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1 *Running head:* Mitigation by dairy intensification

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

5

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11 sparing; consequential LCA

12 Primary research article

13 Abstract

14 Milk and beef production cause 9% of global greenhouse gas (GHG) emissions. Previous life cycle
15 assessment (LCA) studies have shown that dairy intensification reduces the carbon footprint of milk
16 by increasing animal productivity and feed conversion efficiency. None of these studies
17 simultaneously evaluated indirect GHG effects incurred via teleconnections with expansion of feed
18 crop production and replacement suckler-beef production. We applied consequential LCA to
19 incorporate these effects into GHG mitigation calculations for intensification scenarios among
20 grazing-based dairy farms in an industrialised country (UK), in which milk production shifts from
21 average to intensive farm typologies, involving higher milk yields per cow and more maize and
22 concentrate feed in cattle diets. Attributional LCA indicated a reduction of up to 0.10 kg CO₂e kg⁻¹
23 milk following intensification, reflecting improved feed conversion efficiency. However,
24 consequential LCA indicated that land use change associated with increased demand for maize and
25 concentrate feed, plus additional suckler-beef production to replace reduced dairy-beef output,
26 significantly increased GHG emissions following intensification. International displacement of
27 replacement suckler-beef production to the “global beef frontier” in Brazil resulted in small GHG
28 savings for the UK GHG inventory, but contributed to a net increase in international GHG emissions
29 equivalent to 0.63 kg CO₂e kg⁻¹ milk. Use of spared dairy grassland for intensive beef production can
30 lead to net GHG mitigation by replacing extensive beef production, enabling afforestation on larger
31 areas of lower quality grassland, or by avoiding expansion of international (Brazilian) beef
32 production. We recommend that LCA boundaries are expanded when evaluating livestock
33 intensification pathways, in order to avoid potentially misleading conclusions being drawn from
34 “snapshot” carbon footprints. We conclude that dairy intensification in industrialised countries can
35 lead to significant international carbon leakage, and only achieves GHG mitigation when spared dairy
36 grassland is used to intensify beef production, freeing up larger areas for afforestation.

37 **Introduction**

38 Milk and beef production currently contribute 9% of global greenhouse gas (GHG) emissions (Opio et
39 al., 2013). Milk production in Europe continues to intensify as dairy farms consolidate under
40 economic pressures (AHDB Dairy, 2016; Eurostat, 2016), and Europe is expected to become the
41 world's largest milk exporter (Chatzopoulos et al., 2016). The UK dairy sector exemplifies this
42 intensification trend, with farm numbers falling by one third, milk yield per cow increasing by 14%
43 (AHDB Dairy, 2016) and concentrate feed use increasing by 17% (Defra, 2016b) between 2005 and
44 2015. Sustainable intensification is regarded as a priority GHG mitigation measure for agriculture
45 (Garnett et al., 2013), partly because it can spare natural habitats from agricultural expansion,
46 avoiding disturbance of large terrestrial carbon stores (Burney, Davis, & Lobell, 2010) and/or
47 enabling carbon capture through afforestation of spared land (Lamb et al., 2016). Dairy
48 consolidation and intensification shifts milk production from many smaller farms to fewer larger
49 farms, affecting GHG emissions directly (Del Prado et al., 2013), and indirectly via coupled dairy-beef
50 (Flysjo et al., 2011) and feed production when cattle are fed a higher share of maize and concentrate
51 feeds (Styles et al., 2015a; Vellinga & Hoving, 2011) (Fig. 1). Life cycle assessment (LCA) is used to
52 benchmark the carbon footprint of milk production (BSI, 2011; Kristensen et al., 2011; O'Brien et al.,
53 2014). Reasons to expect dairy intensification supported by concentrate feed to reduce the GHG
54 intensity of milk production include: (i) reduced enteric methane (CH₄) emissions owing to increased
55 ratio of highly-digestible starch-based concentrate feed in cattle diets (Hristov et al., 2013); (ii) more
56 feed energy going into milk production rather than animal maintenance at higher yields per cow
57 (Capper et al., 2009); (iii) sparing of grassland (Burney et al., 2010; Lamb et al., 2016) (Fig. 1). Indeed,
58 there is considerable evidence that livestock intensification can lead to GHG mitigation (Cohn et al.,
59 2014) and reduce product footprints (Gerber et al., 2013; Gerber et al., 2011). However, previous
60 studies showing that dairy intensification reduces the carbon footprint of milk by increasing animal
61 productivity and feed conversion efficiency (Capper et al., 2009; Gerber et al., 2011) did not fully

62 capture the GHG implications of consequential changes in feed and beef production. Marginal milk
63 yield gains from further increases in the use of concentrate feeds on moderately intensive farms are
64 small, and could induce carbon leakage via indirect land use change (iLUC) in global crop systems
65 (Fig. 1), analogous to biofuel-induced iLUC (Elshout et al., 2015; Searchinger et al., 2008). Higher milk
66 yields per cow also result in fewer dairy calves being exported to beef farms, leading to more suckler
67 beef production with larger land and carbon footprints (Nguyen et al., 2010). Such inter-system
68 consequences are at best only partially captured by carbon footprints based on attributional LCA, in
69 which dairy system emissions are allocated between milk and beef (BSI, 2011), and may not be
70 reflected in national GHG inventories (Fig. 1). Weiss & Leip (2012) went some way to address this
71 gap, using national datasets to undertake a regional LCA for European livestock production that
72 simultaneously accounted for multiple livestock sectors, and for cropland expansion within Europe.
73 However, there remains a need to apply a coherent modelling approach that attributes important
74 indirect consequences of dairy intensification displayed in Fig. 1 to specific transition pathways in
75 order to generate robust conclusions on the GHG mitigation efficacy of particular “sustainable
76 intensification” strategies.

77 Previous studies applied attributional LCA to compare milk footprints from different types of dairy
78 system (Gerber et al., 2011; Kristensen et al., 2011; O'Brien et al., 2012; Van Middelaar et al., 2013;
79 Yan et al., 2013; Battini et al., 2016), but did not evaluate changes that occur when certain types of
80 farm systems replace others, as happens during intensification transitions. Consequential LCA (cLCA)
81 accounts for indirect effects of system changes incurred via market signals (Weidema & Schmidt,
82 2010) and has been applied to quantify iLUC emissions driven by increased demand for animal feed
83 (Schmidt 2008; Styles et al. 2015a), and to calculate residual milk carbon footprints by subtracting
84 avoided suckler-beef emissions from dairy system emissions (Thomassen et al., 2008). For the first
85 time, we apply cLCA to specific pathways of dairy intensification in order to investigate the major
86 direct and indirect consequences for GHG emissions that arise when milk production shifts to more

87 intensive farm types (Fig. 1), and compare results against simple carbon footprints for milk produced
88 on these farm types pre- and post- intensification.

89 **Materials and methods**

90 Life cycle assessment goal and scope

91 Our goal was to quantify GHG emission changes arising from dairy farm consolidation and
92 intensification. We first calculated the simple carbon footprint of milk produced on “average” and
93 “intensive” farms using attributional life cycle assessment (aLCA). Then, we applied consequential
94 LCA (cLCA) to explore the GHG emission implications of reduced dairy beef production and altered
95 animal feed demand associated with a shift in milk production from average to intensive farms
96 during consolidation and intensification (Table 1). GHG emissions were calculated as CO₂ equivalents
97 (CO₂e), according to 100-yr global warming potentials of 1, 25 and 298 per kg of CO₂, CH₄ and N₂O
98 emitted, respectively (IPCC, 2006).

99 Average and intensive dairy farm typologies characterised from UK statistics and used in previous
100 studies (del Prado et al., 2010; Styles et al., 2015a) were adopted for this study (Table 2), and
101 underpinned the derivation of system boundaries. The intensive dairy farm houses 481 milking cows,
102 almost 3.5 times as many as the average dairy farm, and puts animals out to graze for just two
103 months of the year, compared with six months for the average farm. Milk yields per cow are over
104 20% higher, and replacement rate slightly higher, on the intensive farm (Table 2).

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

110 For cLCA calculations, we accounted for direct and indirect effects associated with a shift in the
111 production of 4 149 102 kg milk from 4.09 average farms (Table 2), representing the baseline
112 situation, to a single intensive farm, representing the intensification scenario. The reference flow is
113 defined as the annual production of 4 149 102 kg of milk plus 153,008 kg of beef. The latter
114 represents the amount of beef produced from 154 culled milking cows plus 262 dairy bull calves and
115 108 heifers exported from the average dairy farms and reared for beef, detailed in S3. The
116 intensification scenario involves the annual production of 126 728 kg of dairy-beef from 149 culled
117 milking cows, 217 dairy bull calves and 70 heifers. The 26 280 kg yr⁻¹ shortfall in beef production for
118 the intensive compared with the average dairy farms is made up for by the rearing of additional
119 “replacement” suckler-beef, represented by carbon and land footprints previously calculated for
120 typical European (Nguyen et al., 2010) or Brazilian (Ruviano et al., 2015) suckler-beef systems
121 depending on the intensification scenario (see Table 4), as elaborated in S3. Cattle are fed a higher
122 share of maize and concentrate feed on the intensive farm compared with the average farm (Table
123 3). Land use changes associated with shifting feed production are accounted for in cLCA (Table 1). All
124 scenario results calculated using cLCA are presented in relation one kg of milk production shifting to
125 the intensive farm, facilitating comparison with simple carbon footprint results expressed per kg of
126 milk.

127

128 Simple carbon footprints

129 Animal feed intake for all milking cows and followers for the two farm typologies was modelled in
130 Farm adapt (Gibbons et al., 2006) based on energy requirements for animal cohorts calculated using
131 IPCC Tier 2 methodology (IPCC, 2006), at milk yields specified in Table 2 and metabolisable energy
132 contents of different feeds listed in Table S1.1. Land areas required to produce imported feed
133 ingredients (Table 3) were calculated based on the composition of dairy feed (Defra, 2016a) and

134 marginal yields for relevant crops in major source regions (Overmars et al., 2015), elaborated in S2,
135 and expressed per kg of milk produced on the average and intensive farms.

136 All upstream emissions arising from the manufacture of fertiliser, production of concentrate feed,
137 generation of electricity and supply of diesel were calculated using Ecoinvent v.3 (Wernet et al.,
138 2016). Enteric CH₄ and manure management CH₄ and N₂O emissions were calculated using IPCC Tier
139 2 equations (IPCC, 2006) and animal feed characteristics described in S1, assuming all manure
140 excreted indoors was stored in an open tank, and the remaining annual manure production was
141 excreted on to grazed pasture (CH₄ conversion factors of 19% and 1%, respectively, at an annual
142 average temperature of 11°C). Field N₂O emissions were calculated for nitrogen (N) excreted during
143 grazing, and applied in manures and synthetic fertilisers using an IPCC Tier 1 approach. Indirect N₂O
144 emissions were based on NH₃-N emissions and N leaching factors taken from national inventory
145 reports (Misselbrook et al., 2015; Duffy et al., 2014).

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

157

158 Intensification scenarios

159 We investigated eight core intensification scenarios representing alternative storylines (Table 4)
160 through analyses of 63 permutations of national and international consequences. Spared dairy
161 grassland in the UK was calculated as the difference between the sum of grassland and maize areas
162 required for milk production before and after intensification. Medium- and high- intensity
163 replacement suckler-beef production on this spared grassland leads to smaller or larger areas of
164 residual spared ex-dairy grassland that is available for other uses. Low-intensity replacement suckler
165 beef production would require a larger area of land than the area of spared dairy grassland. This was
166 investigated in sensitivity analyses, and results are displayed in supplementary tables (Table S6.1 and
167 6.2), but it is not presented as a core scenario, given that dairy farms occupy more productive
168 grassland likely to support at least medium-intensity beef production. Net spared ex-dairy grassland
169 may be used for fallow, forestry or additional beef production, with secondary consequences (Table
170 4). For example, the use of all spared dairy grassland for medium- or high-intensity beef production
171 can lead to the substitution of extensive beef production elsewhere in the UK or in Brazil – the
172 world’s largest, and growing, exporter of beef (FAOStat, 2017). The net effect is to make larger areas
173 of less productive grassland available for either fallow or afforestation (Fig. 2), or to curtail ongoing
174 expansion of grassland into forest at the agricultural frontier in Brazil (Table 4). Conversely, if dairy-
175 beef production is not replaced within the UK, then we assume it will be replaced within the global
176 market for beef by an expansion of production in Brazil, leaving land to fallow or available for
177 afforestation in the UK, but leading to deforestation from agricultural expansion in Brazil. Emissions
178 of GHGs associated with these secondary consequences were accounted for within the cLCA
179 framework.

180 Fig. 2 illustrates changes in land use arising during the transition from baseline average to intensive
181 dairy production for the H-Beef + Trees scenario. Land use changes for the other seven scenarios are
182 illustrated in S4.

183 Land use change GHG emissions

184 During dairy intensification, additional feed-crop production will arise through intensification of
185 cropping, optimised integration of specific crops within arable rotations, e.g. maize as a break crop
186 (Styles et al. 2015b), or expansion of cropland. We represented these possibilities as scenario
187 permutations, and did not attribute dLUC to maize or iLUC to concentrate feed crops in best-case
188 permutations. For mid-case and worst-case scenario permutations, dLUC emissions were calculated
189 by multiplying the increase in cultivated area necessary to satisfy additional maize demand at
190 constant yield (S2), by the annualised GHG emission factor of 7.0 Mg CO₂e ha⁻¹ reported for UK
191 grass-to-cropland conversion based on the IPCC Tier 1 approach (BSI, 2011). Mid-case iLUC emissions
192 driven by additional demand for concentrate feed following intensification were calculated based on
193 crop-specific land footprint and iLUC CO₂ factors derived for biofuel emissions calculations
194 (Overmars et al., 2011). Worst-case iLUC emissions driven by additional demand for concentrate
195 feed following intensification were calculated by multiplying land footprints for concentrate feed
196 ingredients (Table S 2.1) by a weighted-mean CO₂e factor calculated using the IPCC Tier 1 approach
197 for the five dominant land use transformations at the global agricultural frontier (Styles et al. 2015b)
198 – after correcting for changes in Brazilian beef production areas (see below). Concentrate feed iLUC
199 methods are elaborated in S2, and for all scenarios apply to the marginal net additional concentrate
200 feed demand for dairy and beef production relative to the baseline.

201 The area of land required for, or spared from, expansion of medium-intensity Brazilian beef
202 production was derived from Ruviano et al. (2015), with sensitivity analyses undertaken for land
203 footprints associated with low- and high-intensity production (S3). For worst-case iLUC, these areas

204 were added to international cropland expansion areas associated with additional concentrate feed
205 demand in order to calculate net expansion, or avoided expansion, at the global agricultural frontier
206 (S3). For mid-case iLUC, additional or avoided Brazilian beef production was multiplied by LUC
207 carbon footprints previously attributed to Brazilian beef (Persson et al., 2014). For scenarios
208 involving conversion of UK grassland to forestry, the carbon sink was calculated based on the IPCC
209 Tier 1 method for above- and below- ground carbon accumulation for newly-established temperate
210 oceanic forests (S5).

211

212 **Results**

213 Simple land and carbon footprints

214 The average and intensive dairy systems (excluding dairy-beef rearing) require 1.203 and 1.110 m².yr
215 per kg of milk produced (Table 5 and Table S6.1), equating to milk footprints of 1.059 and 0.987
216 m².yr, respectively, after allocation between milk and animal live weight co-products. Attributional
217 LCA indicates a 10% reduction in simple milk carbon footprint following intensification, from 1.02 to
218 0.92 kg CO₂e kg⁻¹ milk, reflecting smaller CH₄ emissions per kg milk from higher-yielding cows eating
219 more digestible starchy feeds, and smaller N₂O emissions from less urine-N deposited during a
220 shorter grazing period, somewhat offset by greater CH₄ and indirect N₂O (via NH₃) emissions from
221 more manure storage (Chadwick et al., 2011) (Table 3 and Table S6.2). Soil carbon release caused by
222 conversion of dairy grassland to forage maize production can negate most of the reduction in enteric
223 CH₄ and grazing N₂O emissions when accounted for within LCA boundaries, as previously
224 demonstrated (Vellinga & Hoving, 2011).

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

228 Production of one kg of milk plus 0.037 kg of dairy-beef in the baseline situation requires 1.57 m².yr
229 spread across dairy, beef-rearing and feed-cropping farms (Table 5). Land footprints for intensive
230 dairy and coupled dairy-beef systems shrink by 8% and 26% following intensification (Table 5 and
231 Table S6.1). A 0.456 m².yr reduction in grassland area is partially offset by a 0.266 m².yr increase in
232 cropland (maize plus concentrate feed) area. However, at medium-intensity suckler-beef production
233 in the UK, 0.271 m².yr is required to replace the reduced output of dairy-beef per kg of milk
234 produced on the intensive dairy farm, resulting in a 5% increase in overall land footprint to maintain
235 constant milk and beef production despite 0.223 m².yr less grassland being used within the UK (M-
236 Beef vs Baseline in Table 5). Results show that the total land footprint of milk and beef production is
237 always higher following dairy intensification unless replacement beef is produced at high intensity.

238 Forage maize and cropland expansion

239 Changes in dairy farm carbon footprints presented in Fig. 3a, expressed per kg of milk produced
240 without allocation to ensure compatibility with indirect factors accounted for in cLCA, illustrate the
241 relative importance of the indirect factors that we link to dairy intensification. All GHG flux changes
242 in Fig. 3, and overall percentage changes referred to hereafter, relate to baseline GHG emissions of
243 1.63 kg CO₂e arising from the dairy and coupled dairy-beef rearing systems to produce one kg of milk
244 plus 0.037 kg of dairy-beef.

245 Indirect LUC driven by increased demand for concentrate feed contributes 0.09 (mid-case) and 0.39
246 (worst case) kg CO₂e per kg of shifted milk production, and the latter factor drove a net increase in
247 GHG emissions following dairy intensification (upper error bar) in all scenarios except H-Beef + Tree

248 and H-MaxBeef. For example, if spared dairy grassland is left fallow (M-Beef), dLUC, iLUC and
249 replacement beef production together outweigh the benefit of improved feed conversion efficiency,
250 leading to an 8% increase in GHG emissions for reference milk and beef production, ranging from a
251 4% reduction if all LUC emissions are excluded to a 26% increase assuming worst-case iLUC (Fig. 3b;
252 Table S6.2). Concentrate feed iLUC is a critical factor that can cause significant international carbon
253 leakage during dairy intensification.

254 Replacement beef production

255 The GHG and land intensities of additional suckler-beef production required to replace reduced
256 dairy-beef output critically determine the climate efficiency of dairy intensification. Replacing
257 foregone dairy beef production with medium-intensity (M-Beef and M-Beef + Trees) suckler-beef
258 production in the UK leads to additional “Beef production” GHG emissions of 0.06 kg CO₂e per kg of
259 shifting milk production (Fig. 3a). If foregone dairy-beef was replaced by low-intensity suckler-beef
260 production in the UK, “Beef production” GHG emissions would increase by 0.10 kg CO₂e per kg of
261 shifting milk production (Table S6.2). If all replacement beef production was displaced to Brazil (Imp-
262 Beef, Imp-Beef + Trees), GHG emissions from “Beef production” would increase by 0.19 (0.14 to
263 0.43) kg CO₂e per kg of milk owing to the comparatively high footprint of Brazilian beef (Ruviano et
264 al., 2015). Conversely, replacing Brazilian beef production in the M-MaxBeef and H-MaxBeef
265 scenarios increases “Beef production” emissions in the UK by 0.11 and 0.26 kg CO₂e, respectively,
266 but leads to “Avoided beef production” emissions of 0.08 and 0.34 kg CO₂e per kg shifting milk
267 production. Similarly, when spared dairy grassland is all used to produce high-intensity suckler-beef
268 in the H-Beef and H-Beef + Trees scenarios, additional “Beef production” emissions of 0.21 kg CO₂e
269 per kg milk are more than offset by 0.23 kg CO₂e per kg milk “Avoided beef production” emissions
270 arising from the substitution of medium-intensity suckler-beef production on extensive grassland.
271 Sensitivity analyses indicate that up to 0.28 kg CO₂e per kg milk can be avoided if high-intensity beef

272 production on spared dairy grassland substitutes low-intensity beef production (Table S6.2). An even
273 more important effect of the aforementioned beef intensification on spared dairy grassland is the
274 indirect sparing of larger areas of land elsewhere, either for afforestation (H-Beef + Trees), or from
275 deforestation (H-MaxBeef). Afforestation and avoided deforestation in those scenarios result in GHG
276 credits of 0.43 and 0.50 kg CO₂e per kg of shifting milk production, respectively. These credits more
277 than offset the additional emissions incurred by dairy intensification, including worst-case iLUC
278 attributed to feed supply chains, but only when sufficient land is spared via high-intensity
279 replacement beef production: H-Beef + Trees and H-MaxBeef result in significant overall GHG
280 savings of 23% (5–50%) and 34% (31–88%), respectively, under default and worst-case assumptions,
281 whilst M-Beef + Trees and M-MaxBeef do not (Fig. 3b). Sensitivity analyses emphasise the sensitivity
282 of results to intensity of substituted beef production (Table S6.2 and error bars in Fig. 3b), and
283 indicate that net GHG emissions would increase significantly if spared dairy grassland was used to
284 produce beef at low intensity (Table S6.1), owing to a significant increase in land requirement for
285 baseline milk and beef production (Table S6.1).

286 International GHG inventory effects

287 The location of replacement beef production, and use of ex-dairy land for additional beef
288 production, can have very large and geographically divergent GHG flux implications via incurred or
289 avoided agricultural expansion (iLUC). We partitioned GHG emission changes between UK and rest-
290 of-world (RoW) inventories (S6.2). If all replacement beef production is displaced to Brazil (Imp-
291 Beef), national GHG emissions arising from reference milk and beef production decline slightly
292 compared with the baseline, but RoW emissions attributable to reference quantities of milk and beef
293 production increase by 0.72 kg CO₂e per kg shifting milk production under mid-case iLUC (equivalent
294 to 44% of baseline emissions: Fig. 4). The comparatively high carbon and land footprints of Brazilian
295 beef production (Ruviaro et al., 2015) contribute 0.19 and 0.44 kg CO₂e per kg shifting milk

296 production, respectively (“Beef production” and “Beef indirect land use change” in Fig. 3a), to this
297 RoW emission increase. Thus, the net emission increase is highly sensitive to the intensity of
298 Brazilian beef production and to the iLUC factor employed, ranging from 1% of baseline GHG
299 emissions for high-intensity production with no iLUC factor applied, to 126% of baseline emissions
300 for low-intensity production with a worst-case iLUC factor applied (error bars on Fig. 3b).
301 International displacement of replacement beef production therefore represents a second major,
302 but somewhat uncertain, potential source of international carbon leakage associated with dairy
303 intensification.

304 Conversely, when productive pastures spared on dairy farms are used for additional intensive beef
305 production that substitutes Brazilian beef (H-MaxBeef), national emissions associated with reference
306 milk and beef production increase by 0.17 kg CO₂e per kg of shifting milk production but RoW
307 emissions decrease by 0.73 kg CO₂e per kg of shifting milk production (Fig. 4), leading to overall
308 emission savings of between 31% and 88% for reference milk and beef production depending on the
309 intensity of avoided Brazilian beef production (Fig. 3b).

310 Afforestation of spared dairy and beef grassland in the Imp-Beef + Trees and H-Beef + Trees
311 scenarios could reduce net emissions arising in the UK by approximately 0.46 kg CO₂e per kg of
312 shifting milk production (28% of baseline emissions from milk and beef production; Fig. 4). For Imp-
313 Beef + Trees, that is significantly less than the 0.72 kg CO₂e increase in emissions arising in the RoW
314 inventory, so that overall GHG emissions arising from dairy and beef production still increase by 16%
315 – ranging from a saving of 26% to an increase of 100% depending on the intensity of replacement
316 beef production in Brazil and the iLUC factor applied (Fig. 3b).

317

318 **Discussion**

319 *Evaluating sustainable intensification*

320 For the first time, we applied consequential life cycle assessment to account for the suite of direct
321 and indirect factors contributing to the GHG mitigation efficacy of widespread dairy farm
322 consolidation and intensification. Dairy intensification can reduce simple milk footprints by
323 increasing animal productivity and feed conversion efficiency, although life cycle assessment has
324 already been applied to show that carbon loss following conversion of grassland to forage maize
325 production can offset these carbon footprint savings (Van Middelaar et al., 2013; Vellinga & Hoving,
326 2011). Recent studies have shown that land sparing from suckler beef intensification can achieve
327 significant GHG mitigation (Cohn et al., 2014; deOliveira Silva et al., 2016; Herrero et al., 2016), but
328 our results demonstrate that intensification of dairy production does not necessarily translate into
329 the same land sparing advantages owing to complex interlinkages with beef production and
330 teleconnections with global beef and feed production. Specifically, indirect land use change
331 associated with increased demand for concentrate feed, plus additional suckler-beef production
332 required to replace reduced dairy-beef output, can significantly increase land occupation and GHG
333 emissions following intensification. Dairy farms are inherently dual-purpose systems, producing milk
334 and calves for rearing. Optimisation therefore needs to consider consequences of changes in both of
335 these outputs, rather than allocating away the relatively small (on a mass or energy basis) calf live-
336 weight outputs.

337

338 Wide uncertainty ranges around our results highlight sensitivities to uncertain indirect effects, and
339 emphasise the lower precision of consequential LCA compared with footprints calculated using
340 attributional LCA. In agreement with proponents of consequential LCA (Ekvall & Weidema, 2004;
341 Weidema & Schmidt, 2010), we contend that this loss of precision more accurately represents the

342 wide range of outcomes associated with intensification transitions, and provides valuable new
343 insight to stakeholders on the sustainability of these transitions.

344

345 Use of spared grassland

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

360

361 Limitations and future work

362 Large GHG emission ranges (Fig. 3b) highlight uncertainties involved in predicting indirect GHG
363 consequences of dairy intensification, especially where there are interactions between beef
364 displacement and iLUC effects that occur via cascades of consequence following market

365 perturbations (Persson et al., 2014). Full accounting of indirect consequences arising from dairy
366 intensification within the consequential LCA framework would require regional to global scale
367 economic modelling of effects on trade in animal feed, milk and beef commodities linked to price
368 signals and possibly also changing consumer (dietary) preferences (Westhoek et al., 2014). Here, we
369 employed a simplified approach assuming 1:1 replacement of displaced food and feed commodities,
370 analogous to bioenergy iLUC modelling applied in previous studies (Vázquez-Rowe et al. 2014; Tonini
371 et al. 2012; Styles et al. 2015b). Our mid-case iLUC estimate for concentrate feed (Overmars et al.,
372 2011) is based on historic rates of LUC (Overmars et al., 2015) that have been ameliorated by
373 intensification of crop production, highlighting the difficulty of untangling effects of intensification in
374 one sector from intensification in another, which may be occurring independently. Nonetheless,
375 attempting to separate out some of these effects does provide unique insight into the relative GHG
376 mitigation efficacy of specific mechanisms associated with different pathways of dairy
377 intensification.

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

385 We used farm models parameterised using UK statistics for average and intensive farms, followed by
386 economic optimisation. Important factors such as grass uptake efficiency and nutrient management
387 planning vary considerably across farms, and may differ from performance predicted by economic
388 optimisation. Default IPCC Tier 1 emission factors may underestimate possible non-linear increases

389 in soil N₂O emissions as dairy and beef farms intensify. There remains a need to parameterise
390 detailed dairy farm models required to evaluate specific mitigation measures (Del Prado et al., 2013)
391 using statistics for exiting and expanding dairy farms, and to couple these with economic trade
392 models, in order to integrate important effects at farm-, regional- and global-scales, and therefore
393 more accurately predict the net GHG mitigation efficacy of dairy intensification pathways. It will also
394 be important to consider additional environmental impact categories and ecosystem services
395 delivery, which could be strongly influenced by the wider land use implications of dairy
396 intensification.

397 Recommendations

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

407

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412

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575

576 **Tables**577 **Table 1. Factors considered in milk footprints (attributional LCA) and consequential LCA, including**
578 **direct land use change (dLUC) and indirect land use change (iLUC).**

	Upstream emissions	Farm emissions	dLUC grass-to-maize*	iLUC from additional concentrate feed crops*	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
<p>*Milk footprints are calculated with and without dLUC attributed to additional maize demand.</p> <p>*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.</p>							

579

580

581 **Table 2. Characteristics of average and intensive dairy farm typologies responsible for milk**
 582 **production before and after intensification, respectively**

	Units	Average dairy farm	Intensive dairy farm
Milking cows	Head	142	481
Milk yield per cow	kg yr ⁻¹	7 124	8 626
Replacement rate	% yr ⁻¹	27	31
Farm area	Ha	85	250
Grazing days	Days yr ⁻¹	183	56
Outputs			
Milk	kg yr ⁻¹	1 013 548	4 149 102
Exported calves	Head yr ⁻¹	90	287
Culled cow live weight	kg yr ⁻¹	22 578	88 023

583 **Table 3. Inventory of key inputs and outputs on average dairy farms, representing the baseline**
 584 **situation, and on an intensive dairy farm, representing the intensification scenario, expressed per**
 585 **kg of milk produced**

	Parameter	Units	Average dairy farm	Intensive dairy farm	
Inputs	Concentrate feed		165	234	
	Imported hay		11.5	4.6	
	Fertiliser-N app.	g kg ⁻¹ milk	14.9	4.5	
	Fertiliser-P ₂ O ₅ app.		2.1	2.3	
	Fertiliser-K ₂ O app.		0.0	1.7	
	Lime app.		28.9	26.8	
	Other agrochems		0.12	0.48	
	Electricity (MJ)		kJ kg ⁻¹ milk	11.99	11.27
	Heating oil (MJ)			6.00	5.64
	Diesel (MJ)	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 volatilisation		6.4	7.8	
	N leaching		2.5	0.9	
	Soil & manure N ₂ O		0.75	0.47	
	P leaching		0.15	0.12	

586 **Table 4. Scenarios representing possible consequences of dairy farm intensification, for which GHG fluxes were quantified using consequential life cycle**
 587 **assessment.**

Scenario	Primary consequences		Secondary consequences	
	Dairy feed	Use of net spared ex-dairy grassland	Displaced beef production	Land use change
M-Beef (medium-intensity replacement)	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)	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* 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).

<p>H-Beef+Trees (high-intensity replacement beef plus</p>	<p>Additional maize (grassland conversion, UK) & concentrate feed demand</p>	<p>High-intensity rearing of as much suckler beef as possible (UK).</p>	<p>Extensive* beef production shifts to intensive beef production on ex-dairy grassland (UK).</p>	<p>Concentrate feed demand drives cascade of crop displacement culminating in cropland expansion (RoW). Afforestation on grassland previously used for extensive beef production (UK).</p>
<p>Imp-Beef (replacement beef imported**)</p>	<p>Additional maize (grassland conversion, UK) & concentrate feed demand</p>	<p>Fallow (UK).</p>	<p>Expansion of beef production in Brazil (varying intensities) for export</p>	<p>Concentrate feed demand drives cascade of crop displacement culminating in cropland expansion (RoW). Expansion of grassland into forest in Brazil.</p>
<p>Imp-Beef+Trees (replacement beef imported**, plus afforestation)</p>	<p>Additional maize (grassland conversion, UK) & concentrate feed demand</p>	<p>Afforestation of entire spared grassland area (UK).</p>	<p>Expansion of beef production in Brazil (varying intensities) for export</p>	<p>Concentrate feed demand drives cascade of crop displacement culminating in cropland expansion (RoW). Expansion of grassland into forest in Brazil.</p>
<p>M-MaxBeef (Medium-intensity rearing of replacement plus additional</p>	<p>Additional maize (grassland conversion, UK) & concentrate feed demand</p>	<p>Medium-intensity rearing of as much suckler beef as possible over entire area (UK).</p>	<p>Avoided expansion of beef production in Brazil (varying intensities) for export</p>	<p>Concentrate feed demand drives cascade of crop displacement culminating in cropland expansion (RoW). Avoided expansion of grassland into forest in Brazil.</p>
<p>H-MaxBeef High-intensity rearing of replacement plus additional suckler</p>	<p>Additional maize (grassland conversion, UK) & concentrate feed demand</p>	<p>High-intensity rearing of as much suckler beef as possible over entire area (UK).</p>	<p>Avoided expansion of beef production in Brazil (varying intensities) for export</p>	<p>Concentrate feed demand drives cascade of crop displacement culminating in cropland expansion (RoW). Avoided expansion of grassland into forest in Brazil.</p>
<p style="text-align: center;">**"Extensive" = low- or medium-intensity suckler beef production (Table S3.2).</p> <p>**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).</p>				

588 **Table 5. Land areas (in m²) 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**
 589 **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					Overall			Total area	Change from baseline
	Grass	Maize	Concentrate	Grass	Maize	Concentrate	Grass-UK	Grass-Brazil	Maize	Concentrate	Afforestation	Grass	Maize	Concentrate		
	m ² .yr 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%

*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.

590

591 **Figure captions**

592

593 **Fig.1. Conceptual representation of major factors affecting GHG emissions at the product (carbon**
594 **footprint), national inventory and global scales following transitions towards dairy cattle diets**
595 **containing a higher proportion of concentrate feed and a lower proportion of grass.**

596

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

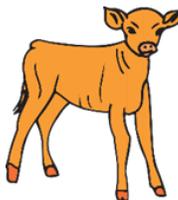
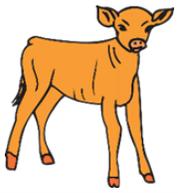
601

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

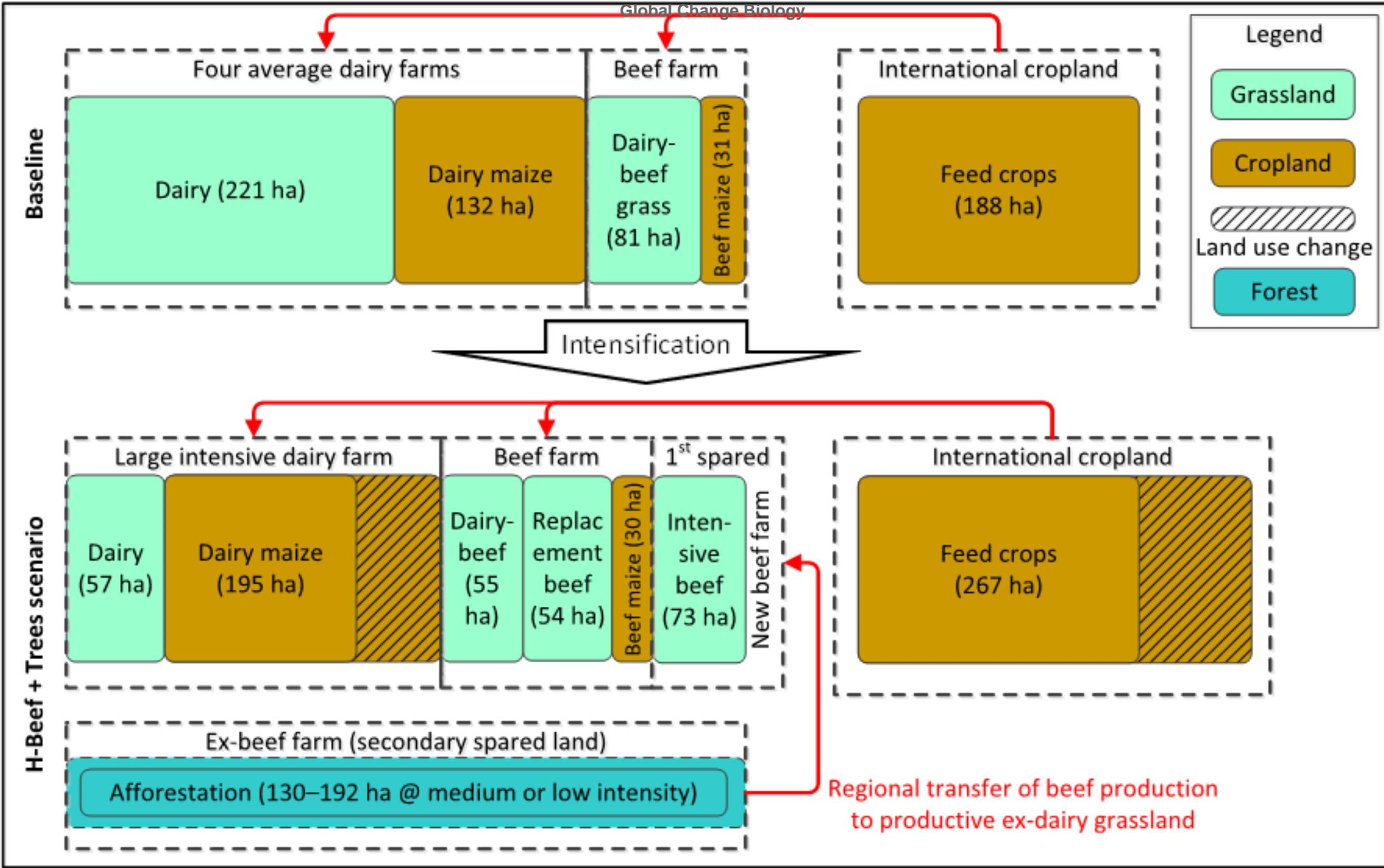
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607 **Fig. 4. GHG emission changes for each dairy intensification scenario partitioned according to**
608 **national and rest-of-world GHG inventories, and expressed as a percentage of baseline emissions**
609 **arising from the production of reference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

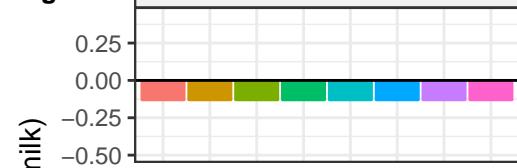
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Factor trend	Milk footprint (per kg milk, life cycle basis)	National GHG Inventory (all sectors)	Rest-of-world GHG Inventory (all sectors)
Milk from maize increasing 	↓Reduced enteric CH ₄ ↓Higher yield per cow ↑Crop production (↑Cropland expansion) 	↓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 	

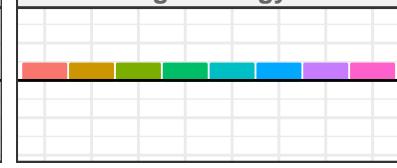
N_{ex}=N excretion; Green=positive effect (reduces footprint); red=negative effect (increases footprint); amber=uncertain net effect.



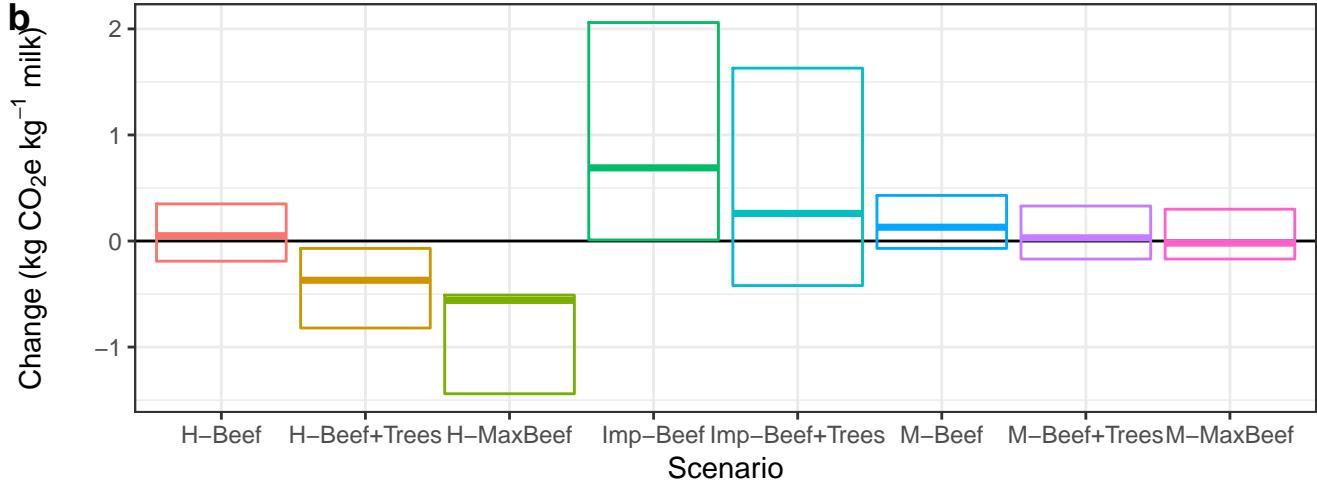
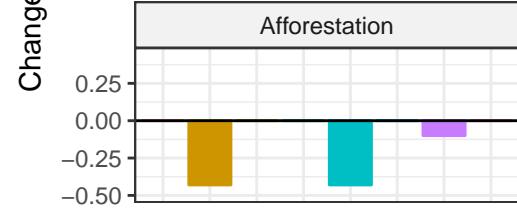
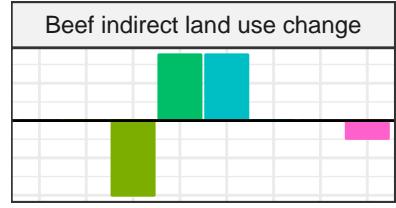
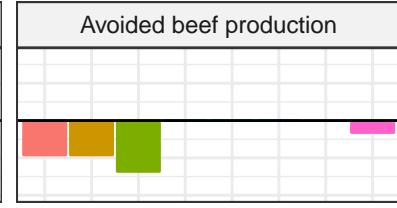
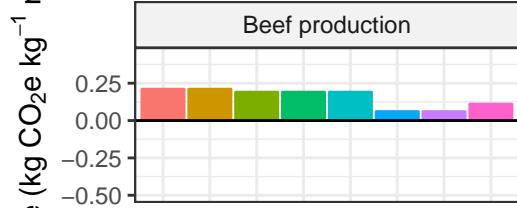
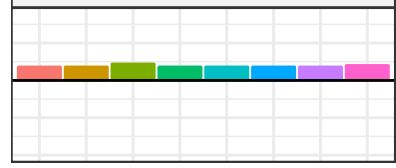
Farm carbon footprint



Maize direct land use change

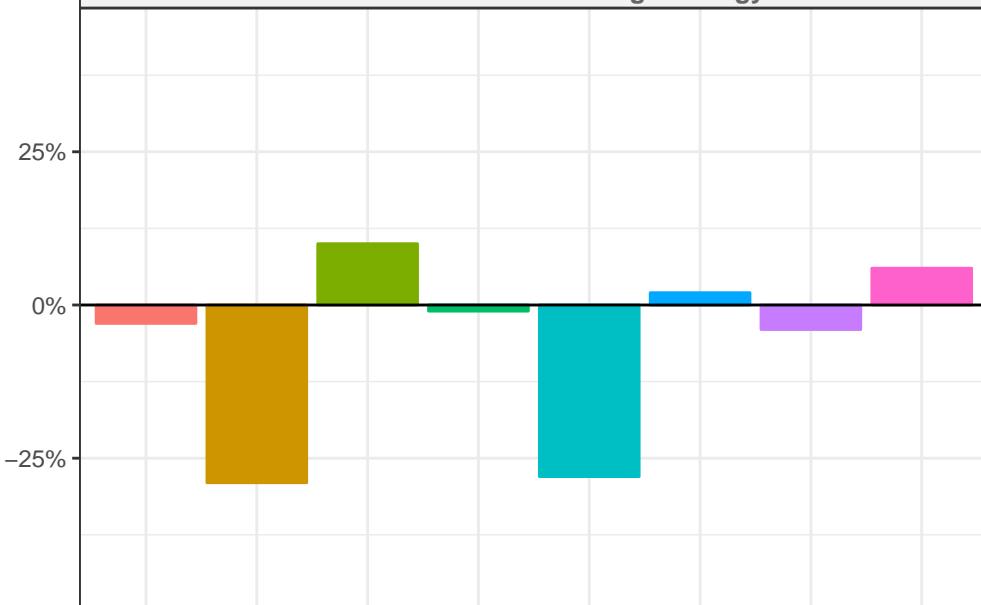


Feed indirect land use change

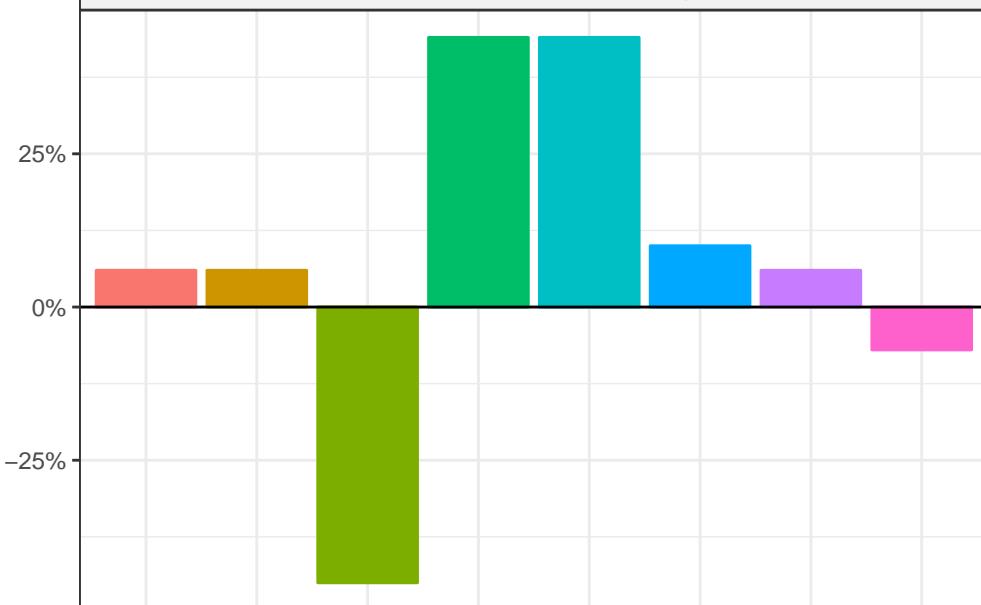


National carbon inventory (UK)

Global Change Biology



Rest of world carbon inventory



Scenario

- H-Beef
- H-Beef+Trees
- H-MaxBeef
- Imp-Beef
- Imp-Beef+Trees
- M-Beef
- M-Beef+Trees
- M-MaxBeef

Change