses in terms of climate change, eutrophication and acidification. The approach taken could be applied to similar land use questions anywhere in the world. These three impact categories relate to the international and national policies (climate change: Kyoto Protocol (UNFCC, 1998), EU Effort Sharing Decision (European Council, 2009); eutrophication: Nitrate Directive (European Council, 1991), Water Framework Directive (EU, 2000) and the good agricultural practice guidelines (GAP; EU, 2014); acidification: National Emissions Ceiling Directive (EU, 2001)).

2. Materials and methods

2.1. Life cycle assessment

The goal of LCA study was defined as: *(i) Reason*: to understand the environmental implications of agricultural policy in the context of competition for marginal land by pasture-based milk, suckler beef and sheep production and coniferous forestry; *(ii) Application*: to allow land use planning to consider environmental information at national and global scale; *(iii) Audience*: assumed to be scientists and policy makers; and *(iv) Comparison*: no explicit comparison of products, but independently verified through the peer review process. Due to differences in goal, scope and assumptions no direct, formal comparison with other studies was undertaken. For the scope, the systems modelled (described in Sections 2.1.1 and 2.1.2) were centred on the use of poorly drained farm land over a period of 1 year. All relevant foreground and background inputs to the systems were included in the life cycle inventory up to the farm gate. The functional unit was 1 ha of land for one year because the goal addressed land use and not the commodities produced. A similar approach was taken by Brandão et al. (2010) (food crops vs energy crops) and Styles and Jones (2007) (energy crops vs agriculture systems). The co-products from the land were kg energy corrected milk (ECM) from dairy, kg live weight (LW) from beef and sheep and m^3 sub (solid under bark) roundwood from forestry. A process-based model was built for each land use and market displacement was based on the specific market for each product (described in Section 2.1.3). Allocation between milk and meat (male calves and culled cows) and sheep and wool was not considered because the goal was to assess land use and not produce (Brandão et al., 2010). The environmental impact categories used were climate change (kg CO_2 eq.), eutrophication (kg PO_4 eq.) and acidification (kg SO_2 eq.), calculated using CML 2001. The LCA models were developed in SimaPro 8.3 (Pre Consultants, 2017).

2.1.1. Livestock farming systems

Pasture-based systems, the most common in Ireland, were assumed for all livestock production. Spring calving, rotational grazing milk production was assumed for the dairy system (Sharma et al., 2018). The cows are fed on grazed grass from mid-March to late-October and then housed for the winter, and fed silage and concentrates (Casey and Holden, 2005a). For beef, a suckler calf-to-beef, grazed-grass, spring calving system was modelled (Foley et al., 2011). All the progeny were retained to slaughter with males finished on grass with supplementary concentrates at 30 months and heifers at 26 months (Foley et al., 2011). The cattle are housed for winter and fed silage and concentrates. For sheep, a pasture-based lowland system was assumed, which represents 85% of national sheep meat production (O'Brien et al., 2016), and with mid-season lambing typically used in Ireland (Bohan et al., 2016). Lambing is in spring to synchronize feed demand of lactating ewes with grass growth. Ewes are housed before lambing and fed silage and concentrate and after lambing the ewes and progeny graze grass. Lambs are weaned at 12 weeks and sold at about 45 kg of live weight at 4 to 6 months of age (O'Brien et al., 2016).

National average activity data were used for each system with data taken from Sharma et al. (2016) for dairy, Teagasc (2016) for beef and O'Brien et al. (2016) for sheep. Data for dairy production on poorly drained soils were directly taken from Sharma et al. (2016). Dairy farms on poorly drained soils have lower stocking rates, longer housing time and more dependence on silage (Sharma et al., 2018). For beef farming on poorly drained soils, similar stocking rates to national average, but with longer housing of 145 days were assumed (O'Loughlin, 2016). For sheep farming on poorly drained soils, similar stocking rates to the national average with 100 days housing during the winter, similar to the conventional system as opposed to year-round grazing (Keady and Hanrahan, 2007). In each case the inventory included grass and silage production, manure management, production and transportation of fertiliser and concentrates, production and use of electricity and diesel on farm (Fig. 1). Capital goods and machinery were not included due to lack of suitable data (Chen et al., 2016). The concentrate feed ingredients and their proportions were taken from O'Brien et al. (2012) (dairy), Foley et al. (2011) (beef: a barley-soybean mix ration (Kavanagh, 2016) for both finishing and growing cattle) and O'Brien et al. (2016) (sheep). The environmental impacts were calculated based on the emissions factors in Table 1. Emissions from electricity and diesel production and use were taken from Ecoinvent 3.3.

2.1.2. Forestry

Stika Spruce (*Picea sitchensis*) plantation was assumed because it is the most commonly planted species in Ireland (Murphy et al., 2014; Upton et al., 2014). A reduction in productivity of Stika Spruce is reported on poorly drained soils (Farrelly et al., 2011; Upton et al., 2013). A 17% reduction was applied to the national average weighted yield class (17 m^3/ha/yr) for Stika Spruce (Fitzpatrick, 2016) to represent production on poorly drained soil.

Based on the Irish Soil Information System land use categories, managed grassland are the predominant use for poorly drained soils (O'Sullivan et al., 2015), so the reference system to be displaced by forestry was taken to be grassland. The IPCC (2006), stock-difference method was used to estimate the carbon stock change from conversion of grassland to forestry. The soil carbon change was calculated by estimating the difference in 'soil organic matter + below ground + litter' for the initial grassland state and after 40 years of forestry using data from Black et al. (2009), but was not accounted in the net results. The above ground biomass was assumed to be similar to the wood product

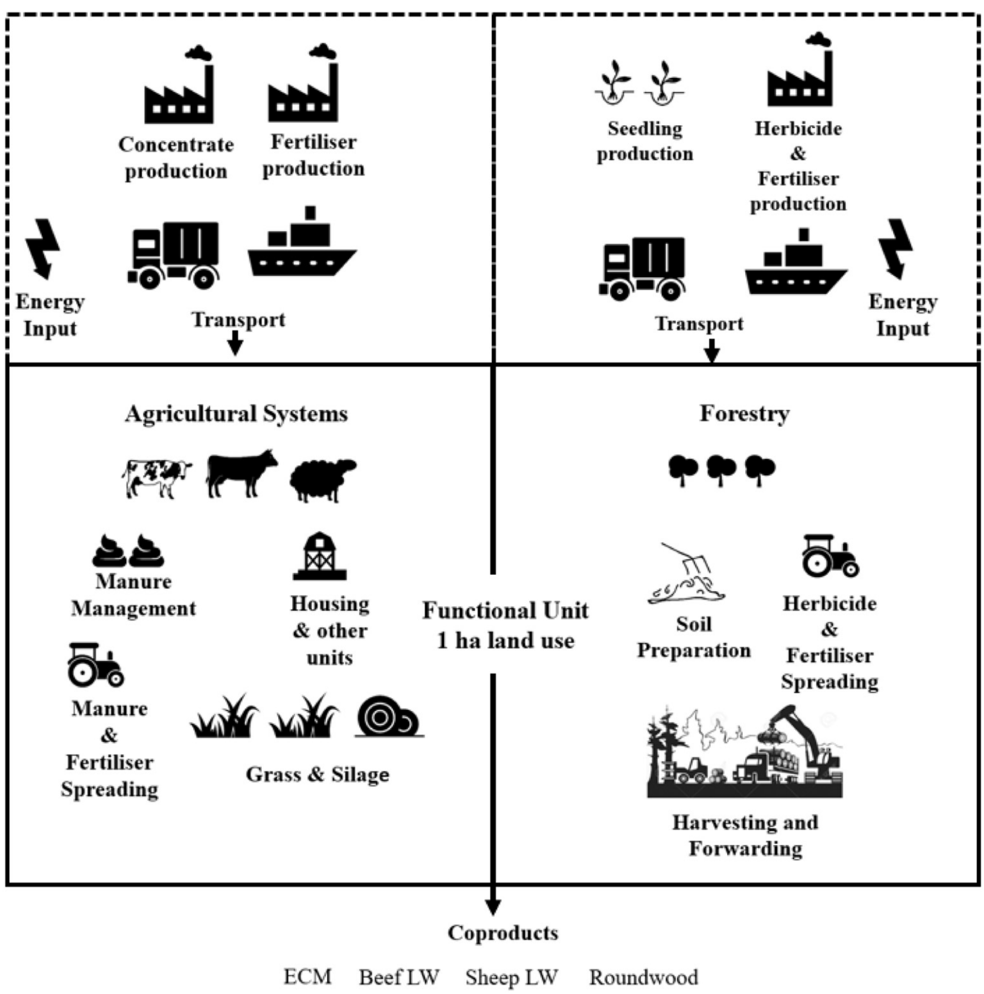


Fig. 1. System diagram of alternative land uses showing foreground and background processes, functional unit and co-products. ECM: energy corrected milk; LW: live weight.

Table 1
Emission factors used in the LCA model to quantify environmental impacts.

Emissions	Emission factor			Unit	Reference
	Dairy	*Beef*	*Sheep*		
Methane					
Enteric methane	111.6–29*	73.1–29*	8–2.7*	kg CH_4/head/yr	Duffy et al., 2015
Manure management[a]	10.2	6.40–0.75*	0.5–0.3*	kg CH_4/head/yr	Duffy et al., 2015
Slurry application	6.8–12^	6.8–12^	–	g CH_4/m^3	Chadwick et al., 2000
Direct nitrous oxide					
Manure management	0.002–0.005#	0.002–0.005#	0.01	kg N_2O-N/kg N	IPCC, 2006
Fertiliser spreading	0.01	0.01	0.01	kg N_2O-N/kg N	IPCC, 2006
Manure spreading	0.01	0.01	0.01	kg N_2O-N/kg N	IPCC, 2006
Manure excreted on pasture	0.02	0.02	0.01	kg N_2O-N/kg N	IPCC, 2006
Indirect nitrous oxide					
Manure management	0.01	0.01	0.01	kg N_2O-N/kg N	IPCC, 2006
Fertiliser application	0.01	0.01	0.01	kg N_2O-N/kg N	IPCC, 2006
Manure spreading	0.01	0.01	0.01	kg N_2O-N/kg N	IPCC, 2006
Manure excreted on pasture	0.01	0.01	0.01	kg N_2O-N/kg N	IPCC, 2006
Nitrate leaching	0.3	0.3	0.3	kg N_2O-N/kg N	IPCC, 2006
Phosphorous leaching	0.5	0.06	0.5	kg P/ha	Chen et al., 2016; Nguyen et al., 2012; O'Brien et al., 2016
Ammonia					
Housing	7.3[b] + 38.2[c]	38.2–10.6*	5.63–2.82*	g NH_3-N/head/day	Duffy et al., 2011
Manure storage [d]	94	94	0.22	g NH_3/m^2 over 30 days Sheep: kg NH_3/kg TAN	Duffy et al., 2011; O'Brien et al., 2016
Manure application	37–81%+	37–81%+	0.65	kg NH_3/kg TAN	Duffy et al., 2011; O'Brien et al., 2016
Manure excreted on pasture	0.2	4.3–1.3*	2–1*	g NH_3-N/head/day	Duffy et al., 2011
Fertiliser application	1.6%	1.6%	1.6%	kg N_2O/kg N applied	Hyde et al., 2003

*Range of values for animals with different ages groups.
^Depending on the time of slurry spreading.
#Values depending on manure storage system.
+Depending on the solid or liquid manure spreading.
[a] Includes emissions from manure excreted on pasture.
[b] NH_3 emissions from cow-collecting yards during milking over a lactation period of 305 days.
[c] Includes NH_3 emissions slurry stored below the slates.
[d] Area = (cows * 0.28 * 20 week) + (cows * 20 * 0.04 seepage) (EU, 2014).

displaced in the global market thus was not accounted for in the net results.

The foreground processes included site preparation, excavation and application of fertiliser and herbicide, harvesting and forwarding of forest wood to the farm gate. The background processes included seedling, fertiliser, herbicide, diesel and electricity production and transport (Fig. 1). Due to the very small environmental impact of infrastructure such as fencing and forest road construction, these were excluded (Whittaker et al., 2011). The life cycle inventory was taken from Fitzpatrick (2016). Emissions from fertiliser application were estimated based on Fitzpatrick (2016) (Table 2).

2.1.3. Identification of competing product system

System expansion was used to avoid allocation (Weidema and Schmidt, 2010). Product substitution was used to displace the environmental burdens of co-product by subtracting the burdens of appropriate competing products that would be displaced from the market (Weidema et al., 1999) due to an increase in production in Ireland. This method is sometimes also called substitution or the avoided burden method (Guinee, 2002). Bringing more land into each of the alternative land uses will increase the co-product production (in this case the agricultural commodities: milk, beef LW, sheep LW and roundwood). In each case it was assumed that the substituted products had the same function (Ekvall and Weidema, 2004). If the market was increasing, the most competitive was displaced and if the market was decreasing, the least competitive was displaced (Weidema et al., 1999). Ireland has both European and International markets for all agricultural products. The marginal suppliers were chosen assuming two cases (a) product displaced in the global market; (b) product displaced in the European market.

(a) Product displaced in Global market

World milk production is projected to increase by 177 Mt. (25%) by 2025 compared to the base years (2013 to 2015) (OECD/FAO, 2016). The removal of EU milk quota has promoted growth of milk production in the EU. From 2014 to 2015 milk deliveries increased by 18% in Ireland, 3.7% in Germany, 2.9% in the United Kingdom and 11.9% in Netherlands (OECD/FAO, 2016). Around 49% of total Irish milk exports were to International markets which grew by 19% (Borad Bia, 2017). EU milk exports are expected to increase by 58.5% by 2025 compared with production in the base years (2013 to 2015; OECD/FAO, 2016). Apart from the EU, New Zealand is one of the biggest milk exporters with a long history

Table 2
Emission factors used in the LCA model to quantify environmental impacts from fertiliser application for forestry land use.

Emissions	Emission factors	Unit	Reference
Nitrous Oxide	1.5%	kg N_2O/kg N applied	Fitzpatrick, 2016
Ammonia	22%	kg NH_3/kg TAN	Fitzpatrick, 2016
Nitrate	30%	kg N_2O-N/kg N	IPCC, 2006
Phosphate	25%	kg PO_4/kg N applied as phosphate	Fitzpatrick, 2016

of production (FAO, 2017), and is forecast to increase sales (FAO, 2016). Milk from New Zealand is therefore assumed to be the global substituted product.

Growth in per capita demand for livestock products is projected to increase by 26% and 28% for beef and sheep plus goat meat, respectively (Robinson and Pozzi, 2011). The kg/capita demand of beef meat has decreased in the EU (OECD, 2017) over recent years. Based on these data the market for beef was not considered to be limited to Europe. Beef production data shows that Brazil is one of the largest producers and has continuously increased its production from 1961 to 2014 (FAO, 2017). Thus beef from Brazil was assumed to be the global substituted product.

Ireland produced around 57.6 thousand tonnes of sheep meat in 2014 out of which 47.5 thousand tonnes was exported (Bord Bia, 2016). The Irish sheep market had been heavily dependent upon the French market, which accounts for around 40% of exports compared with 60% during the mid-2000s (Colby, 2015). Besides the EU market, Ireland is now developing trade in global markets, mainly Hong Kong (Colby, 2015). Australia is one of the largest producers and exporters of sheep meat in the world and has an increasing trend for sheep meat production (FAO, 2017). Thus Australia was assumed to be the global substituted sheep meat product.

Global industrial roundwood production was about 3.7 billion cubic meters (m^3) and grew approx. 48% between 1961 and 2016 (FAO, 2017). In 2012, industrial roundwood demand was 1.5 billion m^3 and it will reach over 1.7 billion m^3 in 2030 (Indufor, 2012). Irish wood exports are mainly to Europe, but some of the global export destinations are Algeria, Canada, China, Cuba, India, South Africa Turkey, United Arab Emirates and Uruguay (European Commission, 2017b). The demand for wood and wood products in China and India is increasing (FAO, 2017). Europe and Northern America are the main exporters of industrial roundwood. At country level, the five largest producers of industrial roundwood are the USA, the Russian Federation, China, Canada and Brazil. The USA is by far the largest producer in the world (369 million m^3, (FAO, 2015). Thus roundwood from the USA was assumed to be the global substituted product.

(b) Product displaced in the European market

Around a quarter of Irish dairy exports are to the UK and another quarter to other EU markets (Bord Bia, 2017). Consumption of milk products is expected to grow over 300 kg per capita in Australia, the EU and the USA (European Commission, 2016). The greatest milk production increase is expected in the EU, by 1.3 million t per year (European Commission, 2016). There is an increasing market for dairy in EU. Germany is one of the largest milk producers in the EU based on 1991 to 2014 data (FAO, 2017). Thus milk from Germany was assumed to be the substituted dairy product in the EU.

Around 54% of recent Irish beef was exported to the United Kingdom and 43% to the rest to the EU (Bord Bia, 2016). The per capita consumption of beef meat in the EU has decreased from 12.5 kg per capita in 1995 to 10.7 kg per capita in 2015, and is expected to reduce to 10.5 kg per capita by 2025 (OECD, 2017). The UK beef consumption is increasing (AHDB, 2016) and UK is the main beef market for Ireland with demand increasing. Thus the UK increasing beef market would be the target for increased Irish beef. UK is almost 75% self-sufficient in beef and veal with increasing production (FAO, 2017), and mainly imports beef from Ireland (AHDB, 2016). Considering the above arguments, beef from the UK would be the substituted product in the EU market.

Over two third (44,759 t) of Irish sheep meat output was exported in 2014 (DAFM, 2015). Apart from France and the United Kingdom (the biggest importers), Germany, Belgium and Sweden remain the key growth markets for Irish lamb. With a total production of 925 thousand tonnes carcass weight, the EU is far from self-sufficient, and imports around 212 thousand tonnes mainly from New Zealand and Australia (European Commission, 2017a). Around 80% of sheep and goat meat imports are from New Zealand and due to the reorientation of export to China (8%) (European Commission, 2017a) these imports are continuously decreasing (European Commission, 2017b). Sheep production in the EU member states has been decreasing (between 1990 and 2014; FAO, 2017), and there was a 25% decrease in sheep meat consumption in EU between 2000 and 2014 (Colby, 2015). Based on these data the EU market is decreasing. Spanish sheep production has decreased the most between 1990 and 2014 (FAO, 2017), therefore sheep meat from Spain was assumed to the substituted product in the EU.

Roundwood production in Ireland is forecast to double from 3.2 million m^3 in 2013 to 6.4 million m^3 by 2028 (IFFPA, 2016). Around 80% of forest products were exported in 2014 (IFFPA, 2016) and the key markets were the UK, Germany and Benelux countries. Consumption of industrial roundwood in the UK was about 7.9 million m^3 in 2011 and the demand is expected to increase dramatically in the next 15 years (Indufor, 2013). Demand for wood in the EU will also increase by 17% by 2020. Irish sawn timber and panel export to the UK has grown by 15% up to 2013 (Indufor, 2013). The UK is the key market place for Irish forest products (IFFPA, 2016). Considering these data the market for wood is increasing in the EU and as Sweden was the biggest producer of roundwood in Europe from 2000 to 2016 (FAO, 2017) and a major supplier to the UK, it was assumed wood from Sweden was the substituted product.

The environmental impacts per unit product for each impact category for the competing products were taken from literature (Table 3), but due to the lack of AP and eutrophication data for Spanish sheep products, data for a UK sheep system were used as the best available.

2.1.4. Sensitivity analysis

Sensitivity analysis was focused on the key management assumptions for the dairy, beef, sheep and forestry systems by adjusting parameters by 10% in the context of the global marginal market. Dairy, beef and sheep system sensitivity analysis was focused on emission factors for enteric CH_4, N content in manure, stocking rate, milk or LW output, fertiliser application rate, concentrate inputs and housing days. These are the key management drivers of the major contributors to climate change, eutrophication and acidification reported by previous studies (Clarke et al., 2013; Pelletier et al., 2010; Sharma et al., 2018). For forestry, biomass yield, forest management and lifespan have been previously reported to affect the environmental impacts (González-García et al., 2014) so were used for sensitivity analysis.

Identification of competing products in the market is not straightforward (Earles and Halog, 2011) and can significantly change results and interpretation (Chobtang et al., 2016). Sensitivity analysis was performed to investigate the influence of choice of associated competing products. For this analysis the weighted average environmental impact indicators derived from the top exporting countries in the world (Chobtang et al., 2016) representing a 'global average system' were also used instead of the specific country previously identified (Table 4). The EU was also represented by a weighted average of the largest producers of dairy and roundwood in the EU (Table 4).

3. Results

3.1. Summary of production systems for alternative land uses

The dairy farm on poorly drained soils could support 1.55 cows/ha on 20 ha farm, producing 5191 kg/cow/yr and the dairy cows were housed for 205 days. The beef farm could support 1.27 LU/ha on 40 ha farm, producing 297 LW/ha. The sheep farm could support 7.5 ewes/ha on 14.27 ha farm producing 419 LW/ha. The housing days for lambs, ewes and rams would be 116, 122 and 170 days, respectively. Stika Spruce production for forestry would be 9.9 m^3/ha/yr solid

Table 3
Environmental indicators for Global and European marginal suppliers for alternative land uses.

Co-product	Marginal supplier	CC[e] kg CO_2 eq.	EP[f] g PO_4 eq.	AP[g] g SO_2 eq.	FU[a]	Reference
Global marginal suppliers						
Milk	New Zealand	1.07	3.3	9.32	kg ECM[b]	Basset-Mens et al., 2009
Beef	Brazil	15.8	9.2	3.3	kg LW[c]	Dick et al., 2015
Sheep	Australia	10.1	35.8	128	kg LW	AusLCI, 2017
Wood	USA	11	24.4	112	m^3 sub[d] roundwood	Puettmann, 2015
European Union marginal suppliers						
Milk	Germany	1.43	8.34	19.5	kg ECM	Guerci et al., 2013
Beef	UK	14	141	389	kg LW	Williams et al., 2006
Sheep	Spain	23	94	179	kg LW	Ripoll-Bosch et al., 2013; Williams et al., 2006
Wood	Sweden	0.3	0.57	1.65	m^3 sub roundwood	González-García et al., 2014

[a] FU functional unit.
[b] Energy corrected milk.
[c] Live weight.
[d] Solid under bark.
[e] CC climate change.
[f] EP eutrophication.
[g] AP acidification.

under bark at 30% moisture content on 50 ha of farm. The substituted co-products from the farms were calculated to be 150,450 kg ECM of milk, 11,873 kg LW of beef, 5987 kg LW of sheep and 494 m^3 of solid under bark roundwood. Other details such as concentrate feed, fertiliser and energy use are shown in Table 5. An increase of 1.17 t C/ha/yr in soil organic carbon was calculated due to converting from grassland to forestry.

3.2. Environmental impacts

The climate change impact for Irish land uses were 10,900 kg CO_2 eq. per ha for dairy, 4600 kg CO_2 eq. per ha for beef, 4880 kg CO_2 eq. per ha for sheep and 105 kg CO_2 eq. per ha for forestry. The eutrophication for Irish land uses were 31 kg PO_4 eq. per ha for dairy, 24 kg PO_4 eq. per ha for beef, 19 kg PO_4 eq. per ha for sheep and 0.8 kg PO_4 eq. per ha for

Table 4
Environmental indicators for Global weighted – average marginal suppliers for alternative land uses and their relative market share of exports.

Co-product	Marginal supplier	Share (%)	CC^ kg CO_2 eq.	EP+ g PO_4 eq.	AP$ g SO_2 eq.	FU*	Reference
Global average							
Milk	European Union	34%	1.34	8.59	15.34	kg ECM¶	From EU average
	New Zealand	27%	1.07	3.34	9.32	kg ECM	Basset-Mens et al., 2009
	Weighted average		1.22	3.34	12.71	kg ECM	
Beef	Brazil	37%	15.84	9.24	3.3	kg LW[X]	Dick et al., 2015
	Australia	37%	13.10	61.5	275	kg LW	AusLCI, 2017
	USA	26%	12.65	22.5	180.4	kg LW	Lupo et al., 2013
	Weighted average		18.91	43.27	202.5	kg LW	
Sheep	Australia	46%	10.1	25	128	kg LW	AusLCI, 2017 (unpublished)
	New Zealand	41%	8.5	36	148	kg LW	Wiedemann et al., 2015; O'Brien et al., 2016; Zonderland-Thomassen et al., 2014
	Weighted average		9.3	30	138	kg LW	
Wood	European Union	56%	0.27	0.57	1.54	m^3 sub#	From EU average
	USA	12%	11	0.19	112	m^3 sub	Puettmann, 2015
	Australia	6%	28.2	1.14	303	m^3 sub	AusLCI, 2017
	Weighted average		4.28	0.52	43.89	m^3 sub	
EU average							
Milk	Germany	20%	1.43	8.34	19.58	kg ECM	Guerci et al., 2013
	France	16%	1.23	8.41	9.00	kg ECM	van der Werf et al., 2009
	United Kingdom	9%	1.05	6.26	16.11	kg ECM	Williams et al., 2006
	Netherlands	8%	1.49	12.45	12.23	kg ECM	Thomassen et al., 2008
	Italy	7%	1.54	8.35	20.27	kg ECM	Guerci et al., 2013
	Weighted average	60%	1.34	8.59	15.34	kg ECM	
Wood	Sweden	24%	0.30	0.57	1.65	m^3 sub	González-García et al., 2014
	Germany	14%	0.09	0.19	0.55	m^3 sub	González-García et al., 2014
	France	6%	0.57	1.14	3.40	m^3 sub	González-García et al., 2014
	Weighted average	44%	0.27	0.52	1.54	m^3 sub	

¶Energy corrected milk.
[X]Live weight.
#Solid under bark.
^CC climate change.
+EP eutrophication.
$AP acidification.
*FU functional unit.

Table 5
Agricultural and forestry systems description.

Parameters	Dairy	Beef	Sheep	Forestry
System	Spring calving, pasture based	Pasture based, suckler-calf-beef system	Pasture based, mid season lambing system	Stika spruce farming
Stocking rate	1.55 cows/ha	1.27 LU*/ha	7.5 ewes/ha	2400 stem/ha
Production	7523 ECM¶/ha	297 LWX/ha	419 LW/ha	9.9 m^3/ha sub#
Concentrates	730 kg/ha	250 kg/LU	50 kg/ewe	–
N Fertiliser	195 kg/ha	55 kg/ha	73.5 kg/ha	8.75 kg/ha
P fertiliser	7.3 kg/ha	21.5 kg/ha	3.3 kg/ha	8.75 kg/ha
Electricity use	28,062 kWh/yr	4421 kWh/yr	171 kWh/yr	–
Diesel use	2639 L	1401 L	656 L	211 L

*Live stock unit.
¶Energy corrected milk.
XLive weight.
#Solid under bark.

forestry. The acidification for Irish land uses were 69 kg SO_2 eq. per ha for dairy, 77 kg SO_2 eq. per ha for beef, 44 kg SO_2 eq. per ha for sheep and 1.85 kg SO_2 eq. per ha for forestry. When no product displacement was considered forestry had the lowest emissions for all three categories (Figs. 2 and 3).

When the co-product displacement was included, the net result changed and varied with the choice of marginal supplier (Figs. 2 and 3). With global marginal supplier the net climate change was lowest for beef, net eutrophication was lowest for forestry and net acidification was lowest for sheep and with EU as marginal supplier sheep had the lowest net climate change and dairy had the lowest net eutrophication and acidification.

The net climate change for land uses with global marginal substitution reduced by 74% for dairy, 102% for beef, 87% for sheep and 104% for forestry as compared to Irish land use impacts. The net eutrophication for land uses with global marginal substitution reduced by 82% for dairy, 11% for beef, 78% for sheep and 30% for forestry. The net acidification for land uses with global marginal substitution reduced by 122% for dairy, 1.4% for beef, 148% for sheep and 72% for forestry.

The net climate change for land uses with EU marginal substitution reduced by 99% for dairy, 90% for beef, 197% for sheep and 3% for forestry. The net eutrophication for land uses with EU marginal substitution reduced by 204% for dairy, 172% for beef, 204% for sheep and 1% for forestry. The net acidification for land uses with EU marginal substitution reduced by 254% for dairy, 179% for beef, 207% for sheep and 1% for forestry.

The sensitivity analysis of the selection of competing displaced product as global average showed mixed results compared to global and EU marginal suppliers. The net climate change was lowest for beef and net eutrophication and acidification was lowest for dairy. The key management assumptions for sensitivity analysis did not change the net outcomes of the study. From the sensitivity analysis (Fig. 4) it was seen that livestock systems were sensitive to CH_4 emission factors, stocking rates and output from the system. The forestry system was sensitive to all the parameters in case of climate change as compared to other impacts.

4. Discussion

LCA was used to assess the environmental impacts of alternative uses of poorly drained farm land in Ireland. For assessing the environmental impacts, it was important to extend the LCA to include the displacement effect of products produced on the farm as suggested by Brandão et al. (2010). This methodological approach has been widely used for energy crop LCA studies considering land use as functional unit thus subtracting the avoided impacts of replacing the fossil fuel energy (Styles and Jones, 2007; Tonini et al., 2012). Land use (per ha) was used as the functional unit as it is the common unit across each agricultural system (Styles and Jones, 2007) and for multifunctional land-uses (Brandão et al., 2010).

Due to the differences in scope, inventories and assumptions it was difficult to directly compare the results with other studies, so comparison was limited to a few Irish examples. The climate change for the dairy land use (per ha) in Ireland were greater than reported by Casey and Holden (2006a) and less than O'Brien et al. (2012). The greater value from this study was mainly due to the inputs of fertiliser and energy compared to Casey and Holden (2005b). The per ha climate change for beef land use was within the range reported by Casey and Holden

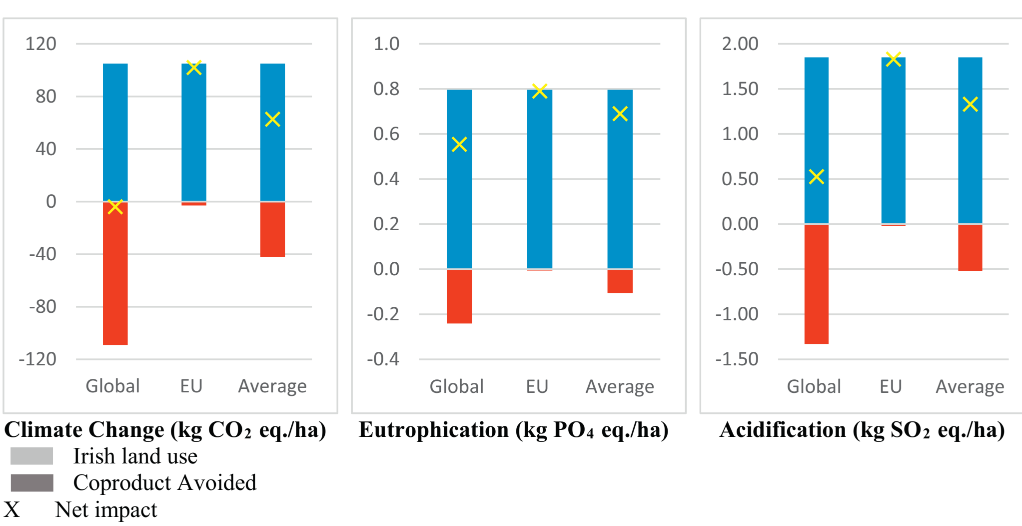


Fig. 2. Environmental indicators of forestry land use with different avoided co-products (global marginal, EU marginal and global average).

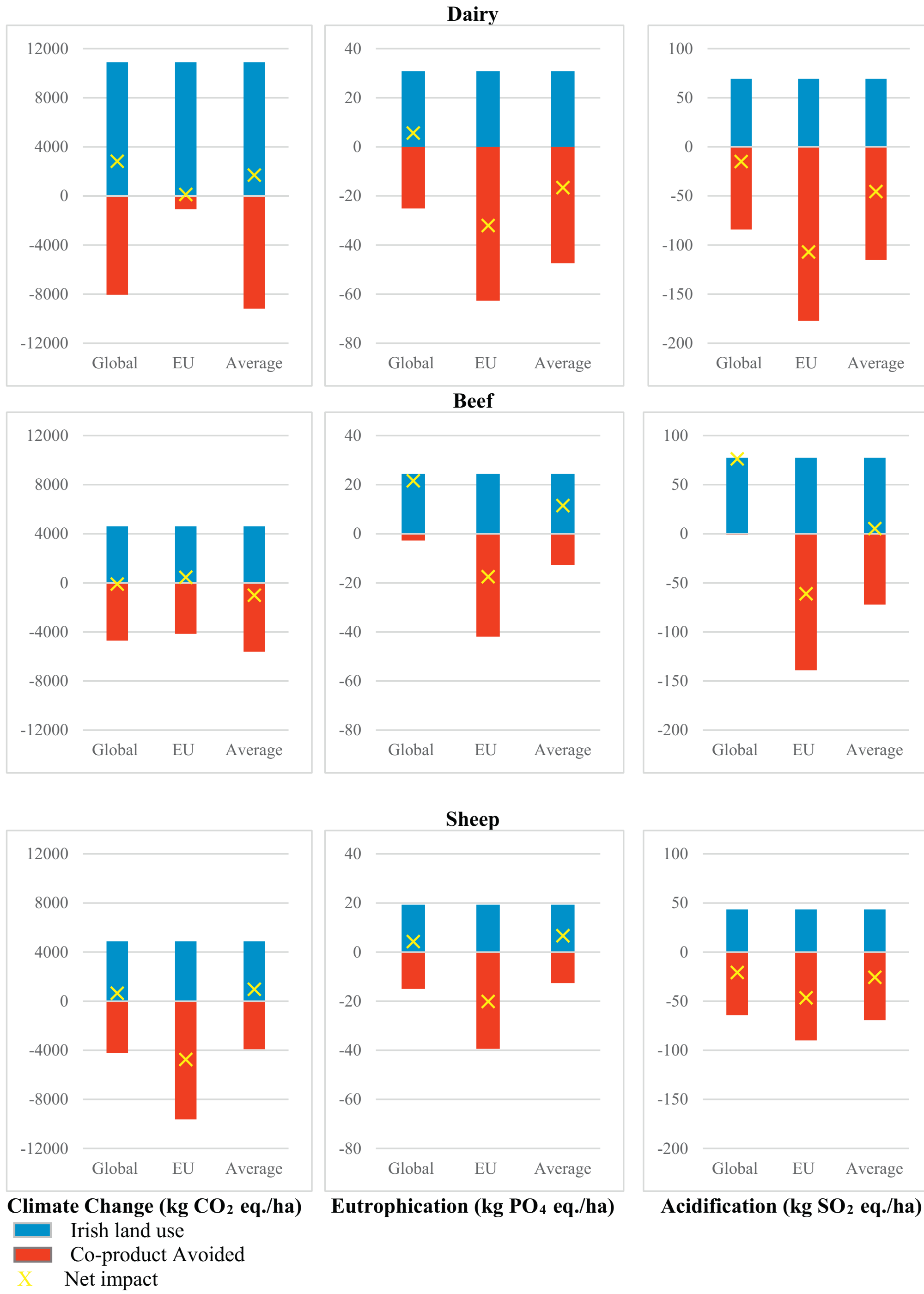


Fig. 3. Environmental indicators of livestock farming land uses with different avoided co-products (global marginal, EU marginal and global average).

(2006a) and lower than Foley et al. (2011). The higher value reported by Foley et al. (2011) was due to the number of suckler cows and progeny.

The climate change for sheep land use were greater than the value reported by Casey (2005). This difference was mainly due to management and emission calculations. The climate change for forestry land use was slightly lower than reported by Murphy et al. (2014) (re-calculated to per ha emissions). This difference was due to the assumptions, scope and emission factors. The eutrophication and acidification for the dairy land use (per ha) in Ireland were less than reported by O'Brien et al. (2012), but the system described by O'Brien et al. (2012) was more intensive than the one assumed for this study because it reflected farms with better soil resources. The eutrophication and acidification values for beef, sheep and forestry could not be compared with other studies as data have not been reported for Ireland.

The results of this study show that the land use environmental impacts for forestry were lower than the alternative land uses in Ireland. However, the displacement of regional and global co-products from the market changed the results, which is very important. The avoided burden of co-products was identified using the approach of the Weidema et al. (1999) and Ekvall and Weidema (2004), which has been used previously (Chobtang et al., 2016; Dalgaard et al., 2014). Land use in Ireland reflects not only demand/supply in the internal market, but also a demand for land-based goods that derive from elsewhere, as suggestion by Rounsevell et al. (2006).

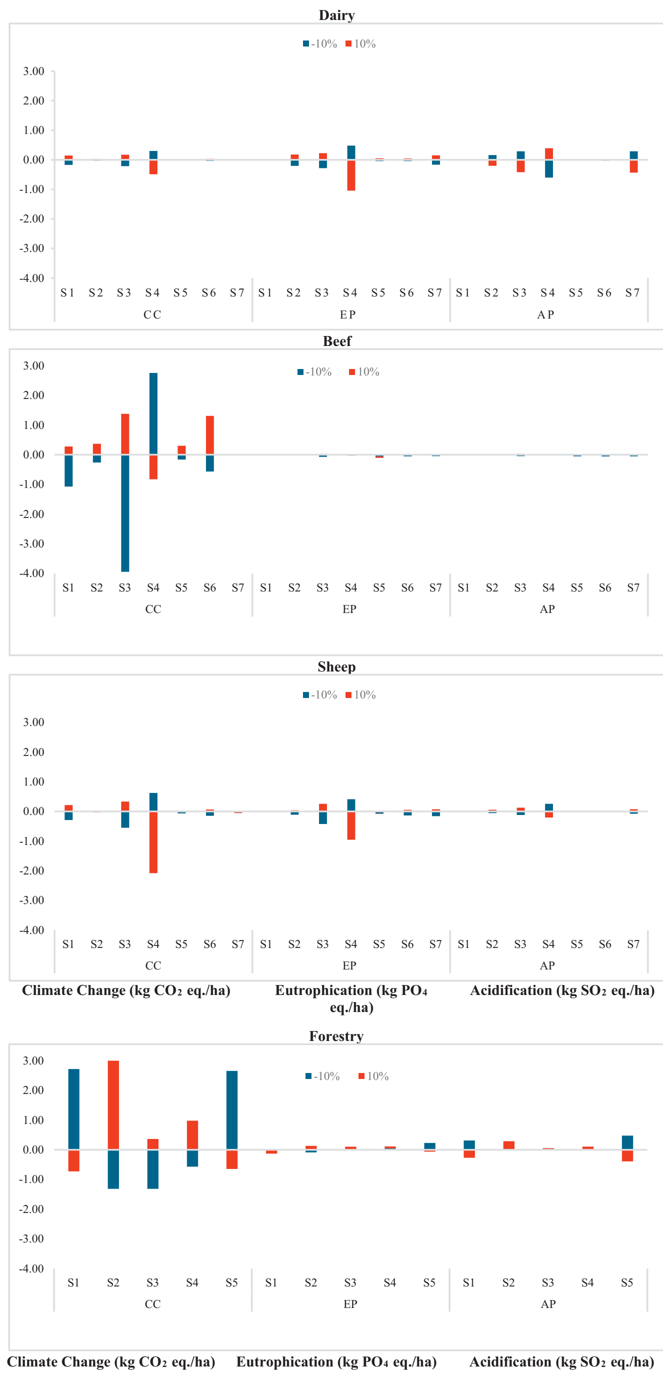


Fig. 4. Sensitivity analysis showing the fractional change in impacts with various scenarios. In case of dairy, beef and sheep production, S1: Enteric methane emission factor (dairy cow, suckler cow and ewes), S2: N content in manure, S3: stocking rate, S4: milk output or liveweight of animal, S5: fertiliser application, S6: concentrate inputs, S7: housing days. In case forestry, S1: biomass yield, S2: N fertiliser application, S3: P fertiliser application, S4: Diesel use, S5: life span.

The environmental impact decisions should be prioritized and reflect the scales (i.e. local, regional, national or global, (Chobtang et al., 2016)), thus global and EU marginal suppliers were chosen for the study. Beef had the lowest net climate change impacts with global marginal and average product substitution because it was displacing Brazilian beef (climate change = 15.8 kg CO_2 eq. per kg LW) that has a relatively large impact compared to other commodities in the analysis. For global marginal market substitution, beef was poor for eutrophication and acidification because of the extremely low impacts for Brazilian beef (eutrophication = 9.2 kg PO_4 eq.; acidification = 3.3 g SO_2 eq. per kg LW) as compared to the UK beef (eutrophication = 141 kg PO_4 eq.; acidification = 389 g SO_2 eq. per kg LW) and global average (eutrophication = 43.27 kg PO_4 eq.; acidification = 202.5 g SO_2 eq. per kg LW), while dairy and sheep came out well for acidification assuming New Zealand milk is displaced. With global marginal displaced product, forestry had the lowest net eutrophication because the impact of the USA timber was much greater than Irish timber.

For the EU market substitution, sheep could be considered as the best land use option with negative impacts (i.e. improvements) for all three categories, because of the very high impacts assumed for the marginal supplier (Spain, climate change = 23 kg CO_2 eq.; eutrophication = 94 g PO_4 eq.; acidification = 179 g SO_2 eq. per kg LW) as compared to Australian sheep (climate change = 10.1 kg CO_2 eq.; eutrophication = 35.8 g PO_4 eq.; acidification = 128 g SO_2 eq. per kg LW). Apart from sheep, dairy and beef also had net negative acidification and eutrophication impacts for EU market substitution with German milk (eutrophication = 8.34 g PO_4 eq.; acidification = 19.5 g SO_2 eq. per kg LW) and the UK beef (eutrophication = 141 g PO_4 eq.; acidification = 389 g SO_2 eq. per kg LW). These values are quite high compared to those reported for Irish milk (O'Brien et al., 2012).

For global average market substitution, dairy was best for eutrophication and acidification because of the higher emissions for European milk (eutrophication = 8.59 g PO_4 eq.; acidification = 15.34 g SO_2 eq. per kg ECM). The only case where forestry had net negative impact was for climate change with global marginal substitution assuming the USA timber products were displaced. The USA wood production climate change impact has been estimated to 4% greater than Irish production. When the EU substitution was assumed, forestry was not the best land use option because of the exceptionally low impacts for Swedish wood production (climate change = 0.3 kg CO_2 eq.; eutrophication = 0.57 g PO_4 eq.; acidification = 1.65 g SO_2 eq. per m^3 sub roundwood) compared to the global marginal supplier (USA: climate change = 11 kg CO_2 eq.; eutrophication = 24.4 g PO_4 eq.; acidification = 112 g SO_2 eq. per m^3 sub roundwood).

Within the bounds set by the study, and the uncertainty of what the true market substitution effect would be no particular land use always appeared to be the best option. Based on average rank order of impact, and giving equal weight to all the impact categories, for global substitution using the land for sheep production appeared to cause the greatest net beneficial change in impact, closely followed by dairy and roundwood production. Based on the rank order of impact for the EU substitution, dairy and sheep production had the greatest net beneficial change in impact, followed by beef. Factoring in uncertainty and considering rank order across all substitution scenarios evaluated, it seemed most likely that using land for dairy or sheep production will have the greatest net beneficial impact. If climate change were given greater weighting to reflect current global political concerns, then beef might emerge as the best land use option.

The results of this work confirm previous studies (Mathiesen et al., 2009; Schmidt, 2015) showing that the choice of the substituted product, depending on the market, has a decisive impact on the choice of the best land use. Thus the marginal supplier becomes a critical decision for each product, yet identification of the competing system and its product is challenging (Chobtang et al., 2017). Comprehensive modelling using economic (Earles and Halog, 2011) and trade network (Pizzol and Scotti, 2017) approaches could be used to identify the affected product systems. Substitution effects associated with market value, potential demand and size of affected product market should also be considered (Chalmers et al., 2015), as opposed to a 1:1 mass-basis substitution of co-products as assumed for this study. The environmental impacts of substituted products were derived from literature and the national statistics that the authors believe to be representative, but specific trade data might influence the interpretation of results. However, there is perhaps even more uncertainty related to the variation in impacts of displaced products. For instance, the very large value for climate change reported for sheep in Spain, very small eutrophication and acidification values reported for Brazilian beef and the exceptionally low values reported for wood production in the EU had a large impact on the interpretation yet may not be universal for all producers in these countries.

Consideration should also be given to the change in SOC. Reidy and Bolger (2013) reported a greater SOC value of 1.83 t C/ha/yr for conversion of grassland to forestry on wet mineral soils. This was due to the difference in carbon stock in a 47 year-old stand (Reidy and Bolger, 2013) and a 45 year-old stand (Black et al., 2009). The carbon stock increase was reported as 97 to 183 t C/ha in Reidy and Bolger (2013) in the 47 years whereas the calculation for this study suggested 97.2 to 103.1 t C/ha in 40 years. The value reported in this study is very high in comparison to some other studies such as 0.34 t C/ha/yr under Norway spruce in Italy (Thuille and Schulze, 2006) and 0.36 t C/ha/yr under Norway spruce in Denmark (Vesterdal et al., 2002). The carbon sequestration from the forestry will depend on input data, initial reference system, location and management practices. For simplicity and due to uncertainty about carbon sequestration of displaced products, the carbon sequestration from forestry was not included in the net results. Furthermore, under the EU Climate and Energy Package 2020, individual member states are currently not permitted to use land use, land use change and forestry (LULUCF) to offset emissions, thus excluding soil carbon stocks was justified in this instance, though the European Commission has informally accepted to revise this regulation for the 2021 to 2030 targets, but until then it is governed by Kyoto Protocol (UNFCC, 1998) for EU members. If carbon sequestration and soil carbon had been included forestry may have emerged as a better land use option depending on the carbon status of the substituted product.

This study is very dependent on assumptions about farm management on poorly drained soils. It has been based on the best available published data, but experimental observations are urgently needed. The sensitivity to farm management practice was used to assess the likelihood of drawing the wrong conclusion. Within reasonable bounds for management activity, there was no change in rank order of land use based on net environmental impacts, but in the case of Irish land use some improvements were perhaps possible. All the livestock systems were sensitive to stocking rate. A higher stocking rate will reduce impacts per FU (Belflower et al., 2012). Installing land drains in poorly drained fields has been reported to improve the productivity of dairy farms (Sharma et al., 2016), beef farms (Tyson et al., 1992) and forestry (Mulqueen, 1998). In the case of forestry, the system is sensitive to biomass yield and life span. González-García et al. (2014) suggested that the intensity of the forest practices affects most of the environmental impacts rather than biomass yield and life span. Using lower application rates of fertilisers as reported by Sandilands and Nebel (2010) (119 and 54 kg/ha for urea and phosphate), will reduce climate change by 34%, acidification by 7% and eutrophication by 8%.

For the current policies of significantly increasing the milk production in Ireland, in terms of impact categories considered in this study, it is likely that the Ireland will increase its absolute emissions, but the product footprints (impact per unit milk) will decrease. Unfortunately, milk production is least beneficial for climate change impact. As climate change is a global issue and policies are focused in stabilising GHG concentrations, from a global point of view, beef production resulted in the greatest net reductions in climate change impact per unit are of land. Based on results of average rank order of this study it is likely that increasing milk production in Ireland will have net global benefit by reducing environmental impacts. Both eutrophication and acidification are local and regional issues and are regulated by various national policies (Nitrate Directive (European Council, 1991); Water Framework Directive (European Union, 2000); GAP (European Union, 2014) and National Emissions Ceiling Directive (European Union, 2001)), but long-range atmospheric transport effects of acidification and eutrophication as a cascade can have an impact at the global level (Erisman et al., 2003; Gruber and Galloway, 2008).

5. Conclusion

Overall it can be concluded that a pasture based dairy or sheep system would have the greatest net global impact reduction (i.e. greatest global benefit) as land use options for farms that are expanding using land with poorly drained soils. Prioritizing climate change, a pasture based suckler beef system would perhaps be more favourable. It is clear that the choice of the displaced regional or global co-product from the market has a great influence on the results and there is also a need to consider more detailed consumption modelling to better understand the substitution process. From an Irish perspective, the results showed that forestry would generate the lowest environmental impacts and would also increase soil carbon stock, but this was not the best land use option from a global perspective. While the current national agricultural policy to encourage significantly increased milk production will increase national and global greenhouse gas emissions, over the three categories considered, and accounting for displacement uncertainty, it is likely to have net global benefit through impact reduction.

Acknowledgements

The authors are thankful to Mr. Tim Grant and Mr. Brett Sharma, Lifecycles, Melbourne and Dr. Sandra Eady, CSIRO for their valuable inputs in this study. This research was conducted with grant support (RSF 11/S/152) from the Department of Agriculture, Food and the Marine through the Research Stimulus Fund.

References

AHDB, 2016. UK Yearbook 2016: Cattle. Agriculture and Horticulture Development Board, UK, Warwickshire.
AusLCI, 2017. The Australian National Life Cycle Inventory Database. Available at:. http://auslci.com.au/.
Basset-Mens, C., Ledgard, S., Boyes, M., 2009. Eco-efficiency of intensification scenarios for milk production in New Zealand. Ecol. Econ. 68 (6), 1615–1625.
Belflower, J.B., Bernard, J.K., Gattie, D.K., Hancock, D.W., Risse, L.M., Alan, R.C., 2012. A case study of the potential environmental impacts of different dairy production systems in Georgia. Agric. Syst. 108, 84–93.
Bia, Bord, 2016. Meat and Livestock Review and Outlook 2015/16. The Thinking House, Bord Bia Insight Centre, Dublin, Ireland.
Bia, Bord, 2017. Market Information – Dairy. Available at:. http://www.bordbiavantage.ie/market-information/sector-overviews/dairy/, Accessed date: 21 September 2017.
Black, et al., 2009. Carbon stock and stock changes across a Sitka spruce chronosequence on surface-water gley soils. Forestry 82 (3), 255–272.
Bohan, A., Shalloo, L., Malcolm, B., Ho, C.K.M., Creighton, P., Boland, T.M., McHugh, N., 2016. Description and validation of the Teagasc lamb production model. Agric. Syst. 148, 124–134.
Brandão, M., Clift, R., Canals, L.M., Basson, L., 2010. A life-cycle approach to Characterising and economic impacts of multifunctional land-use systems: an integrated environmental assessment in the UK. Sustainability 2 (12), 3747.
Casey, J.W., 2005. Greenhouse Gas Emissions from Irish Livestock Production Systems. PhD, Thesis, University College Dublin, Dublin, Ireland.
Casey, J.W., Holden, N.M., 2005a. Analysis of greenhouse gas emissions from the average Irish milk production system. Agr. Syst. 86 (1), 97–114.
Casey, J.W., Holden, N.M., 2005b. The relationship between greenhouse gas emissions and the intensity of milk production in Ireland. J. Environ. Qual. 34 (2), 429–436.
Casey, J.W., Holden, N.M., 2006a. Greenhouse gas emissions from conventional, agri-environmental scheme, and organic Irish Suckler-beef units. J. Environ. Qual. 35 (1), 231–239.
Casey, J.W., Holden, N.M., 2006b. Quantification of GHG emissions from sucker-beef production in Ireland. Agric. Syst. 90 (1–3), 79–98.
Chadwick, D.R., Pain, B.F., Brookman, S.K.E., 2000. Nitrous oxide and methane emissions following application of animal manures to grassland. J. Environ. Qual. 29 (1), 277–287.
Chalmers, N.G., Brander, M., Revoredo-Giha, C., 2015. The implications of empirical and 1:1 substitution ratios for consequential LCA: using a 1% tax on whole milk as an illustrative example. Int. J. Life Cycle Ass. 20 (9), 1268–1276.
Chen, W., White, E., Holden, N.M., 2016. The effect of lameness on the environmental performance of milk production by rotational grazing. J. Environ. Manag. 172, 143–150.
Chobtang, J., Ledgard, S.F., McLaren, S.J., Zonderland, T.M., Donaghy, D.J., 2016. Appraisal of environmental profiles of pasture-based milk production: a case study of dairy farms in the Waikato region, New Zealand. Int. J. Life Cycle Ass. 21 (3), 311–325.
Chobtang, J., McLaren, S.J., Ledgard, S.F., Donaghy, D.J., 2017. Consequential life cycle assessment of pasture-based milk production: a case study in the Waikato Region, New Zealand. J. Ind. Ecol. 21 (5), 1139–1152.

Clarke, A.M., Brennan, P., Crosson, P., 2013. Life-cycle assessment of the intensity of production on the greenhouse gas emissions and economics of grass-based suckler beef production systems. J. Agr. Sci. 151 (5), 714–726.

Colby, L., 2015. World Sheep Meat Market to 2025. AHDB Beef & Lamb and the International Meat Secretariat, United Kingdom Available at:. http://beefandlamb.ahdb.org.uk/wp-content/uploads/2016/01/World-sheep-meat-market-to-2025.pdf, Accessed date: 16 August 2017.

Coyle, C., Creamer, R.E., Schulte, R.P.O., O'Sullivan, L., Jordan, P., 2016. A functional land management conceptual framework under soil drainage and land use scenarios. Environ. Sci. Pol. 56, 39–48.

Crosson, P., 2016. To Advance the Knowledge of Good Grassland Management in Irish Farming: Farming on Challenging Soils. Ireland Irish Grassland Association, Meath, Ireland.

DAFF, 2008. Irish Forestry - A Brief History. Forest Service. Department of Agriculture, Fisheres and Food, Dublin, Ireland.

DAFF, 2010. Food Harvest 2020: A Vision for Irish Agri-Food and Fisheries. Department of Agriculture, Fisheres and Food, Dublin, Ireland.

DAFM, 2015. Food Wise 2025: A 10-Year Vision for the Irish Agri-Food Industry. Department of Agriculture, Food and the Marine, Dublin, Ireland.

Dalgaard, R., Schmidt, J., Flysjö, A., 2014. Generic model for calculating carbon footprint of milk using four different life cycle assessment modelling approaches. J. Clean. Prod. 73, 146–153.

van der Werf, H.M.G., Kanyarushoki, C., Corson, M.S., 2009. An operational method for the evaluation of resource use and environmental impacts of dairy farms by life cycle assessment. J. Environ. Manag. 90 (11), 3643–3652.

Dick, M., Abreu da Silva, M., Dewes, H., 2015. Life cycle assessment of beef cattle production in two typical grassland systems of southern Brazil. J. Clean. Prod. 96, 426–434.

Dillon, P., 2011. The Irish Dairy Industry - Planning for 2020, in National Dairy Conference, Cork, Ireland.

Duffy, P., Hyde, B., Hanley, E., Dore, C., 2011. Ireland Informative Inventory Report 2011. Air Pollutant Emissions in Ireland 1990–2009 Reported to the Secretariat of the UN/ECE on Long Range Transboundary Air Pollution. Environmental Protection Agency, Johnstown Castle, Wexford, Ireland.

Duffy, P., Hanley, E., Black, K., O'Brien, P., Hyde, B., Ponzi, J., Alam, S., 2015. Ireland National Inventory Report 2015. Greenhouse Gas Emissions 1990–2013 Reported to the United Nations Framework Convention on Climate Change. Environmental Protection Agency, Johnstown Castle, Wexford, Ireland.

Earles, J.M., Halog, A., 2011. Consequential life cycle assessment: a review. Int. J. Life Cycle Ass. 16 (5), 445–453.

Ekvall, T., Weidema, B.P., 2004. System boundaries and input data in consequential life cycle inventory analysis. Int. J. Life Cycle Ass. 9 (3), 161–171.

Erisman, J.W., Grennfelt, P., Sutton, M., 2003. The European perspective on nitrogen emission and deposition. Environ. Int. 29 (2), 311–325.

European Commission, 2016. EU Agricultural Outlook: Prospect for the EU Agricultural Markets and Income 2016–2026. The Directorate - General for Agriculture and Rural Development and the Joint Research Centre Avalilable at:. https://ec.europa.eu/agriculture/markets-and-prices/short-term-outlook_en (accessed 11 August 2017).

European Commission, 2017a. Short-term Outlook for EU Agricultural Markets in 2017 and 2018 – No. 19. European Commission Directorate - General for Agricultural and Rureal Development https://ec.europa.eu/agriculture/markets-and-prices/short-term-outlook_en (accessed 11 August 2017).

European Commission, 2017b. Trade Market Access Database. Available at. http://madb.europa.eu/madb/indexPubli.htm, Accessed date: 7 August 2017.

European Council, 1991. Council Directive 91/676/EEC of 12 December 1991 Concerning the Protection of Waters Against Pollution Caused by Nitrates From Agricultural Sources. L375. pp. 1–8.

European Council, 2009. Decision No 406/2009/EC of the European Parliament and of the Council of 23 April 2009 on the effort of Member States to reduce their greenhouse gas emissions to meet the Community's greenhouse gas emission reduction commitments up to 2020. L 140/136.

European Union, 2000. Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 Establishing a Framework for Community Action in the Field of Water Policy. L327. pp. 1–73.

European Union, 2001. Directive 2001/81/EC of the European Parliament and of the Council of 23 October 2001 on National Emission Ceiling for Certain Atmospheric Pollutants. L309. pp. 22–30.

European Union, 2014. Statutory Instruments. S.I. No. 31 of 2010 European Union (Good Agricultural Practice for Protection of Waters) Regulations 2014. Dublin, Ireland.

FAO, 2015. Forest Products Statistics: 2015 Global Forest Products Facts and Figures. Food and Agriculture Organizations of the United Nations, Rome Avilable at:. http://www.fao.org/3/a-i6669e.pdf, Accessed date: 25 October 2017.

FAO, 2016. Food Outlook, Biannual Report on Global Food Markets. Food and Agriculture Organizations of the United Nations, Rome Available at:. http://www.fao.org/3/a-i6198e.pdf, Accessed date: 15 April 2017.

FAO, 2017. FAOSTAT. Food and Agriculture Organizations of the United Nations, Rome Available at:. http://www.fao.org/faostat/en/#home, Accessed date: 7 August 2017.

Farrelly, N., Ní Dhubháin, Á., Nieuwenhuis, M., 2011. Site index of Sitka spruce (*Picea sitchensis*) in relation to different measures of site quality in Ireland. Can. J. For. Res. 41 (2), 265–278.

Fitzpatrick, J.J., 2016. Environmental sustainability assessment of using forest wood for heat energy in Ireland. Renew. Sustain. Energy Rev. 57, 1287–1295.

Foley, et al., 2005. Global consequences of land use. Science 309 (5734), 570.

Foley, P.A., Crosson, P., Lovett, D.K., Boland, T.M., O'Mara, F.P., Kenny, D.A., 2011. Whole-farm systems modelling of greenhouse gas emissions from pastoral suckler beef cow production systems. Agric. Ecosyst. Environ. 142 (3–4), 222–230.

González-García, S., Moreira, M.T., Dias, A.C., Mola-Yudego, B., 2014. Cradle-to-gate life cycle assessment of forest operations in Europe: environmental and energy profiles. J. Clean. Prod. 66, 188–198.

Gruber, N., Galloway, J.N., 2008. An earth-system perspective of the global nitrogen cycle. Nature 451, 293.

Guerci, M., Knudsen, M.T., Bava, L., Zucali, M., Schönbach, P., Kristensen, T., 2013. Parameters affecting the environmental impact of a range of dairy farming systems in Denmark, Germany and Italy. J. Clean. Prod. 54, 133–141.

Guinee, J.B., 2002. Handbook on life cycle assessment operational guide to the ISO standards. Int. J. Life Cycle Ass. 7 (5), 311.

Hyde, B.P., Carton, O.T., O'Toole, P., Misselbrook, T.H., 2003. A new inventory of ammonia emissions from Irish agriculture. Atmos. Environ. 37 (1), 55–62.

IFFPA, 2016. An Overview of the Irish Forestry and Forest Products Sector 2016. Irish Forestry and Forest Products Association, Dublin, Ireland Available at:. http://www.iffpa.ie/Sectors/IFFPA/IFFPA.nsf/vPages/Press_and_Publications~iffpa-annual-review-2016-18-01-2017/$file/IFFPA%20Annual%20Review%202016.pdf, Accessed date: 11 September 2017.

Indufor, 2012. Strategic Review on the Future of Forest Plantations. Forest Stewardship Council, Helsinki, Finland Available at:. http://www.fao.org/forestry/42701-090e8a9fd4969cb334b2ae7957d7b1505.pdf, Accessed date: 11 September 2017.

Indufor, 2013. Study on the Wood Raw Material Supply and Demand for the EU Wood-Processing Industries. European Commission, Enterprise and Industry Directorate General, Finland Available at:. https://ec.europa.eu/docsroom/documents/11920?locale=en, Accessed date: 11 August 2017.

IPCC, 2006. IPCC Guidelines for National Greenhouse Gas Inventories. The Intergovernmental Panel on Climate Change. Hayama, Japan.

Kang, S., Post, W., Wang, D., Nichols, J., Bandaru, V., West, T., 2013. Hierarchical marginal land assessment for land use planning. Land Use Policy 30 (1), 106–113.

Kavanagh, S., 2016. Section 6 - Nutrision : Concentrate Feeds' in Teagasc Beef Manual, Teagasc, Ireland. Available at: https://www.teagasc.ie/media/website/publications/2016/Beef-Manual-Section6.pdf (accessed 4 April, 2017).

Keady, T., Hanrahan, J.P., 2007. Extended grazing–its potentials and limitations. Irish Grass Assoc J 41, 81–96.

Lupo, C.D., Clay, D.E., Benning, J.L., Stone, J.J., 2013. Life-cycle assessment of the beef cattle production system for the northern Great Plains, USA. J. Environ. Qual. 42 (5), 1386–1394.

Mathiesen, B.V., Münster, M., Fruergaard, T., 2009. Uncertainties related to the identification of the marginal energy technology in consequential life cycle assessments. J. Clean. Prod. 17 (15), 1331–1338.

Mulqueen, J., 1998. Depth, spacing and length of mole drains with applications to afforestation. Irish J Agr Food Res 37 (1), 39–49.

Murphy, F., Devlin, G., McDonnell, K., 2014. Forest biomass supply chains in Ireland: a life cycle assessment of GHG emissions and primary energy balances. Appl Energ 116, 1–8.

Nguyen, et al., 2012. Effects of type of ration and allocation methods on the environmental impacts of beef-production systems. Livest. Sci. 145 (1), 239–251.

O'Brien, D., Shalloo, L., Patton, J., Buckley, F., Grainger, C., Wallace, M., 2012. A life cycle assessment of seasonal grass-based and confinement dairy farms. Agric. Syst. 107, 33–46.

O'Brien, D., Bohan, A., McHugh, N., Shalloo, L., 2016. A life cycle assessment of the effect of intensification on the environmental impacts and resource use of grass-based sheep farming. Agric. Syst. 148, 95–104.

OECD, 2017. OECD Data. Organisation for Economic Co-operation and Development Available at:. https://data.oecd.org, Accessed date: 4 October 2017.

OECD/FAO, 2016. Dairy and Dairy Products. OECD - FAO Agrcultural Outlook. OECD Publishing, Paris, France, pp. 2016–2025.

O'Loughlin, J., 2016. Section 5 - Soils and Environment: Beef Farming on Heavy Soils' in Teagasc Beef Manual, Teagasc, Ireland. Available at:. https://www.teagasc.ie/media/website/publications/2016/Beef-Manual-Section5.pdf, Accessed date: 4 April 2017.

O'Sullivan, et al., 2015. Functional land management for managing soil functions: a case-study of the trade-off between primary productivity and carbon storage in response to the intervention of drainage systems in Ireland. Land Use Policy 47, 42–54.

Pelletier, N., Pirog, R., Rasmussen, R., 2010. Comparative life cycle environmental impacts of three beef production strategies in the Upper Midwestern United States. Agric. Syst. 103 (6), 380–389.

Pizzol, M., Scotti, M., 2017. Identifying marginal supplying countries of wood products via trade network analysis. Int J Life Cycle Ass 22 (7), 1146–1158.

Pre Consultants, 2017. SimaPro 8.0 Life Cycle Assessment Software. Amersfoort, The Netherlands.

Puettmann, M., 2015. Life Cycle Inventory of National Average, Roundwood, Softwood at Forest Road (USLCI datbase).

Reidy, B., Bolger, T., 2013. Soil carbon stocks in a Stika spruce chronosequence following afforestation. Irish Forestry 70, 200–219.

Ripoll-Bosch, R., de Boer, I.J.M., Bernués, A., Vellinga, T.V., 2013. Accounting for multi-functionality of sheep farming in the carbon footprint of lamb: a comparison of three contrasting Mediterranean systems. Agric. Syst. 116, 60–68.

Robinson, T.P., Pozzi, F., 2011. Mapping supply and demand for animal-source foods to 2030. Animal Production and Health Working Paper No. 2. Food and agriculture organizations of the United Nations. Rome. Available at. http://www.fao.org/docrep/014/i2425e/i2425e00.pdf (accessed 15 April, 2017).

Rounsevell, et al., 2006. A coherent set of future land use change scenarios for Europe. Agric. Ecosyst. Environ. 114 (1), 57–68.

Sandilands, J., Nebel, B., 2010. Guidelines for Greenhouse Gas Footprinting of Forestry. Ministry of Agriculture and Forestry, New Zealand.

Schmidt, J.H., 2015. Life cycle assessment of five vegetable oils. J. Clean. Prod. 87, 130–138.

Schulte, et al., 2014. Functional land management: a framework for managing soil-based ecosystem services for the sustainable intensification of agriculture. Environ. Sci. Pol. 38, 45–58.
Shahid, S.A., Al-Shankiti, A., 2013. Sustainable food production in marginal lands—case of GDLA member countries. Int. Soil Water Conserv. Res. 1 (1), 24–38.
Sharma, P., Humphreys, J., Holden, N.M., 2016. The Effect of Field Drainage on Productivity and Environmental Impact of Grass Based Dairy Production Systems. Paper in LCA Food 2016 Conference, Dublin, Ireland.
Sharma, P., Humphreys, J., Holden, N.M., 2018. The effect of local climate and soil drainage on the environmental impact of grass-based milk production. Int. J. Life Cycle Ass. 23 (1), 26–40.
Styles, D., Jones, M.B., 2007. Energy crops in Ireland: quantifying the potential life-cycle greenhouse gas reductions of energy-crop electricity. Biomass Bioenergy 31 (11—12), 759–772.
Teagasc, 2016. Beef 2016: Profitable Technologies. Grange Animal & Grassland Research and Innovation Centre, Teagasc, Meath, Ireland Available at:. https://www.teagasc.ie/media/website/publications/2016/Teagasc-Grange-2016.pdf.
Thomassen, et al., 2008. Life cycle assessment of conventional and organic milk production in the Netherlands. Agric. Syst. 96 (1–3), 95–107.
Thuille, A., Schulze, E.D., 2006. Carbon dynamics in successional and afforested spruce stands in Thuringia and the Alps. Glob. Chang. Biol. 12 (2), 325–342.
Tonini, D., Hamelin, L., Wenzel, H., Astrup, T., 2012. Bioenergy production from perennial energy crops: a consequential LCA of 12 bioenergy scenarios including land use changes. Environ. Sci. Technol. 46 (24), 13521–13530.
Tuohy, P., Fenton, O., Holden, N.M., Humphreys, J., 2014. The effects of treading by two breeds of dairy cow with different live weights on soil physical properties, poaching damage and herbage production on a poorly drained clay-loam soil. J. Agric. Sci. 153 (8), 1424–1436.
Tuohy, P., Humphreys, J., Holden, N.M., Fenton, O., 2015. Mole drain performance in a clay loam soil in Ireland. Acta Agric. Scand. Sec. B Soil Plant Sci. 65 (1), 2–13.
Tyson, K.C., Garwood, E.A., Armstrong, A.C., Scholefield, D., 1992. Effects of field drainage on the growth of herbage and the liveweight gain of grazing beef cattle. Grass Forage Sci. 47 (3), 290–301.
UNFCC, 1998. Kyoto Protocol to the United Nations Framework Convention on Climate Change, Dec 10, 1997. The United Nations Framework Convention on Climate Change (U.N. Doc FCCC/CP/1997/7/Add.1, 37 I.L.M. 22).
Upton, V., Ryan, M., Farrelly, N., O'Donoghue, C., 2013. The potential economic returns of converting agricultural land to forestry: an analysis of system and soil effects from 1955 to 2009. Irish For. 70 (1&2), 61–74.
Upton, V., O'Donoghue, C., Ryan, M., 2014. The physical, economic and policy drivers of land conversion to forestry in Ireland. J. Environ. Manag. 132, 79–86.
Vesterdal, L., Ritter, E., Gundersen, P., 2002. Change in soil organic carbon following afforestation of former arable land. For. Ecol. Manag. 169 (1), 137–147.
Weidema, B.P., Schmidt, J.H., 2010. Avoiding allocation in life cycle assessment revisited. J. Ind. Ecol. 14 (2), 192–195.
Weidema, B.P., Frees, N., Nielsen, A.M., 1999. Marginal production technologies for life cycle inventories. Int. J. Life Cycle Ass. 4 (1), 48–56.
Whittaker, C., Mortimer, N., Murphy, R., Matthews, R., 2011. Energy and greenhouse gas balance of the use of forest residues for bioenergy production in the UK. Biomass Bioenergy 35 (11), 4581–4594.
Wiedemann, S.G., Ledgard, S.F., Henry, B.K., Yan, M.J., Mao, N., Russell, S.J., 2015. Application of life cycle assessment to sheep production systems: investigating co-production of wool and meat using case studies from major global producers. Int. J. Life Cycle Ass. 20 (4), 463–476.
Wiegmann, K., Hennenberg, K.J., Fritsche, U.R., 2008. Degraded land and sustainable bioenergy feedstock production. In Joint International Workshop on High Nature Value Criteria and Potential for Sustainable Use of Degraded Lands, Paris, France.
Williams, A.G., Audsley, E., Sandars, D.L., 2006. Dertermining the Environmental Burdens and Resource Use in the Production of Agricultural and Horticultural Commondities. Main Report. DEFRA Research Project IS0205. Cranfield University and Defra, Bedford.
Zonderland-Thomassen, M.A., Lieffering, M., Ledgard, S.F., 2014. Water footprint of beef cattle and sheep produced in New Zealand: water scarcity and eutrophication impacts. J. Clean. Prod. 73, 253–262.