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Climate mitigation by dairy intensification depends on intensive use of spared grassland

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Abstract

Milk and beef production cause 9% of global greenhouse gas (GHG) emissions. Previous life cycle assessment (LCA) studies have shown that dairy intensification reduces the carbon footprint of milk by increasing animal productivity and feed conversion efficiency. None of these studies simultaneously evaluated indirect GHG effects incurred via teleconnections with expansion of feed crop production and replacement suckler-beef production. We applied consequential LCA to incorporate these effects into GHG mitigation calculations for intensification scenarios among grazing-based dairy farms in an industrialized country (UK), in which milk production shifts from average to intensive farm typologies, involving higher milk yields per cow and more maize and concentrate feed in cattle diets. Attributional LCA indicated a reduction of up to 0.10 kg CO_2e kg^{-1} milk following intensification, reflecting improved feed conversion efficiency. However, consequential LCA indicated that land use change associated with increased demand for maize and concentrate feed, plus additional suckler-beef production to replace reduced dairy-beef output, significantly increased GHG emissions following intensification. International displacement of replacement suckler-beef production to the "global beef frontier" in Brazil resulted in small GHG savings for the UK GHG inventory, but contributed to a net increase in international GHG emissions equivalent to 0.63 kg CO_2e kg^{-1} milk. Use of spared dairy grassland for intensive beef production can lead to net GHG mitigation by replacing extensive beef production, enabling afforestation on larger areas of lower quality grassland, or by avoiding expansion of international (Brazilian) beef production. We recommend that LCA boundaries are expanded when evaluating livestock intensification pathways, to avoid potentially misleading conclusions being drawn from "snapshot" carbon footprints. We conclude that dairy intensification in industrialized countries can lead to significant international carbon leakage, and only achieves GHG mitigation when spared dairy grassland is used to intensify beef production, freeing up larger areas for afforestation.

KEYWORDS
agriculture, climate change, consequential life cycle assessment , land sparing, life cycle assessment, sustainable intensification

1 | INTRODUCTION

Milk and beef production currently contribute 9% of global greenhouse gas (GHG) emissions (Gerber, 2013). Milk production in Europe continues to intensify as dairy farms consolidate under economic pressures (AHDB Dairy, 2016; Eurostat, 2016), and Europe is expected to become the world's largest milk exporter (Chatzopoulos et al., 2016). The UK dairy sector exemplifies this intensification trend, with farm numbers falling by one-third, milk yield per cow increasing by 14% (AHDB Dairy, 2016) and concentrate feed use increasing by 17% (Defra, 2016b) between 2005 and 2015. Sustainable intensification is regarded as a priority GHG mitigation measure for agriculture (Garnett et al., 2013), partly because it can spare natural habitats from agricultural expansion, avoiding disturbance of large terrestrial carbon stores (Burney, Davis & Lobell, 2010) and/or enabling carbon capture through afforestation of spared land (Lamb et al., 2016). Dairy consolidation and intensification shifts milk production from many smaller farms to fewer larger farms, affecting GHG emissions directly (Del Prado, Crosson, Olesen & Rotz, 2013), and indirectly via coupled dairy-beef (Flysjo, Henriksson, Cederberg, Ledgard & Englund, 2011) and feed production when cattle are fed a higher share of maize and concentrate feeds (Styles et al., 2015; Vellinga & Hoving, 2011) (Figure 1). Life cycle assessment (LCA) is used to benchmark the carbon footprint of milk production (BSI, 2011; Kristensen, Mogensen, Knudsen & Hermansen, 2011; O'Brien, Capper, Garnsworthy, Grainger & Shalloo, 2014). Reasons to expect dairy intensification supported by concentrate feed to reduce the GHG intensity of milk production include: (i) reduced enteric methane (CH_4) emissions owing to increased ratio of highly digestible starch-based concentrate feed in cattle diets (Hristov et al., 2013); (ii) more feed energy going into milk production rather than animal maintenance at higher yields per cow (Capper, Cady & Bauman, 2009); (iii) sparing of grassland (Burney et al., 2010; Lamb et al., 2016) (Figure 1). Indeed, there is considerable evidence that livestock intensification can lead to GHG mitigation (Cohn et al., 2014) and reduce product footprints (Gerber, 2013; Gerber, Vellinga, Opio & Steinfeld, 2011). However, previous studies showing that dairy intensification reduces the carbon footprint of milk by increasing animal productivity and feed conversion efficiency (Capper et al., 2009; Gerber et al., 2011) did not fully capture the GHG implications of consequential changes in feed and beef production. Marginal milk yield gains from further increases in the use of concentrate feeds on moderately intensive farms are small, and could induce carbon leakage via indirect land use change (iLUC) in global crop systems (Figure 1), analogous to biofuel-induced iLUC (Elshout et al., 2015; Searchinger et al., 2008). Higher milk yields per cow also result in fewer dairy calves being exported to beef farms, leading to more suckler beef production with larger land and carbon footprints (Nguyen, Hermansen & Mogensen, 2010). Such intersystem consequences are at best only partially captured by carbon footprints based on attributional LCA, in which dairy system emissions are allocated between milk and beef (BSI, 2011), and may not be reflected in national GHG inventories (Figure 1). Weiss and Leip (2012) went some way to address this gap, using national datasets to undertake a regional LCA for European livestock production that simultaneously accounted for multiple livestock sectors, and for cropland expansion within Europe. However, there remains a need to apply a coherent modelling approach that attributes important

Factor trend	Milk footprint (per kg milk, life cycle basis)	National GHG Inventory (all sectors)	Rest-of-world GHG Inventory (all sectors)
Milk from maize increasing ↗	↓Reduced enteric CH_4 ↓Higher yield per cow ↑Crop production (↑Cropland expansion)	↓Reduced enteric CH_4 ↑Crop production ↑Cropland expansion	
Milk from concentrate increasing ↗	↓Reduced enteric CH_4 ↓Higher yield per cow ↑Crop production	↓Reduced enteric CH_4	↑Crop production ↑Cropland expansion
Milk from grass decreasing ↘	↓Reduced enteric CH_4 ↓Reduced grass production	Land sparing or extra production ?	Global land sparing?
Dairy-beef production decreasing ↘	Neutral effect, depending on allocation method	↑Increased suckler-beef production?	↑Increased suckler-beef production?
Housing & manure management increasing ↗	↓Reduced grazing N_{ex} ↑Increased housing & storage emissions	↓Reduced grazing N_{ex} ↑Increased housing & storage emissions	

N_{ex}=N excretion; green=positive effect (reduces footprint); red=negative effect (increases footprint); amber=uncertain net effect.

FIGURE 1 Conceptual representation of major factors affecting GHG emissions at the product (carbon footprint), national inventory and global scales following transitions towards dairy cattle diets containing a higher proportion of concentrate feed and a lower proportion of grass indirect consequences of dairy intensification displayed in Figure 1 to specific transition pathways to generate robust conclusions on the GHG mitigation efficacy of particular “sustainable intensification” strategies.

Previous studies applied attributional LCA (aLCA) to compare milk footprints from different types of dairy system (Battini, Agostini, Tabaglio & Amaducci, 2016; Gerber et al., 2011; Kristensen et al., 2011; O'Brien et al., 2014; Van Middelaar, Berentsen, Dijkstra & De Boer, 2013; Yan, Humphreys & Holden, 2013), but did not evaluate changes that occur when certain types of farm systems replace others, as happens during intensification transitions. Consequential LCA (cLCA) accounts for indirect effects of system changes incurred via market signals (Weidema & Schmidt, 2010) and has been applied to quantify iLUC emissions driven by increased demand for animal feed (Schmidt, 2008; Styles, Gibbons, Williams, Dauber et al., 2015), and to calculate residual milk carbon footprints by subtracting avoided suckler-beef emissions from dairy system emissions (Thomassen, Dalgaard, Heijungs & de Boer, 2008). For the first time, we apply cLCA to specific pathways of dairy intensification to investigate the major direct and indirect consequences for GHG emissions that arise when milk production shifts to more intensive farm types (Figure 1), and compare results against simple carbon footprints for milk produced on these farm types pre- and post-intensification.

2 | MATERIALS AND METHODS

2.1 | Life cycle assessment goal and scope

Our goal was to quantify GHG emission changes arising from dairy farm consolidation and intensification. We first calculated the simple carbon footprint of milk produced on “average” and “intensive” farms using attributional life cycle assessment (aLCA). Then, we applied consequential LCA (cLCA) to explore the GHG emission implications of reduced dairy beef production and altered animal feed demand associated with a shift in milk production from average to intensive farms during consolidation and intensification (Table 1). Greenhouse gas emissions were calculated as carbon dioxide (CO_2) equivalents (CO_2e), according to 100-year global warming potentials of 1, 25 and 298 per kg of CO_2, CH_4 and nitrous oxide (N_2O) emitted, respectively (IPCC, 2006).

Average and intensive dairy farm typologies characterized from UK statistics and used in previous studies (del Prado et al., 2010; Styles, Gibbons, Williams, Dauber et al., 2015) were adopted for this study (Table 2), and underpinned the derivation of system boundaries. The intensive dairy farm houses 481 milking cows, almost 3.5 times as many as the average dairy farm, and puts animals out to graze for just 2 months of the year, compared with 6 months for the average farm. Milk yields per cow are over 20% higher, and replacement rate slightly higher, on the intensive farm (Table 2).

For aLCA, the scope was cradle to farm gate over one year of production, and emissions were allocated to milk and animal live weight exported from each of the farm types according to respective energy flows – resulting in 88% and 89% of farm emissions being allocated to milk for the average and intensive farms, respectively. Allocated emissions were then expressed in relation to the functional unit of one kg of milk.

For cLCA calculations, we accounted for direct and indirect effects associated with a shift in the production of 4,149,102 kg milk from 4.09 average farms (Table 2), representing the baseline situation, to a single intensive farm, representing the intensification scenario. The reference flow is defined as the annual production of 4,149,102 kg of milk plus 153,008 kg of beef. The latter represents the amount of beef produced from 154 culled milking cows plus 262 dairy bull calves and 108 heifers exported from the 4.09 average dairy farms and reared for beef, detailed in Table S3.1. The intensification scenario involves the annual production of 126,728 kg of dairy-beef from 149 culled milking cows, 217 dairy bull calves and 70 heifers. The 26,280 kg/year shortfall in beef production for the intensive compared with the average dairy farms is made up for by the rearing of additional “replacement” suckler-beef, represented by carbon and land footprints previously calculated for typical European (Nguyen et al., 2010) or Brazilian (Ruviaro, de Léis, Lampert, Barcellos & Dewes, 2015) suckler-beef systems depending on the intensification scenario (see Table 4), as elaborated in Table S3. Cattle are fed a higher share of maize and concentrate feed on the intensive farm compared with the average farm (Table 3). Land use changes associated with shifting feed production are accounted for in cLCA (Table 1). All scenario results calculated using cLCA are presented in relation to one kg of milk production shifting to the intensive farm, facilitating comparison with simple carbon footprint results expressed per kg of milk.

TABLE 1 Factors considered in milk footprints (attributional LCA) and consequential LCA, including direct land use change (dLUC) and indirect land use change (iLUC)

	Upstream emissions	Farm emissions	dLUC grass-to-maize[a]	iLUC from additional concentrate feed crops[b]	Dairy-beef rearing	Replacement suckler-beef production	Secondary consequences (Table 4)
Milk footprint	X	X	(X)				
Consequential LCA	X	X	(X)	(X)	X	X	X

[a]Milk footprints are calculated with and without dLUC attributed to additional maize demand.
[b]For consequential LCA calculations, dLUC & iLUC are included in mid-case (main results) and worst-case, but not best-case, scenario permutations – representing uncertainty ranges.

TABLE 2 Characteristics of average and intensive UK dairy farm typologies responsible for milk production before and after intensification, respectively

	Units	Average dairy farm	Intensive dairy farm
Milking cows	Head	142	481
Milk yield per cow	kg/year	7124	8626
Replacement rate	%/year	27	31
Farm area	Ha	85	250
Grazing days	Days/year	183	56
Outputs			
Milk	kg/year	1,013,548	4,149,102
Exported calves	Head/year	90	287
Culled cow live weight	kg/year	22,578	88,023

TABLE 3 Inventory of key inputs and outputs on average UK dairy farms, representing the baseline situation, and on an intensive dairy farm, representing the intensification scenario, expressed per kg of milk produced (non-allocated)

Parameter	Units	Average dairy farm	Intensive dairy farm
Inputs			
Concentrate feed	g kg^{-1} milk	165	234
Imported hay		11.5	4.6
Fertilizer-N app.		14.9	4.5
Fertilizer-P_2O_5 app.		2.1	2.3
Fertilizer-K_2O app.		0.0	1.7
Lime app.		28.9	26.8
Other agrochems		0.12	0.48
Electricity	kJ kg^{-1} milk	155	146
Heating oil		78	73
Diesel		438	290
Land areas			
Grassland	m^2 kg^{-1} milk	0.53	0.14
Maize		0.32	0.47
Cereals		0.21	0.30
Oil seeds		0.05	0.07
Palm oil		0.008	0.012
Soybeans		0.08	0.12
Total		1.20	1.1
Outputs			
Animal live weight	g kg^{-1} milk	27.9	25.6
Enteric CH_4		22.7	20.8
Manure CH_4		3.9	5.7
N excretion		24.8	18.1
NH_3 volatilization		6.4	7.8
N leaching		2.5	0.9
Soil & manure N_2O		0.75	0.47
P leaching		0.15	0.12

2.2 | Simple carbon footprints

Animal feed intake for all milking cows and followers for the two farm typologies was modelled in Farm-adapt (Gibbons, Ramsden & Blake, 2006) based on energy requirements for animal cohorts calculated using IPCC Tier 2 methodology (IPCC, 2006), at milk yields specified in Table 2 and metabolizable energy contents of different feeds listed in Table S1.1. Land areas required to produce imported feed ingredients (Table 3) were calculated based on the composition of dairy feed (Defra, 2016a) and marginal yields for relevant crops in major source regions (Overmars et al., 2015), elaborated in Table S2, and expressed per kg of milk produced on the average and intensive farms.

All upstream emissions arising from the manufacture of fertilizer, production of concentrate feed, generation of electricity and supply of diesel were calculated using Ecoinvent v.3 (Wernet et al., 2016). Enteric CH_4 and manure management CH_4 and N_2O emissions were calculated using IPCC Tier 2 equations (IPCC, 2006) and animal feed characteristics described in Table S1.1, assuming all manure excreted indoors was stored in an open tank, and the remaining annual manure production was excreted onto grazed pasture (CH_4 conversion factors of 19% and 1%, respectively, at an annual average temperature of 11°C). Field N_2O emissions were calculated for nitrogen (N) excreted during grazing, and applied in manures and synthetic fertilizers using an IPCC Tier 1 approach. Indirect N_2O emissions were based on NH_3-N emissions and N leaching factors taken from national inventory reports (Duffy et al., 2014; Misselbrook, Gilhespy, Cardenas, Williams & Dragosits, 2015).

Maize consumed on dairy farms may be grown on the farm, or imported from neighbouring farms, and on land that was recently under permanent pasture, or on land that has been in arable production for decades. According to carbon footprint standards (BSI, 2011), direct land use change (dLUC) is accounted for in aLCA when it has occurred within the past 20 years in the production system being evaluated. However, traceability limitations can complicate detection and attribution of dLUC in animal feed production chains, in which case BSI (2011) recommend the statistical attribution of dLUC to production chains based on data for relevant crops in relevant source countries. Given the uncertainty about whether all additional maize production is associated with dLUC, and the omission of dLUC in many simple carbon footprint calculators, we calculated milk footprints both including and excluding dLUC emissions arising from grassland converting to cropland for additional forage maize production, annualized over a 20-year transition period.

2.3 | Intensification scenarios

We investigated eight core intensification scenarios representing alternative storylines (Table 4) through analyses of 63 permutations of national and international consequences. Spared dairy grassland in the UK was calculated as the difference between the sum of grassland and maize areas required for milk production before and after intensification. Medium- and high-intensity replacement suckler-beef

TABLE 4 Scenarios representing possible consequences of UK dairy farm intensification, for which GHG fluxes were quantified using consequential life cycle assessment

	Primary consequences		Secondary consequences	
Scenario	Dairy feed	Use of net spared ex-dairy grassland	Displaced beef production	Land use change
M-Beef (medium-intensity replacement beef)	Additional maize (grassland conversion, UK) & concentrate feed demand	Medium-intensity rearing of replacement suckler beef, with remaining area left as fallow (UK)	NA	Concentrate feed demand drives cascade of crop displacement culminating in cropland expansion (RoW)
M-Beef + Trees (medium-intensity replacement beef plus afforestation)	Additional maize (grassland conversion, UK) & concentrate feed demand	Medium-intensity rearing of replacement suckler beef, with remaining area afforested (UK)	NA	Concentrate feed demand drives cascade of crop displacement culminating in cropland expansion (RoW)
H-Beef (high-intensity replacement plus additional beef)	Additional maize (grassland conversion, UK) & concentrate feed demand	High-intensity rearing of as much suckler beef as possible (UK)	Extensive[a] beef production shifts to intensive beef production on ex-dairy grassland (UK)	Concentrate feed demand drives cascade of crop displacement culminating in cropland expansion (RoW). Fallow on grassland previously used for extensive beef production (UK)
H-Beef + Trees (high-intensity replacement beef plus afforestation)	Additional maize (grassland conversion, UK) & concentrate feed demand	High-intensity rearing of as much suckler beef as possible (UK)	Extensive[a] beef production shifts to intensive beef production on ex-dairy grassland (UK)	Concentrate feed demand drives cascade of crop displacement culminating in cropland expansion (RoW). Afforestation on grassland previously used for extensive beef production (UK)
Imp-Beef (replacement beef imported[b])	Additional maize (grassland conversion, UK) & concentrate feed demand	Fallow (UK)	Expansion of beef production in Brazil (varying intensities) for export	Concentrate feed demand drives cascade of crop displacement culminating in cropland expansion (RoW). Expansion of grassland into forest (deforestation) in Brazil
Imp-Beef + Trees (replacement beef imported[b], plus afforestation)	Additional maize (grassland conversion, UK) & concentrate feed demand	Afforestation of entire spared grassland area (UK)	Expansion of beef production in Brazil (varying intensities) for export	Concentrate feed demand drives cascade of crop displacement culminating in cropland expansion (RoW). Expansion of grassland into forest (deforestation) in Brazil
M-MaxBeef (Medium-intensity rearing of replacement plus additional suckler beef)	Additional maize (grassland conversion, UK) & concentrate feed demand	Medium-intensity rearing of as much suckler beef as possible over entire area (UK)	Avoided expansion of beef production in Brazil (varying intensities) for export	Concentrate feed demand drives cascade of crop displacement culminating in cropland expansion (RoW). Avoided expansion of grassland into forest in Brazil
H-MaxBeef High-intensity rearing of replacement plus additional suckler beef)	Additional maize (grassland conversion, UK) & concentrate feed demand	High-intensity rearing of as much suckler beef as possible over entire area (UK)	Avoided expansion of beef production in Brazil (varying intensities) for export	Concentrate feed demand drives cascade of crop displacement culminating in cropland expansion (RoW). Avoided expansion of grassland into forest in Brazil

[a]"Extensive" = low - or medium-intensity suckler beef production (Table S3.2).

[b]Replacement beef may be imported, or may reduce national beef exports, with the same effect of displacing beef production to the marginal global exporter (Brazil).

production on this spared grassland leads to smaller or larger areas of residual spared ex-dairy grassland that is available for other uses. Low-intensity replacement suckler beef production would require a larger area of land than the area of spared dairy grassland. This was investigated in sensitivity analyses, and results are displayed in (Table S6.1 and S6.2), but it is not presented as a core scenario, given that dairy farms occupy more productive grassland likely to support at least medium-intensity beef production. Net spared ex-dairy grassland may be used for fallow, forestry or additional beef production, with secondary consequences (Table 4). For example, the use of all spared dairy grassland for medium- or high-intensity beef production can lead to the substitution of extensive beef production elsewhere in the UK or in Brazil – the world's largest, and growing, exporter of beef (FAOStat, 2017). The net effect is to make larger areas of less productive grassland available for either fallow or afforestation (Figure 2), or to curtail ongoing expansion of grassland

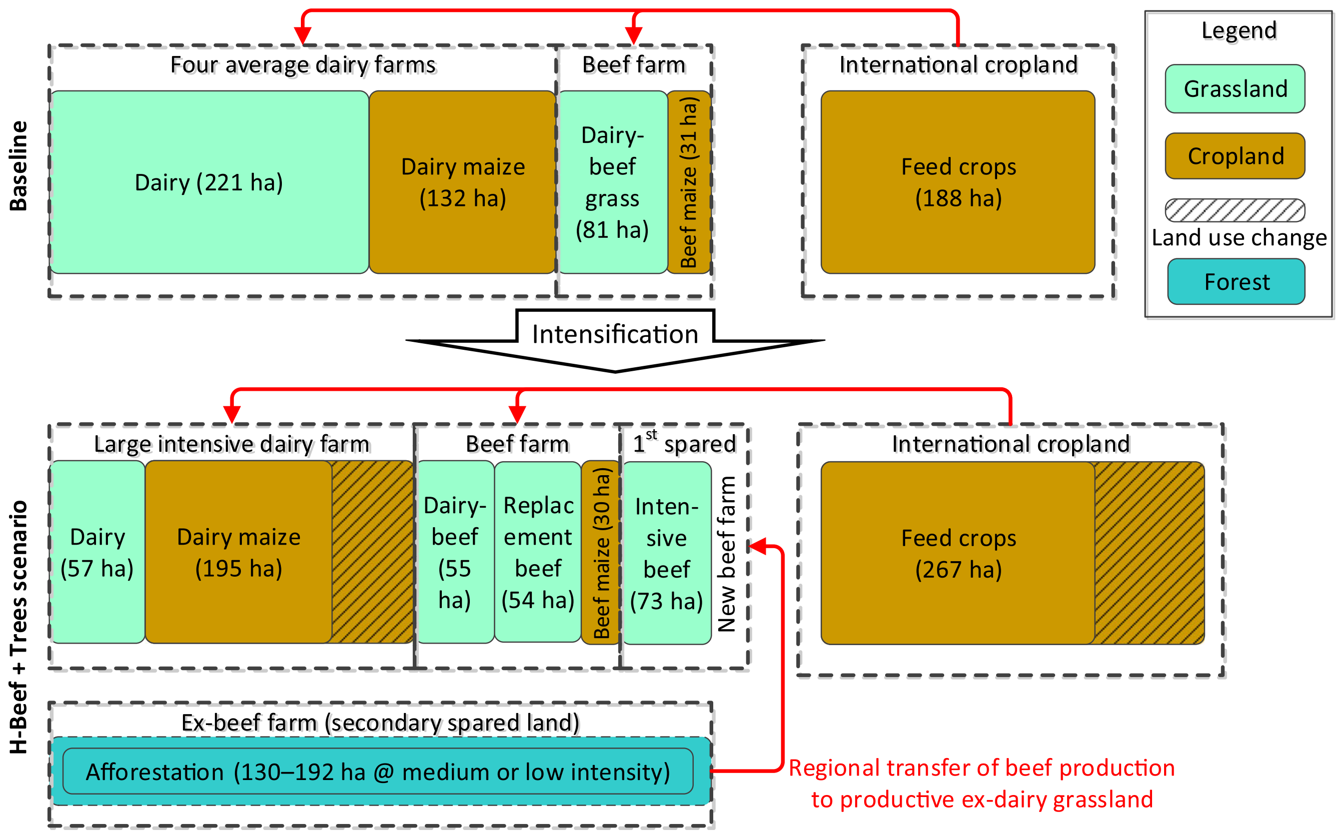

FIGURE 2 Land area changes arising from dairy intensification in scenario H-Beef + Trees (Table 4), under constant milk and beef output, including use of spared dairy grassland for intensive beef production that leads to sparing of a larger area of grassland previously used for extensive beef production

into forest habitats at the agricultural frontier in Brazil (Table 4). Conversely, if dairy-beef production is not replaced within the UK, then we assume that it will be replaced within the global market for beef by an expansion of production in Brazil, leaving land to fallow or available for afforestation in the UK, but leading to deforestation from agricultural expansion in Brazil. Emissions of GHGs associated with these secondary consequences were accounted for within the cLCA framework.

Figure 2 illustrates changes in land use arising during the transition from baseline average to intensive dairy production for the H-Beef + Trees scenario. Land use changes for the other seven scenarios are illustrated in Table S6.1 and Figures S4.1 to S4.8.

2.4 | Land use change GHG emissions

During dairy intensification, additional feed-crop production will arise through intensification of cropping, optimized integration of specific crops within arable rotations, e.g., maize as a break crop (Styles, Gibbons, Williams, Stichnothe et al., 2015), or expansion of cropland. We represented these possibilities as scenario permutations, and did not attribute dLUC to maize or iLUC to concentrate feed crops in best-case permutations. For mid-case and worst-case scenario permutations, dLUC emissions were calculated by multiplying the increase in cultivated area necessary to satisfy additional maize demand at constant average UK yield, by the annualized GHG emission factor of 7.0 Mg CO_2e ha^{-1} reported for UK grass-to-cropland conversion based on the IPCC Tier 1 approach (BSI, 2011). Mid-case iLUC emissions driven by additional demand for concentrate feed following intensification were calculated based on crop-specific land footprint and iLUC CO_2 factors (Table S2.1) derived for biofuel emissions calculations (Overmars, Stehfest, Ros & Prins, 2011). Worst-case iLUC emissions driven by additional demand for concentrate feed following intensification were calculated by multiplying land footprints for concentrate feed ingredients (Table S2.1) by a weighted-mean CO_2e factor calculated using the IPCC Tier 1 approach for the five dominant land use transformations at the global agricultural frontier (Styles, Gibbons, Williams, Stichnothe et al., 2015) – after correcting for changes in Brazilian beef production areas (see below). Concentrate feed iLUC methods are elaborated in Table S2.1, and all iLUC calculations apply to the marginal net additional concentrate feed demand for dairy and beef production relative to the baseline.

The area of land required for, or spared from, expansion of medium-intensity Brazilian beef production was derived from Ruviaro et al. (2015), with sensitivity analyses undertaken for land footprints associated with low- and high-intensity production (Table S3.2). For worst-case iLUC, these areas were added to international cropland expansion areas associated with additional concentrate feed demand to calculate net expansion, or avoided expansion, at the global agricultural frontier (Table S6.1). For midcase iLUC, additional or avoided Brazilian beef production was multiplied by LUC carbon footprints previously attributed to Brazilian beef (Persson, Henders & Cederberg, 2014). For scenarios involving conversion of UK grassland to forestry, the carbon sink was calculated based on the IPCC Tier 1 method for above- and below- ground carbon accumulation for newly established temperate oceanic forests (Table S5.1).

3 | RESULTS

3.1 | Simple land and carbon footprints

The average and intensive dairy systems (excluding dairy-beef rearing) require 1.203 and 1.110 m^2.year per kg of milk produced (Table 5 and Table S6.1), equating to milk footprints of 1.059 and 0.987 m^2.year, respectively, after allocation between milk and animal live weight co-products. Attributional LCA indicates a 10% reduction in simple milk carbon footprint following intensification, from 1.02 to 0.92 kg CO_2e kg^{-1} milk, reflecting smaller CH_4 emissions per kg milk from higher-yielding cows eating more digestible starchy feeds, and smaller N_2O emissions from less urine-N deposited during a shorter grazing period, somewhat offset by greater CH_4 and indirect N_2O (via NH_3) emissions from more manure storage (Chadwick et al., 2011) (Table 3 and Table S6.2). Soil carbon release caused by conversion of dairy grassland to forage maize production can negate most of the reduction in enteric CH_4 and grazing N_2O emissions when accounted for within LCA boundaries, as previously demonstrated (Vellinga & Hoving, 2011).

In addition to summary results presented in Table 5 and Figure 3 for the baseline and eight core scenarios, land use and GHG emission results are presented in Tables S6.1 and S6.2 for 20 and 63 scenario permutations, respectively (MS Excel file).

Production of one kg of milk plus 0.037 kg of dairy-beef in the baseline situation requires 1.57 m^2.year spread across dairy, beef-rearing and feed-cropping farms (Table 5). Land footprints for intensive dairy and coupled dairy-beef systems shrink by 8% and 26% following intensification (Table 5 and Table S6.1). A 0.456 m^2.year reduction in grassland area is partially offset by a 0.266 m^2.year increase in cropland (maize plus concentrate feed) area. However, at medium-intensity suckler-beef production in the UK, 0.271 m^2.year is required to replace the reduced output of dairy-beef per kg of milk produced on the intensive dairy farm, resulting in a 5% increase in overall land footprint to maintain constant milk and beef production despite 0.223 m^2.year less grassland being used within the UK (M-Beef vs Baseline in Table 5). Results show that the total land footprint of milk and beef production is always higher following dairy intensification unless replacement beef is produced at high intensity.

3.2 | Forage maize and cropland expansion

Changes in dairy farm carbon footprints presented in Figure 3a, expressed per kg of milk produced without allocation to allow comparison with indirect factors accounted for in cLCA, illustrate the relative importance of the indirect factors that we link to dairy intensification. All GHG flux changes in Figure 3, and overall percentage changes referred to hereafter, relate to baseline GHG emissions of 1.63 kg CO_2e arising from the dairy and coupled dairy-beef rearing systems to produce one kg of milk plus 0.037 kg of dairy-beef.

Indirect LUC driven by increased demand for concentrate feed contributes 0.09 (mid-case) and 0.39 (worst case) kg CO_2e per kg of shifted milk production, and the latter factor drove a net increase in GHG emissions following dairy intensification (upper error bar) in all scenarios except H-Beef + Tree and H-MaxBeef. For example, if spared dairy grassland is left fallow (M-Beef), dLUC, iLUC and replacement beef production together outweigh the benefit of improved feed conversion efficiency, leading to an 8% increase in GHG emissions for reference milk and beef production, ranging from a 4% reduction if all LUC emissions are excluded to a 26% increase assuming worst-case iLUC (Figure 3b; Table S6.2). Concentrate feed iLUC is a critical factor that can cause significant international carbon leakage during dairy intensification.

3.3 | Replacement beef production

The GHG and land intensities of additional suckler-beef production required to replace reduced dairy-beef output critically determine the climate efficiency of dairy intensification. Replacing foregone dairy beef production with medium-intensity (M-Beef and M-Beef + Trees) suckler-beef production in the UK leads to additional "Beef production" GHG emissions of 0.06 kg CO_2e per kg of shifting milk production (Figure 3a). If foregone dairy-beef was replaced by low-intensity suckler-beef production in the UK, "Beef production" GHG emissions would increase by 0.10 kg CO_2e per kg of shifting milk production (Table S6.2). If all replacement beef production was displaced to Brazil (Imp-Beef, Imp-Beef + Trees), GHG emissions from "Beef production" would increase by 0.19 (0.14 to 0.43) kg CO_2e per kg of milk owing to the comparatively high footprint of Brazilian beef (Ruviaro et al., 2015). Conversely, utilising spared dairy grassland in the UK to replace Brazilian beef production in the M-MaxBeef and H-MaxBeef scenarios increases "Beef production" emissions in the UK by 0.11 and 0.26 kg CO_2e, respectively, but leads to "Avoided beef production" emissions of 0.08 and 0.34 kg CO_2e per kg shifting milk production. Similarly, when spared dairy grassland is all used to produce high-intensity suckler-beef in the H-Beef and H-Beef + Trees scenarios, additional "Beef production" emissions of 0.21 kg CO_2e per kg milk are more than offset by 0.23 kg CO_2e per kg milk "Avoided beef production" emissions arising from the substitution of medium-intensity suckler-beef production on extensive grassland within the UK. Sensitivity analyses indicate that up to 0.28 kg CO_2e per kg milk can be avoided if high-intensity beef production on spared dairy grassland substitutes low-intensity beef production (Table S6.2). An even more important effect of the aforementioned beef intensification on spared dairy grassland is the indirect sparing of larger areas of land elsewhere, either for afforestation (H-Beef + Trees), or from deforestation

TABLE 5 Land areas (in m^2) for the production of one kg of milk plus 0.037 kg of beef for the baseline average dairy and dairy-beef farms, and for the large dairy farm and associated dairy-beef and replacement suckler beef farms across eight central scenarios

	Dairy farms			Dairy-beef rearing			Net suckler-beef rearing[a]				Overall					
	Grass	Maize	Concentrate	Grass	Maize	Concentrate	Grass-UK	Grass-Brazil	Maize	Concentrate	Afforestation	Grass	Maize	Concentrate	Total area	Change from baseline
	m^2.year kg^{-1} milk (plus 0.037 kg^{-1} beef)															
Baseline	0.531	0.319	0.353	0.194	0.074	0.099	0.000		0.000	0.000	0.000	0.726	0.393	0.453	1.571	
M-Beef	0.137	0.470	0.502	0.133	0.061	0.078	0.234		0.011	0.027	0.000	0.503	0.543	0.607	1.653	5%
M-Beef + Trees	0.137	0.470	0.502	0.133	0.061	0.078	0.234		0.011	0.027	0.072	0.503	0.543	0.607	1.653	5%
H-Beef	0.137	0.470	0.502	0.133	0.061	0.078	0.306		0.011	0.027	0.000	0.263	0.543	0.607	1.413	-10%
H-Beef + Trees	0.137	0.470	0.502	0.133	0.061	0.078	0.306		0.011	0.027	0.313	0.263	0.543	0.607	1.413	-10%
Imp-Beef	0.137	0.470	0.502	0.133	0.061	0.078	0	0.405	0.000	0.000	0.000	0.674	0.532	0.580	1.786	14%
Imp-Beef + Trees	0.137	0.470	0.502	0.133	0.061	0.078	0	0.405	0.000	0.000	0.317	0.674	0.532	0.580	1.786	14%
H-MaxBeef	0.137	0.470	0.502	0.133	0.061	0.078	0.292	-0.494	0.025	0.061	0.000	0.068	0.557	0.641	1.266	-19%
M-MaxBeef	0.137	0.470	0.502	0.133	0.061	0.078	0.303	-0.123	0.015	0.035	0.000	0.449	0.546	0.615	1.611	3%

[a]Net suckler-beef rearing area is the area required for replacement suckler beef, plus any additional beef produced on the spared dairy grassland, minus the area of extensive beef production replaced by the aforementioned additional production on spared dairy grassland (Table 4) – leading to a net reduction in suckler-beef areas in some scenarios.

(H-MaxBeef). Afforestation and avoided deforestation in those scenarios result in GHG credits of 0.43 and 0.50 kg CO_2e per kg of shifting milk production, respectively. These credits more than offset the additional emissions incurred by dairy intensification, including worst-case iLUC attributed to feed supply chains, but only when sufficient land is spared via high-intensity replacement beef production: H-Beef + Trees and H-MaxBeef result in significant overall GHG savings of 23% (5%–50%) and 34% (31%–88%), respectively, under default and worst-case assumptions, whilst M-Beef + Trees and M-MaxBeef do not (Figure 3b). Sensitivity analyses emphasize the sensitivity of results to intensity of substituted beef production (Table S6.2 and error bars in Figure 3b), and indicate that net GHG emissions would increase significantly if spared dairy grassland was used to produce beef at low intensity (Table S6.1), owing to a significant increase in land requirement for baseline milk and beef production (Table S6.1).

3.4 | International GHG inventory effects

The location of replacement beef production, and use of ex-dairy land for additional beef production, can have very large and geographically divergent GHG flux implications via incurred or avoided agricultural expansion (iLUC). We partitioned GHG emission changes between UK and rest-of-world (RoW) inventories (Table S6.2 and Table S6.3). If all replacement beef production is displaced to Brazil (Imp-Beef), national GHG emissions arising from reference milk and beef production decline slightly compared with the baseline, but RoW emissions attributable to reference quantities of milk and beef production increase by 0.72 kg CO_2e per kg shifting milk production under mid-case iLUC (equivalent to 44% of baseline emissions: Figure 4). The comparatively high carbon and land footprints of Brazilian beef production (Ruviaro et al., 2015) contribute 0.19 and 0.44 kg CO_2e per kg shifting milk production, respectively ("Beef production" and "Beef indirect land use change" in Figure 3a), to this RoW emission increase. Thus, the net emission increase is highly sensitive to the intensity of Brazilian beef production and to the iLUC factor employed, ranging from 1% of baseline GHG emissions for high-intensity production with no iLUC factor applied, to 126% of baseline emissions for low-intensity production with a worst-case iLUC factor applied (error bars on Figure 3b). International displacement of replacement beef production therefore represents another major, but somewhat uncertain, potential source of international carbon leakage associated with dairy intensification.

Conversely, when productive pastures spared on dairy farms are used for additional intensive beef production that substitutes Brazilian beef (H-MaxBeef), national emissions associated with reference milk and beef production increase by 0.17 kg CO_2e per kg of shifting milk production but RoW emissions decrease by 0.73 kg CO_2e per kg of shifting milk production (Figure 4), leading to overall emission savings of between 31% and 88% for reference milk and beef production depending on the intensity of avoided Brazilian beef production (Figure 3b).

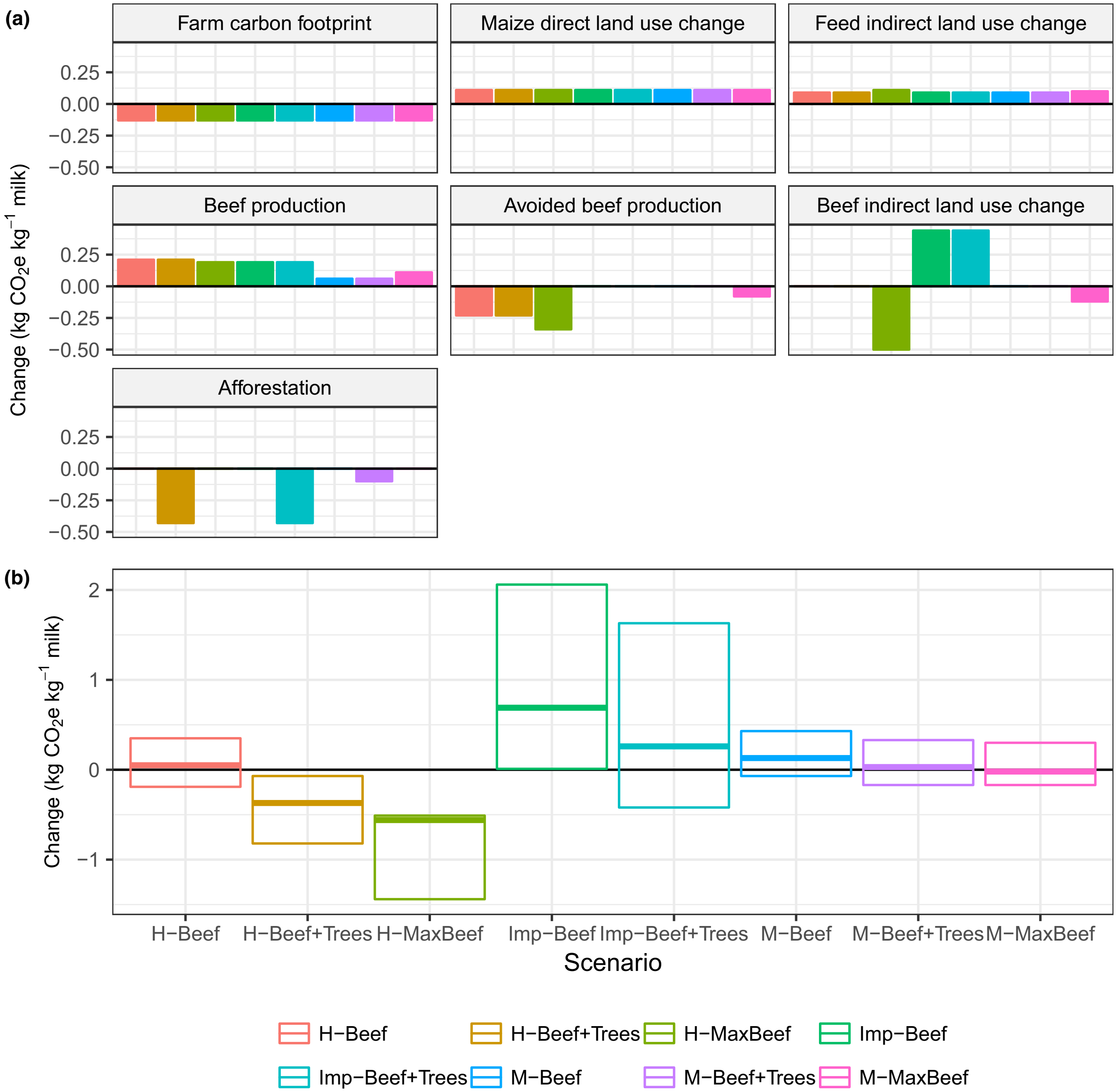

FIGURE 3 Factors contributing to net GHG flux changes that arise when one kg of milk production shifts from exiting average to expanding intensive farms under the eight scenarios considered (a). Error bars around net GHG changes (b) represent best- to worst-case land use change effects and production intensities for incurred (Imp-Beef) or substituted (MaxBeef) Brazilian beef

Afforestation of spared dairy and beef grassland in the Imp-Beef + Trees and H-Beef + Trees scenarios could reduce net emissions arising in the UK by approximately 0.46 kg CO_2e per kg of shifting milk production (28% of baseline emissions from milk and beef production; Figure 4). For Imp-Beef + Trees, that is significantly less than the 0.72 kg CO_2e increase in emissions arising in the RoW inventory, so that overall GHG emissions arising from dairy and beef production still increase by 16% – ranging from a saving of 26% to an increase of 100% depending on the intensity of replacement beef production in Brazil and the iLUC factor applied (Figure 3b).

4 | DISCUSSION

4.1 | Evaluating sustainable intensification

For the first time, we applied consequential life cycle assessment to account for the suite of direct and indirect factors contributing to the GHG mitigation efficacy of widespread dairy farm consolidation and intensification. Dairy intensification can reduce simple milk footprints by increasing animal productivity and feed conversion efficiency, although life cycle assessment has already been

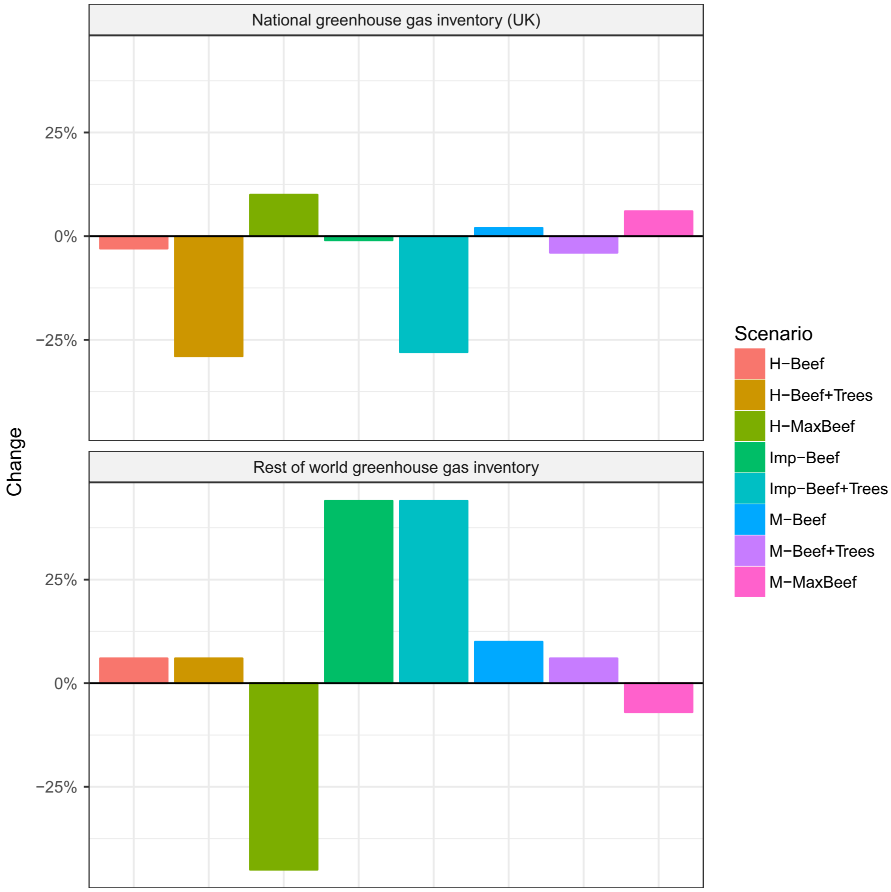

FIGURE 4 GHG emission changes for each dairy intensification scenario partitioned according to national and rest-of-world GHG inventories, and expressed as a percentage of baseline emissions arising from the production of reference quantities of milk and beef

applied to show that carbon loss following conversion of grassland to forage maize production can offset these carbon footprint savings (Van Middelaar et al., 2013; Vellinga & Hoving, 2011). Recent studies have shown that land sparing from suckler beef intensification can achieve significant GHG mitigation (Cohn et al., 2014; Herrero et al., 2016; deOliveira Silva et al., 2016), but our results demonstrate that intensification of dairy production does not necessarily translate into the same land sparing advantages owing to complex interlinkages with beef production and teleconnections with global beef and feed production. Specifically, indirect land use change associated with increased demand for concentrate feed, plus additional suckler-beef production required to replace reduced dairy-beef output, can significantly increase land occupation and GHG emissions following intensification. Dairy farms are inherently dual-purpose systems, producing milk and calves for rearing. Optimization therefore needs to consider consequences of changes in both of these outputs, rather than allocating away the relatively small (on a mass or energy basis) calf live-weight outputs.

Wide uncertainty ranges around our results highlight sensitivities to uncertain indirect effects, and emphasize the lower precision of consequential LCA compared with footprints calculated using attributional LCA. In agreement with proponents of consequential LCA (Ekvall & Weidema, 2004; Weidema & Schmidt, 2010), we contend that this loss of precision more accurately represents the wide range of outcomes associated with intensification transitions, and provides valuable new insight to stakeholders on the sustainability of these transitions.

4.2 | Use of spared grassland

We find that climate mitigation from dairy intensification is highly dependent on the intensity of beef production arising on spared dairy grassland. Leaving or directly afforesting grassland spared by dairy intensification, as may be encouraged by national conservation and agri-environmental objectives, may not fully offset emissions indirectly incurred by dairy intensification via iLUC and replacement beef production. However, the use of grassland spared by dairy intensification for intensive beef production can lead to net GHG mitigation by replacing extensive UK beef production, enabling afforestation on less productive grassland, or by avoiding expansion of Brazilian beef production. The magnitude of carbon leakage or GHG savings attributable to international displacement of beef production is highly sensitive to the intensity (land footprint) of marginal global beef production, here considered to occur in Brazil, owing to the dominant effect of incurred or avoided agricultural expansion (iLUC). These findings may align with wider rationalization of agricultural production, but may conflict with agri-environmental and rural development policies that favour the maintenance of low-intensity agriculture on marginal land in Europe and other industrialized regions where dairy intensification is widespread (FAO, 2016).

4.3 | Limitations and future work

Large GHG emission ranges (Figure 3b) highlight uncertainties involved in predicting indirect GHG consequences of dairy intensification, especially where there are interactions between beef displacement and iLUC effects that occur via cascades of consequence following market perturbations (Persson et al., 2014). Full accounting of indirect consequences arising from dairy intensification within the consequential LCA framework would require regional to global scale economic modelling of effects on trade in animal feed, milk and beef commodities linked to price signals and possibly also changing consumer (dietary) preferences (Westhoek et al., 2014). Here, we employed a simplified approach assuming 1:1 replacement of displaced food and feed commodities, analogous to bioenergy iLUC modelling applied in previous studies (Styles, Gibbons, Williams, Stichnothe et al., 2015; Tonini, Hamelin, Wenzel & Astrup, 2012; Vázquez-Rowe, Marvuglia, Rege & Benetto, 2014). Our mid-case iLUC estimate for concentrate feed (Overmars et al., 2011) is based on historic rates of LUC (Overmars et al., 2015) that have been ameliorated by intensification of crop production, highlighting the difficulty of untangling effects of intensification in one sector from intensification in another, which may be occurring independently. Nonetheless, attempting to separate out some of these effects does provide unique insight into the relative GHG mitigation efficacy of specific mechanisms associated with different pathways of dairy intensification.

Our results depend on characteristics of average, moderately intensive dairy farms assumed to exit the sector and intensive farms assumed to expand as part of the consolidation and intensification trend observed across dairy sectors in industrialized countries. Key characteristics include animal diets, milk yields and replacement rates, influencing cropping patterns to provide feed and quantities of replacement beef production required to replace reduced dairy-beef output. Conclusions may not be applicable to dairy intensification in developing countries where there is greater scope for efficiency gains and land sparing (Gerber et al., 2011).

We used farm models parameterized using UK statistics for average and intensive farms, followed by economic optimization. Important factors such as grass uptake efficiency and nutrient management planning vary considerably across farms, and may differ from performance predicted by economic optimization. Default IPCC Tier 1 emission factors may underestimate possible nonlinear increases in soil N_2O emissions as dairy and beef farms intensify. There remains a need to parameterize detailed dairy farm models required to evaluate specific mitigation measures (Del Prado et al., 2013) using statistics for exiting and expanding dairy farms, and to couple these with economic trade models, to integrate important effects at farm-, regional- and global-scales, and therefore more accurately predict the net GHG mitigation efficacy of dairy intensification pathways. It will also be important to consider additional environmental impact categories and ecosystem services delivery, which could be strongly influenced by the wider land use implications of dairy intensification.

4.4 | Recommendations

Future studies evaluating the sustainability of dairy farm intensification should consider: (i) possible indirect land use change associated with increased demand for concentrate feed; (ii) replacement beef production; (iii) use of spared dairy grassland. We recommend the use of consequential life cycle assessment to evaluate the climate efficiency of intensification pathways for livestock systems, to avoid potentially misleading conclusions being drawn from snapshot carbon footprints based on attributional life cycle assessment. We conclude that dairy intensification can lead to significant carbon leakage not captured in farm carbon footprints, and that net GHG mitigation is only achieved when coupled with intensification of beef production that can spare larger areas of land for forest, regionally or in major beef-exporting countries such as Brazil.

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