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Diversification not specialization reduces global and local environmental burdens from livestock production

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ABSTRACT

Milk and beef production generates environmental burdens globally and locally. Across many regions a typical dairy intensification pathway is for dairy farms to specialize on milk production and reduce the co-production of beef (i.e. 'dairy-beef'). Dairy-beef thus reduces and beef needs to be produced elsewhere if beef production is to be maintained. Life Cycle Assessment (LCA) studies quantifying the environmental implications of dairy and beef production have largely focused on the farm level and not captured system connections. Further LCA work has generally represented the 'average' farm of a region, consequently ignoring the range in farm management observed in practice and few studies consider a range of LCA environmental footprints other than carbon footprints. For the first time, we present comprehensive LCA results for multiple environmental burdens based on a large panel dataset for commercial dairy and suckler-beef farms. We present a 15-year LCA assessment of a total of 738 dairy (3624 data points in 15 years) and 1887 suckler-beef (10,340 data points in 15 years) UK farms for five major LCA footprints. We also explore the footprint implications of compensating for reduced dairy-beef through producing this 'displaced' beef on suckler-beef farms. We found a substantial variation in farm footprints not captured in 'average farm' studies. Dairy-beef was much more efficient than beef produced on suckler-beef farms in terms of footprints per unit of beef output. Reducing dairy-beef and replacing it on a suckler-beef farm generally significantly increased environmental burdens. A reduction in carbon footprint was also associated with a reduction in other burdens suggesting no trade-off between local and global emissions. Increasing dairy farm diversification via higher dairy-beef output per unit of milk reduced burdens by up to 11–56%, on average, depending on burden and sensitivity run. We conclude that overspecialization of dairy farms in milk production increases the combined burdens from beef and milk, and that more intensive beef systems that make more efficient use of forage land play a crucial role in mitigating these burdens.

1. Introduction

Global demand for milk and meat products is projected to increase significantly in the forthcoming decades (Alexandratos and Bruinsma, 2012). In order to keep up with demand, dairy and beef farms have achieved notable increases in production intensity measured as output (mass of milk or meat) per animal and per farming area (Domingues et al., 2018; Gonzalez-Mejia et al., 2018; Puillet et al., 2014). However, farming for milk and beef generates substantial environmental burdens both globally (e.g. global warming, non-renewable energy use) and locally (e.g. eutrophication, acidification; Guerci et al., 2013; Modernel et al., 2013). Although increased dairy farming intensity can reduce environmental footprints per unit of milk, the lower number of cows needed to maintain- or increase- milk production levels has displaced beef production from dairy farms on to specialized beef farms. A consequence is that total environmental burdens arising from the separated dairy and beef farms may in fact be higher than if beef production levels were maintained on the dairy farm (Zehetmeier et al., 2012).

A conceptual framework of the interconnectedness between milk and beef production is illustrated in Fig. 1. Dairy farm 1 represents a typical situation observed on many commercial dairy farms whereby dairy and beef production are co-produced, thus surplus calves are transferred out of the dairy enterprise and into an adjacent beef enterprise for beef production (Styles et al., 2018). Dairy farm 1 is more 'diversified' in that it produces beef that comes from either its dairy enterprise (from cull dairy cows) or the beef enterprise (from fattened

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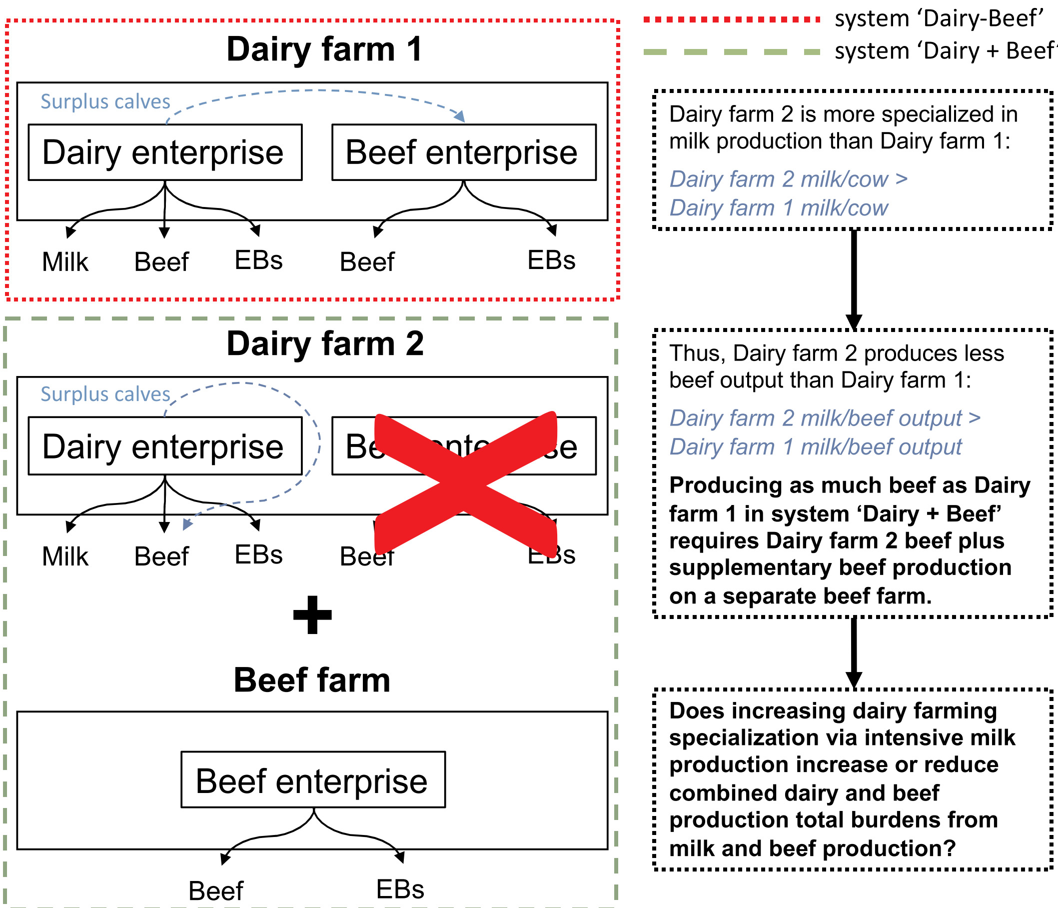

Fig. 1. Conceptual framework on which this study was based. LWG: live weight gain; EBs: environmental burdens.

surplus dairy animals).[1] In contrast, dairy farm 2 is 'specialized' in intensive milk production by increasing milk yields per cow, and exporting all surplus dairy calves for slaughter at weaning, thus producing significantly less beef (Fig. 1). Given high and increasing demand for beef (Alexandratos and Bruinsma, 2012), the shortfall in beef production must be compensated for by 'displaced' production on a separate beef farm (system 'Dairy + Beef' in Fig. 1). Because dairy farms 1 and 2 and the beef farm all generate environmental burdens (Fig. 1), the question is whether dairy farm 1 (system 'Dairy-Beef' in (Fig. 1) aggregate environmental burdens are lower or higher than Dairy + Beef aggregate burdens per unit of product. In other words, does increasing dairy farming specialization via intensive milk production increase or reduce 'inter-system-level' (i.e. combined dairy and beef production) total burdens from milk and beef production?

This close relationship between milk and beef production has been the subject of numerous studies quantifying the environmental impacts of compensating for beef no longer produced on the dairy farm (see Styles et al., 2018; Vellinga and de Vries, 2018). These studies clearly demonstrate the influence that beef production can have on environmental footprints (i) on the dairy farm (Vellinga and de Vries, 2018); and (ii) globally, through land use change, as a greater area of land for beef production would be required to counterbalance reduced dairy-beef production (Styles et al., 2018).

Most of these studies are confined to a single indicator of environmental performance, typically the carbon footprint, i.e. the sum of greenhouse gas emissions from different farming activities and/or from land use change. The carbon footprint primarily concerns pollution at a global scale. Additional indicators are needed to fully assess the environmental performance of milk and beef production from the dairy farm; and to capture environmental impacts that are more relevant at the local scale (Modernel et al., 2013; Soteriades et al., 2018). Life cycle assessment (LCA) is a methodology that can be used in such a manner to estimate whole-system resource use and environmental impacts, beyond carbon footprints (Ledgard et al., 2003).

Comprehensive studies face the difficulty of obtaining sufficiently detailed data for an adequately large set of commercial farms and over extended time periods. Generally, studies either consider a small number of farm scenarios representing 'typical' systems (e.g. Styles et al., 2018; Zehetmeier et al., 2012) or base their analysis on a few real farms (e.g. Flysjö et al., 2012 studied 23 farms). In addition, the environmental footprint intensities of beef produced on a beef farm that would compensate for lower beef output from the dairy farm are typically assumed to be those of a 'representative' European or North American beef system (Styles et al., 2018; Vellinga and de Vries, 2018). The wide range of environmental footprint intensities and farm management efficiency of commercial dairy farms over time is therefore left unaccounted for, an issue that can be resolved with the use of commercial farm panel data (Gonzalez-Mejia et al., 2018).

For the first time, we develop and apply a method to estimate the environmental footprint for a large 15-year panel dataset containing thousands of data points and estimate the implications of displacing beef output from dairy farms to beef farms (Fig. 1). The second major contribution of our study is the reporting of several important local and global LCA burdens for the whole panel dataset.

[1] We define 'diversification' according to Summer and Wolf (2002, p. 447), i.e. '[…] the presence of multiple production enterprises with distinct marketed outputs in a single management unit'.

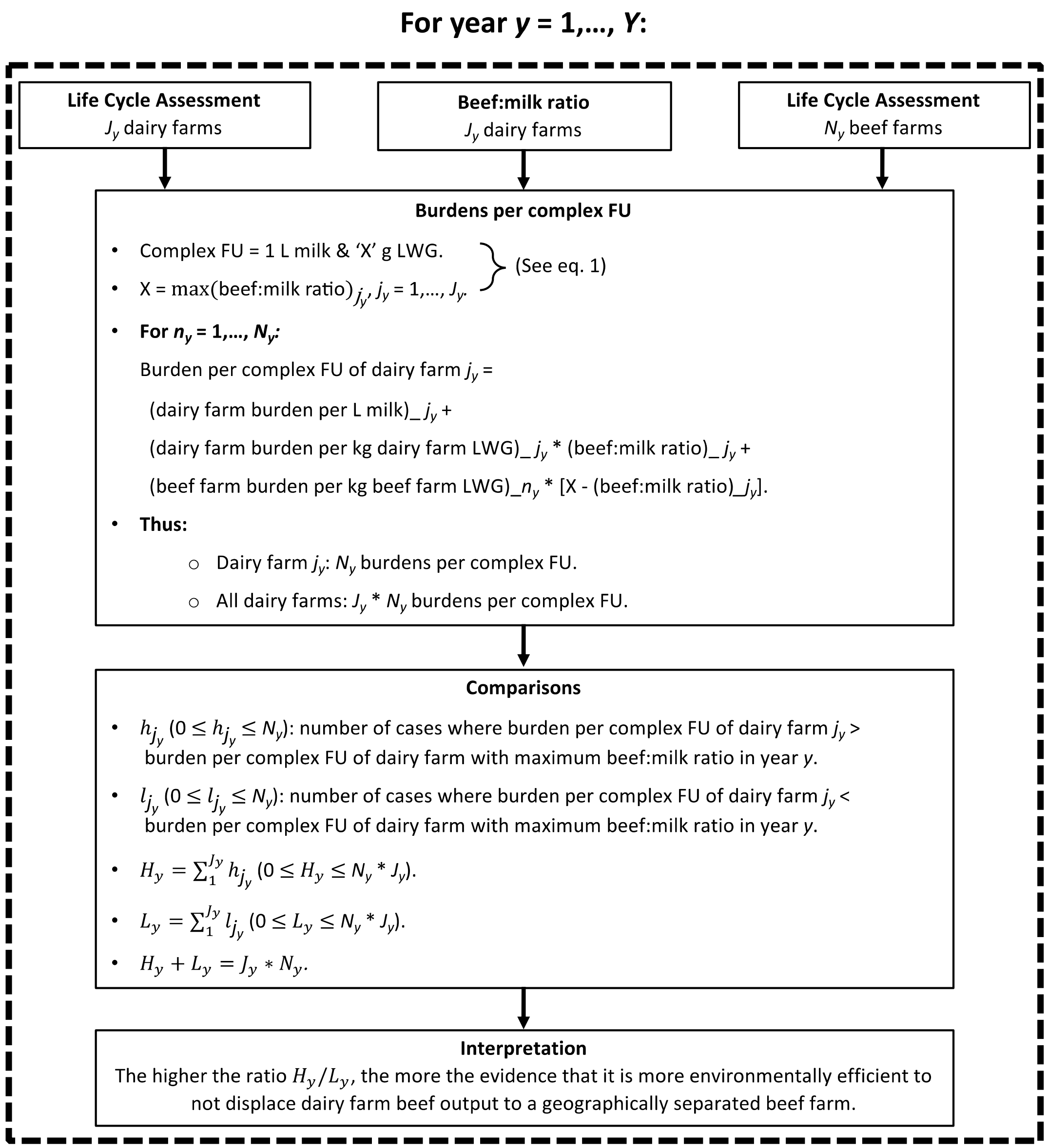

Fig. 2. Algorithm to assess the effects that intensifying milk production can have on inter-system-level burdens. FU: functional unit; LWG: live weight gain.

2. Material and methods

2.1. Putting the conceptual framework into effect

2.1.1. Primary approach

The main approach was to assess environmental footprints at the 'inter-system-level' (i.e. total dairy and beef production; Dairy-Beef versus Dairy + Beef in Fig. 1) when lower dairy-beef output (i.e. live weight gain; LWG; see McAuliffe et al., 2018; Ruviaro et al., 2015) from an intensified dairy farm is necessarily compensated by beef produced on a geographically separated beef farm (see Introduction and Fig. 1). This is based on the logic that total demand for beef is considerably higher than dairy-beef supply (Nguyen et al., 2010). Our conceptual framework (Fig. 1) represents two extreme cases:

- Diversified dairy farms containing both dairy and dairy-beef enterprises, (dairy farm 1 in Fig. 1), with milk and beef burdens largely attributable to the same farm.
- Specialized dairy farms containing an intensive dairy enterprise (dairy farm 2 + beef farm in Fig. 1), with beef burdens largely attributable to 'displaced' beef produced on separate beef farms, which we consider to be suckler-beef farms for the purposes of conceptual clarity (Styles et al., 2018) – discussed later.

In reality, actual dairy farms are on a continuum between the two extremes. This calls for an accounting approach that represents the quantities of milk and beef produced on dairy farms, considering coupled beef enterprises. A recent study (Vellinga and de Vries, 2018) recommends calculating the beef:milk ratio for individual dairy farms. This ratio indicates the level of a dairy farm's milk specialization: the lower it is, the more milk-intensive the farm is, so it forgoes a larger amount of beef output. When comparing dairy farm efficiency across a population of farms, one way to look at this is to take the maximum beef:milk ratio from that population, and consider that the quantity of beef production below this ratio for individual farms must be compensated for on a separate suckler-beef farm.

Vellinga and de Vries (2018) recommend expressing burdens for a functional unit (FU) that represents a fixed volume of milk and beef output. Following their approach, we here define this complex FU as:

$$1\text{ L milk and } X \text{ g of LWG} \tag{1}$$

where X represents the maximum beef:milk ratio across dairy farms within a given year (see Results and Vellinga and de Vries, 2018). The inter-system-level environmental footprints were evaluated based on this complex FU, which is based on LCA boundary expansion to satisfy milk and beef demand. System expansion using this complex FU is essential because allocation of dairy farm system burdens across milk and meat products, based on e.g. energy content, economic value or protein content, is based upon a truncation of system boundaries in a manner that does not capture the important inter-system effects we elaborate in this paper.

This method makes three major assumptions:

1. The quality of meat is the same for dairy and beef breeds. This is further discussed in Section 4.3.
2. Beef production displaced from dairy farms is equally likely to be drawn from any UK suckler-beef farm. This can be justified on the grounds that the decline in dairy production and cow numbers has been highest in areas more marginal for dairy production- drier areas where grass production is low or more upland areas. In these locations, other cattle numbers have increased, suggesting that there is a substitution of beef for dairy production (Defra, 2009).
3. A kilogram of displaced dairy-beef will be provided by additional beef production sourced elsewhere in the UK. This assumption of domestic substitution is justifiable on the basis of UK milk and beef production trends: milk production has declined very gradually since 2001, while total beef production has increased gradually since 1996 (FAOSTAT, 2019).

2.1.2. An algorithm for applying the conceptual framework in practice

Our approach involved two separate LCA exercises, for the (i) dairy farms; and (ii) beef farms. Because our dataset contained thousands of dairy farms (J dairy farms) as well as thousands of beef farms (N beef farms), we ran J LCAs for the dairy farms and N LCAs for the beef farms. We assessed the effects that intensifying milk production can have on inter-system-level burdens per complex FU within each year of the study period. Fig. 2 describes the algorithm that was developed to assess these effects. As illustrated in Fig. 2, the algorithm accounted for the variation in environmental efficiencies observed in real beef farms that is not captured in scenario studies assuming average environmental efficiencies of beef farms (Styles et al., 2018; Vellinga and de Vries, 2018).

The algorithm can be better understood through a series of simple illustrative examples presented in the Supplementary Material. Examples S1–S2 use a limited number of farms and a single beef farm. They thus resemble typical scenario-based exercises where only one, 'representative' beef farm is used to calculate burdens per complex FU for a few 'representative' dairy farm scenarios with different milk production intensities (Styles et al., 2018; Vellinga and de Vries, 2018). Based on such few data, it is challenging to determine whether intensifying milk production increases or reduces burdens per complex FU at the inter-system-level. In addition, scenario-based exercises assume a fixed amount of burden per beef output for the beef farm. This amount is likely to vary between commercial beef farms.

By contrast, Example S3 expands Examples S1–S2 to cases where there are multiple dairy farms and multiple beef farms. Thus, for each dairy farm, each beef-farm serves as a permutation for calculating burdens per complex FU (Fig. 2; Table S1). Depending on the beef farm, the burdens per complex FU of a dairy farm may be higher or lower than of the dairy farm with the maximum beef:milk ratio. We could not possibly expect all burdens per complex FU to be higher (or lower) because there is a large range of beef farms in our sample that cannot be captured by a 'representative' beef farm. But when they are higher for the majority of cases, we may conclude that, on the one hand, displacing beef generally increases burdens and, on the other hand, that there may be a few cases where displacing beef to a beef farm could actually reduce inter-system-level burdens per complex FU.

Finally, note that we carried out the analysis on an annual basis, i.e. the farm with the maximum beef:milk ratio is different in each year. We have chosen to use year-specific benchmarks to explicitly acknowledge that farm structure and technology change over time- it may be inappropriate to benchmark farms against a farm from an earlier or a later year.

2.1.3. Sensitivity analysis and statistical modelling

We explore the sensitivity of the results to the benchmark beef:milk ratio using the algorithm described in Section 2.1.2 and Fig. 2, in particular to define the benchmark farm as the average of a selected population of farms with the highest beef:milk ratios. We therefore performed the following sensitivity analysis on the algorithm of Fig. 2: We replaced the maximum beef:milk ratio across the whole farm population in each year by the average of the top-'x%' of farms in terms of beef:milk ratio in that year, where 'x%' took the values 2.5, 5 and 10%.

While we carry out the core analysis at the national level as we are primarily interested in dairy and beef production in aggregate we also explore regional effects. Specifically, we quantified the environmental implications of diversifying dairy farming by fitting five sets of robust regression models (robust regression is less sensitive to outliers than parametric linear regression; Venables and Ripley, 2002) where each of the five burdens per complex FU was regressed against the beef:milk ratio. For the data generated from the original algorithm (Fig. 2), each regression equation also included (i) a 'region' control variable; (ii) a 'region-beef:milk ratio' interaction term to capture regional effects on the dependent variable; and (iii) year dummy variables, to increase the degrees of freedom and consequently improve the estimated regression coefficients. The region variable and interaction term allowed for a variable intercept and slope respectively, so that any region effects were explicitly accounted for. In this analysis the farms were weighted in the regression models by their 'size', namely their milk production.

For the data generated from the sensitivity analysis (see previous paragraph), the regression did not include the region control variable and interaction term, because the top-'x%' of farms were from more than one region (i.e. averaging these farms creates a 'synthetic' benchmark farm that belongs to no region). The two sets of regression models can thus be seen as complementary ways of addressing this methodological trade-off ('extreme' benchmark farms, region included in the regressions versus mean of benchmark farms, region not included in the regression).

2.1.4. 'Virtual' beef farms and their intensity profiles

Based on the algorithm in Fig. 2, intensity profiles were created for the beef farms that determine the 'Higher' and 'Lower' categories of Table S1 (see previous sub-subsection and Section S1). However, as Table S1 shows, the same beef farm could contribute to both categories ('Higher' or 'Lower'), for example beef farm B2, where we get a 'Lower' for dairy farm D2 and a 'Higher' for D3. Since the same beef farm can belong to both categories, the intensity profiles were based on two groups of 'virtual' beef farms where the variables of interest were averaged over all 'Higher' or 'Lower' occurrences. For instance, choosing the stocking rate as an intensity variable, the average stocking rates for each group of 'virtual' beef farms is (based on Table S1): SR of 'Higher' group = (SR_B1 + SR_B1 + SR_B2 + SR_B3 + SR_B3 + SR_B4 + SR_B4)/7 SR of 'Lower' group = SR_B2.

We used the following variables to create intensity profiles for the 'virtual' beef farms at the animal- and farm-levels: stocking rate ($LU\ ha^{-1}$); concentrate use (t dry matter LU^{-1}); animal-level beef production ($kg\ LWG\ LU^{-1}$); farm-level beef production ($kg\ LWG\ ha^{-1}$); on-farm area (ha); and off-farm area (ha). We tested for significant differences between 'virtual' beef farms in terms of the intensity variables using the Mann-Whitney test (Conover, 1999).

2.2. Data

2.2.1. Farm business survey data

The Farm Business Survey (FBS) is a comprehensive source of business information from farms in England and Wales. The survey provides information on the financial position and physical and economic performance of farm businesses for each year of the survey (FBS, 2018a). We used data from 15 annual surveys spanning the period 2001/02–2015/16. These 15 datasets are available under special license from the UK Data Service (2018) and described in detail in Gonzalez-Mejia et al. (2018) and Parsons and Williams (2015).

The FBS variables (FBS, 2018b) used include farm area (grazing; grass silage; maize silage), number of animals in each enterprise (Dairy; Other Cattle; Sheep, Pigs, Poultry and Other Livestock) and cohort (dairy/beef calves, heifers, cows and bulls; other male/female beef cattle < 1y, 1–2y and > 2y, etc.), concentrate and fertilizer costs and milk production.

We defined a 'dairy farm' as a farm with at least 10 dairy cows producing between 4000 and 15,000 L of milk yr^{-1} per cow. A large proportion of dairy farms had several enterprises other than 'Dairy'. The dairy (dairy cows, calves, heifers and bulls) and beef (i.e. 'Other Cattle': surplus calves, bulls and heifers) enterprises were separated out by apportionment of main farm variables (grazing and silage areas; and concentrate costs) to the dairy and beef enterprises only, based on the number of dairy and beef livestock units (LU) as a proportion of all LU on the farm (for LU equivalents consistent with the FBS cohorts see Redman, 2017, p. 89). A similar process was followed for beef farms, based on the proportion of beef LUs only.

We assumed that the dairy and beef animals consumed three forage types produced on the farm: grazed grass, grass silage and maize silage. This assumption is consistent with published information on UK dairy and beef farm forage sources (Brown et al., 2017) and was supported by the fact that the vast majority of the studied farms had zero entries for other forages and crops such as hay and barley.

Concentrate costs were converted into amount of concentrate used on the farm based on historical price data for standard concentrates (AHDB Dairy, 2018). Similarly, fertilizer costs were converted into volumes based on historical price data for nitrogen (N), phosphorous (P) and potash (K) fertilisers (AHDB Dairy, 2017) and on N:P:K ratios for grasslands and forage crops taken from UK fertilizer recommendations (AHDB, 2017).

The dataset contained 2021 unique beef farms of several distinct systems (FBS, 2016) of which 1887 (or 10,340 data points over 15 years) were 'suckler-beef' systems. Given the lack of sufficient coverage of other beef farm types over the 15-year period, we considered the 1887 suckler-beef farms only. Suckler-beef farms are quite prevalent in the UK and Northern Europe, as they are responsible for about 70% of EU beef production (AHDB Beef and Lamb, 2016; Nguyen et al., 2010; Weidema et al., 2008). Suckler-beef farms are semi-extensive systems (summer grazing and indoor feeding with silages and concentrates in the winter) in which the beef is produced from the suckler cow and its offspring (bull or heifer calves for meat and/or replacement; Nguyen et al., 2010). Studies comparing the environmental efficiency of dairy-beef systems with dedicated beef systems, or measuring the impacts of compensating for reduced dairy-beef production, typically consider that the beef farm is a suckler-beef system, because non-dairy-beef must be reared by dedicated beef breeding animals (Nguyen et al., 2010; Styles et al., 2018; Vellinga and de Vries, 2018).

The dataset contained 1316 unique dairy farms with several distinct types of adjacent beef enterprises (FBS, 2016). We considered only dairy farms with a 'dairy followers' adjacent beef enterprise, i.e. 738 dairy farms (or 3624 data points over 15 years). This means that the selected diversified farms are those where beef production is sourced from surplus dairy animals, rather than representing a co-located suckler-beef system.

2.2.2. Cattle data

Assumptions were made for dairy and beef cattle variables that were not available in the FBS dataset. These variables (see Section S1) included: number of days an animal spent in its cohort in one year; body weight (initial and final); and average daily gain (assumed constant for the entire period for each animal cohort; Modernel et al., 2013). Animals' nutritional requirements were estimated using standard equations (AFRC, 1993; NRC, 2001). These variables were also used in conjunction with the number of animals in each cohort to calculate the total gained output (LWG) from each farm in each year.

Using the nutritional requirements, the amounts of forages and concentrates required to fulfil those requirements were calculated, based on published information on the feeds' nutritional characteristics (Brown et al., 2017; NRC, 2001; Redman, 2017), on typical rates of concentrate consumption per animal and cohort (Section S.2.1) and on average dry matter yields of forage crops (Qi et al., 2017; Redman, 2017). The full process is described in Section S.2.2. The advantage of our method is that we used partial (i.e. average) published data and partial FBS information (i.e. area data) to create *farm-specific* estimates of the amounts of forages used on each farm.

2.3. Life cycle assessment

We performed an attributional LCA in accordance with ISO principles (ISO, 2006), accounting for upstream impacts associated with the production and transport of inputs and all major animal, manure management and field emissions on the dairy and suckler-beef farms (Styles et al., 2015). The functional units were (i) one L milk (dairy farms); (ii) one kg LWG exported from the farm gate (dairy and beef farms); and (iii) the complex FU defined earlier (dairy farms), i.e. 1 L milk and a fixed amount of LWG (see Eq. (1)). For dairy farms, farm system burdens were allocated to milk and LWG based on the respective gross energy outputs of milk and animal LWG.[2] No allocation was necessary when burdens were expressed per unit of complex FU.

The environmental footprint of dairy and beef production was quantified in terms of global warming potential (GWP, kg CO_2 equivalents; eq.), eutrophication potential (EP, g PO_4 eq., g = 10^{-3} kg), acidification potential (AP, g SO_2 eq.), fossil resource depletion potential (RDP, MJ eq., MJ = 10^6 J) and land occupation (LO, m^2). These five indicators represent significant environmental burdens from livestock farming on land, air and waters, largely owing to CH_4, NH_3 and N_2O emissions, nutrient leaching and the use of non-renewable resources and land (Steinfeld et al., 2006). We expressed GWP, EP, AP, RDP and LO in the following units, based on the CML methodology (CML, 2017; Guinée et al., 2002): kg CO_2 equivalents (eq.), g PO_4 eq., g SO_2 eq., MJ eq. and m^2 land, respectively.

The method largely followed the LCA of Soteriades et al. (2018), with the following differences:

1. We estimated enteric methane emissions, volatile solids and N excretion using IPCC Tier 2 equations (IPCC, 2006) directly, rather than obtaining these estimates from simulation modelling (Van Amburgh et al., 2015).
2. We used the recently revised N_2O-N emission factor applied to N

[2] Where system separation or expansion is not possible, the ISO 14040 standard recommends allocation based on physical flows, such as energy. Moreover, energy-based allocation is a common approach in LCA, and one the objectives of this paper is to show how common footprint approaches do not necessarily generate reliable results when assessing the environmental efficiency of dairy intensification. Methodological developments in allocation procedures, such as biophysical allocation of farm burdens (Thoma et al., 2013), improve the accuracy of *dairy system* burden allocation between milk and beef production. But ultimately such approaches do not address the need to expand system boundaries to capture important downstream effects on beef production, which is the primary point of our paper.

excreted during grazing (0.0044 kg kg^{-1}); and N_2O-N factor applied to ammonium-nitrate fertilizer spread on grassland (0.013 kg kg^{-1}), that more accurately represent UK national greenhouse gas accounting (Brown et al., 2017).
3. We assumed that the proportion of ME from grazed grass was an approximation of the time animals spent grazing. In this way, we approximated the amount of manure stored and spread instead of being deposited directly on the field during grazing.

Because manure storage and spreading can contribute considerably to ammonia (NH_3) and nitrous oxide (N_2O) emissions, as well as to eutrophication and acidification, we considered six permutations of manure management practices (three manure storage types and two manure spreading methods) observed in commercial UK farms (see Soteriades et al., 2018). Because interpretations were similar under all six permutations, we only report results for a single one: tank without crust cover, trailing shoe.

2.4. Software

All calculations were performed in the R programming language (R Core Team, 2018). Visualizations were performed with R packages *ggplot2* (Wickham, 2016) and *interactions* (Long, 2019). Robust regressions were run with R package *MASS* (Venables and Ripley, 2002).

3. Results

In Section 3.1 we present the yearly LCA results per kg LWG (dairy and suckler-beef farms) and per L milk (dairy farms) and compare the environmental efficiency of dairy and suckler-beef farms in terms of burdens per kg LWG. In Section 3.2 we report the findings of our primary approach (Section 2.1 and Figs. 1–2) for the dairy farms based on the complex FU (see Eq. (1)). The LCA results are available as supplementary files (see Supplementary Material). The raw farm data are protected by a confidentiality agreement and thus were not made available.

3.1. LCA results for suckler-beef and dairy farms

Boxplots in Fig. 3 summarize the environmental footprints per FU for the suckler-beef farms (1887 unique farms, 10,340 data points) and for the dairy farms (738 unique farms, 3624 data points) for each year of the study period. For dairy farms, burdens are expressed both per kg LWG (left-hand side y-axes) and per L milk (right-hand side y-axes).[3] For clarity of presentation, some outliers were removed from Fig. 3, but are included in the boxplots of Fig. S1 (see Section S3 for a discussion on the observed outliers). Note the large variation in footprints of real dairy and suckler-beef farm data observed in these figures.

For suckler-beef farms, Figs. 3 and S1 show a slight increase in mean annual GWP, AP and LO per kg LWG, and more constant levels in mean annual EP and RDP per kg LWG across the study period, suggesting that suckler-beef environmental efficiency generally stagnated over time. The burden sources that contributed more heavily to these trends in suckler-beef farms were imported feed, manure storage and fertilisers (Fig. 4): imported feed per LU increased over time (background calculations), thus increasing, on the one hand, off-farm land occupation (on average, between 6 and 7% of total LO in each year) and reducing, on the other hand, the grazing period, which in turn drove up burden contributions from manure storage (Fig. 4). Meanwhile, on-farm silage consumption per LU slightly decreased during the period 2006–2013 (background calculations), marginally reducing RDP from fertilisers (Fig. 4). Suckler-beef burdens per kg LWG were much higher than for dairy-beef (Figs. 3 and S1).

For dairy farms we observe downward trends for the first years of the study period, followed by increasing trends in mean annual burdens per kg LWG and L milk in later years (Figs. 3 and S1). Interpretations of these trends (Fig. 4 and background calculations) are very similar to those for suckler-beef farms above. It seems, however, that the heavier use of imported feed per LU in dairy farms (1.19 times higher, on average, than suckler-beef farms; mean off-farm LO between 30 and 40% of total LO in each year) made these trends more pronounced than in the suckler-beef case. Note, consequently, the increasing contribution of imported feed and manure management to total burdens, along with a decreasing contribution of enteric fermentation to GWP (Fig. 4).

3.2. LCA results for dairy farms using the complex FU

The maximum beef:milk ratio that was used to define the complex FU (see Eq. (1)) in each year ranged between: 66 and 138 g LWG per L milk (mean = 95, median = 86, SD = 23) in the original data; 56 and 74 g LWG per L milk (mean = 63, median = 62, SD = 5) in the top-5% sensitivity run; 63 and 92 g LWG per L milk (mean = 72, median = 70, SD = 8) in the top-2.5% sensitivity run; and 50 and 79 g LWG per L milk (mean = 54, median = 54, SD = 3) in the top-5% sensitivity run.

The boxplots in Fig. 5 report burdens per complex FU for each year of the study period by summarizing over all N_y runs within each year for the top-5% sensitivity run (see Fig. 2 and Section 2.1.3). For better presentation, some outliers were removed from Fig. 5, but are included in the boxplots of Fig. S2. Boxplots from the top-2.5% and top-10% sensitivity scenarios are Figs. S3–S6 respectively. Using the complex FU that accounts for displaced beef gave a different picture in mean dairy farm environmental efficiency trends (Figs. 5 and S2–S6) compared with the conventional footprint trends displayed in Figs. 3 and S1. Inter-annual variability was higher and longer-term trends were less clear in Figs. 5 and S2–S6 than in Figs. 3 and S1, especially for GWP, RDP and LO.

3.2.1. Environmental implications of diversifying dairy farming

Figs. 6–7 display the results of the five robust regression models where each burden per complex FU was regressed against the beef:milk ratio with the regression equations that included region (see Section 2.1.3). The scatterplots of Fig. 6 plot the results of the five regression models for the North West- a main UK dairy farming region- for the years 2003, 2009 and 2014. Each dot represents a dairy farm in each year. For better presentation, displayed burdens for each farm in Fig. 6 are averages of all N_y runs in the year (see Fig. 2). The red, green and blue solid lines are the fitted robust regression linear models for 2003, 2009 and 2014 respectively. The red, green and blue dashed horizontal lines pass through the dairy farm with the maximum beef:milk ratio in 2003, 2009 and 2014 respectively. They thus split the scatterplots into two areas: the areas above (equivalently, below) display the dairy farms for which displacing dairy farm beef to the suckler-beef farms resulted

[3] The boxplots of burdens per kg LWG and per L of milk are identical because there is a proportional relationship between the left-hand side and right-hand side y-axes determined by the allocation ratio. Indeed, because of the energy allocation, burdens apportioned to milk output for a farm are:
burden/L × total gross energy from milk/total gross energy from milk and LWG (1)
Similarly, burdens apportioned to LWG output are:
burden/kg LWG × total gross energy from LWG/total gross energy from milk and LWG (2)
Now,
total gross energy from milk = farm milk production in L × gross energy from milk/L (3)
and
total gross energy from LWG = farm beef production in kg LWG × gross energy from LWG/kg LWG. (4)
Because of (3) and (4), the ratio of (1) over (2) is:
(gross energy from milk/L) / (gross energy from LWG/kg LWG),
which is constant among burdens and proportionally scales down the left-hand side y-axes to the values reported in the right-hand side y-axes of Fig. 3 for the dairy farms.

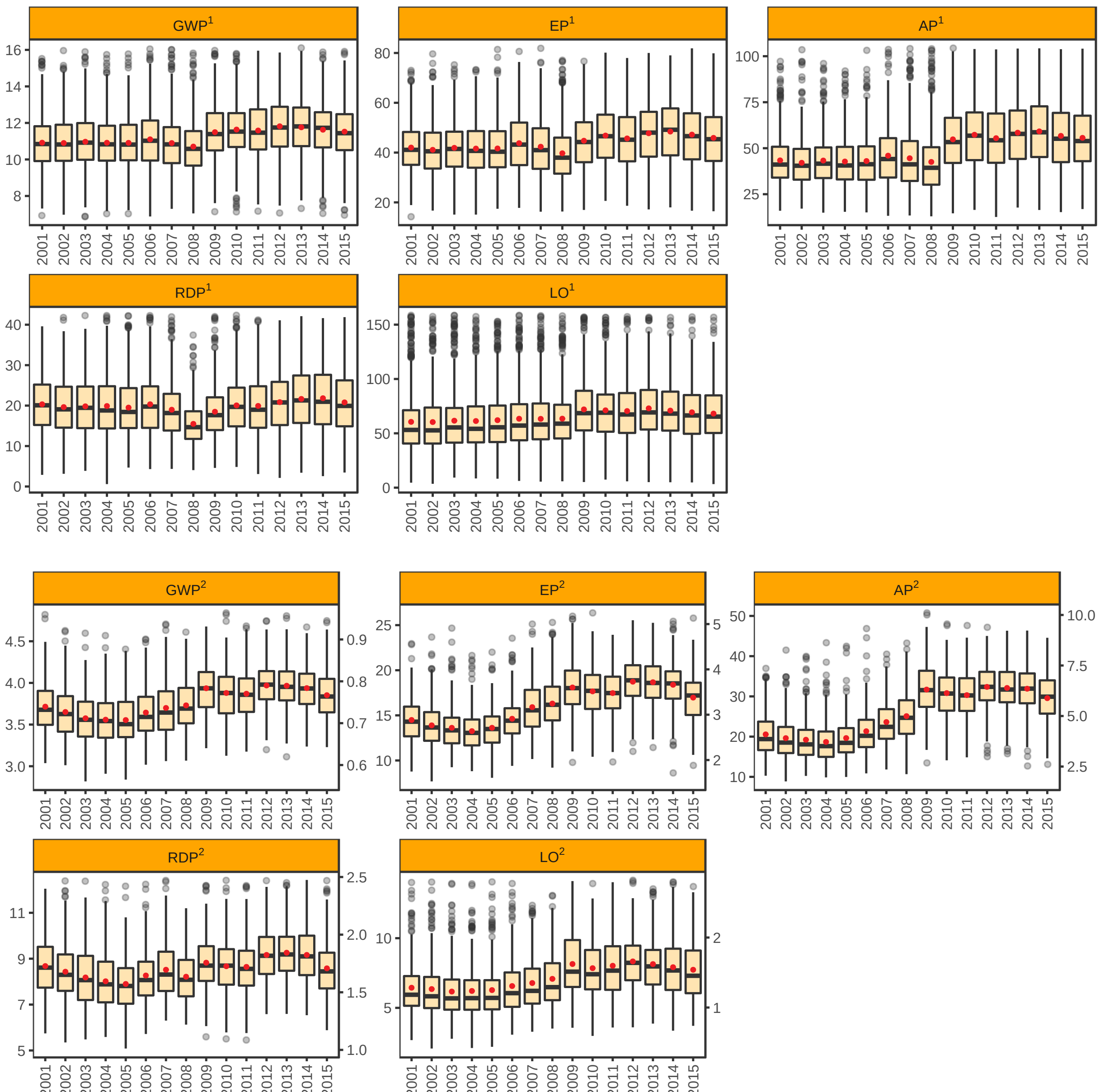

Fig. 3. Boxplots of burdens per kg live weight gain for [1]: suckler-beef farms; and per kg live weight gain (left-hand side y-axes) and per L milk (right-hand side y-axes) for [2]: dairy farms. Red dots and horizontal lines within boxplots are the means and medians respectively. GWP: global warming potential (kg CO_2 equivalents); EP: eutrophication potential (g PO_4 eq.); AP: acidification potential (g SO_2 eq.); RDP: resource depletion potential (MJ); LO: land occupation (on-farm + off-farm; m^2). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

in higher (equivalently, lower) burdens per complex FU than the dairy farm with the maximum beef:milk ratio in a particular year. Fig. 7 displays the robust regression lines for all years and regions.

Besides some exceptions (e.g. year 2003 for LO), the density of dairy farms with higher burdens per complex FU than the farm with the maximum beef:milk ratio was clearly greater in all burdens and years (Fig. 6), indicating that displacing beef via intensifying milk production on dairy farms generally increased burdens per complex FU at the inter-system-level. The fitted lines in Figs. 6–7 confirm this trend, i.e. that burdens per complex FU tended to reduce for dairy farms that displaced less beef to suckler-beef farms. The only exceptions were Wales, East Midlands, North East and West Midlands for RDP, where the regression lines had negligibly positive slopes (Fig. 7). These exceptions aside, it is interesting that trends are consistently downward for all burdens and regions, despite some high-leverage points with high values for both the beef:milk ratio and the burdens per complex FU (Figs. 6–7).

There was considerable variation between farms with a given beef:milk production ratio and Figs. 6–7 show a few cases where displacing beef from dairy farms to suckler-beef farms reduced burdens per complex FU. Although these cases were comparatively few in most years and burdens (Figs. 6–7), they highlight the variation observed in real-farm data.

Interestingly, within each year, dairy farms with a beef:milk ratio below the maximum beef:milk had lower ‘milk footprints’ (i.e. burdens expressed per L milk than per unit of complex FU) than the farm with the maximum beef:milk ratio in, on average (across all years), 92, 64, 45, 76 and 94% of cases for GWP, EP, AP, RDP and LO respectively. Although this meant that more intensive dairy farms did often reduce burdens per L of milk, not accounting for displaced beef, as in Figs. 6–7, the milk footprint alone mischaracterizes the inter-system-level impacts of intensive dairy farming.

We quantified the environmental implications of diversifying dairy farming using the robust regression equations for the three top-‘x%’ sensitivity runs (see sub-subsection 2.1.3). We thus calculated the

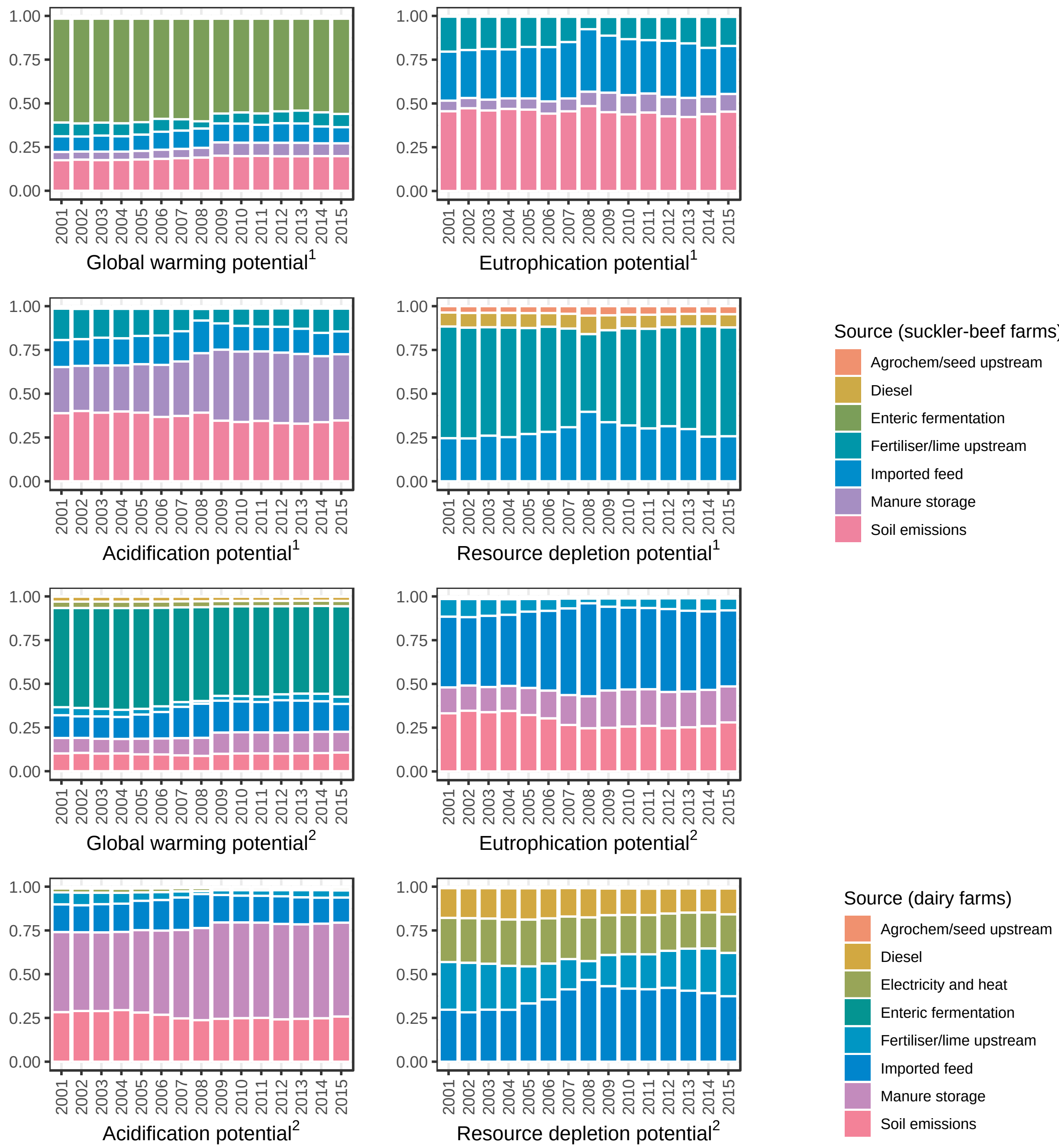

Fig. 4. Burdens per source for: [1]suckler-beef farms; and [2]dairy farms. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

percent reductions in burdens per complex FU between the dairy farms with the lowest and highest beef:milk ratios in each year (recall that the farms with the highest ratios are in this case the average of the top-'x%' of farms). Then, for each year, we predicted the burdens per complex FU for the two farms whose beef:milk ratios were the lowest (least diversified farm) or highest (most diversified farm) and subsequently calculated the percent differences in the predicted burdens per complex FU. We also considered midpoints by assuming increases in the beef:milk ratio of the least diversified farm in each year from the minimum beef:milk ratio to the: (i) first quartile; (ii) median; (iii) third quartile; and (iv) maximum beef:milk ratio. For better presentation, Fig. 8 reports results averaged across all years for the top-5% sensitivity run. Fig. 8 is complemented by Figs. S7–S8 that report the results of the top-2.5% and top-10% sensitivity runs respectively. It is observed that GWP, EP, AP and LO per complex FU could be reduced by on average 13, 21, 26 and 54% respectively, when shifting from the most specialized to the most diversified dairy farm (Fig. 8). These percentages are 13, 23, 29 and 56% respectively in Fig. S7 and 11, 18, 22 and 51% in Fig. S8. Percent reductions were smaller when shifting from the most specialized dairy farm to farms of intermediate specialization levels, but still noticeable in many instances (Figs. 8 and S7–S8). On the other hand, RDP increased; although by a negligible percentage (Figs. 8 and S7–S8).

3.2.2. Intensity profiles of 'virtual' suckler-beef farms

Based on the number of cases for which the dairy farm burdens per complex FU were higher or lower than the dairy farm with the highest beef:milk ratio in each year, we created two groups of 'virtual' suckler-

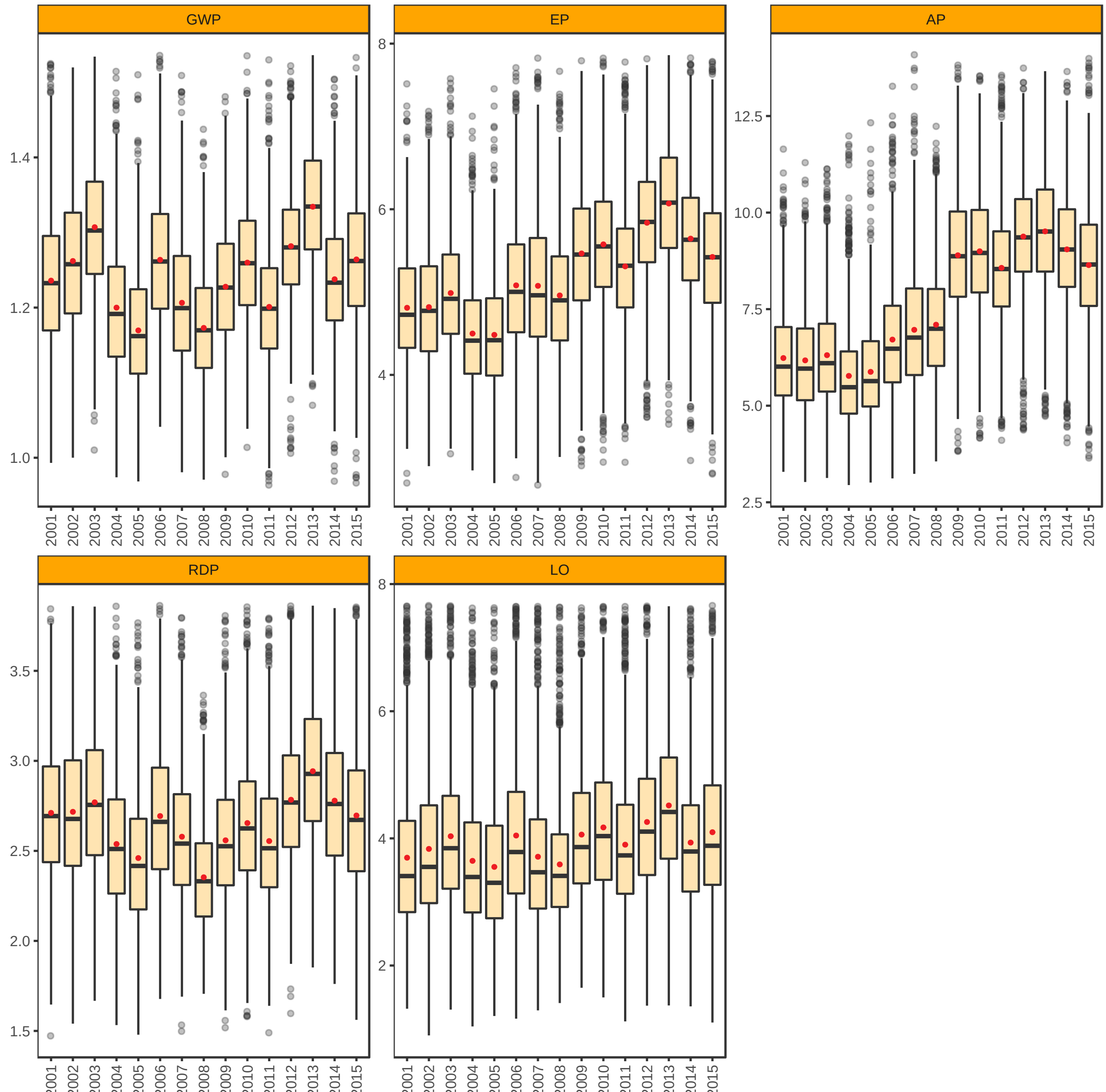

Fig. 5. Boxplots of burdens per complex functional unit (1 L milk and a fixed amount of g LWG- see Eq. (1)) for the top-5% sensitivity run. Red dots and horizontal lines within boxplots are the means and medians respectively. GWP: global warming potential (kg CO_2 equivalents); EP: eutrophication potential (g PO_4 eq.); AP: acidification potential (g SO_2 eq.); RDP: resource depletion potential (MJ); LO: land occupation (on-farm + off-farm; m^2). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

beef farms and tested for differences in their intensity profiles (see Section 2.1.4). Under all sensitivity runs, the Mann–Whitney test found significant differences between the two groups for each variable ($p < 0.01$). Table 1 indicates that some degree of increased intensity at lower concentrate use levels is required to reduce inter-system-level burdens attributed to displaced beef production. Interestingly, the contrast between higher stocking rates and lower concentrate use for the 'Lower' group relative to the 'Higher' group (Table 1) may be implying that suckler-beef farms appearing in the 'Lower' group solely, or appearing in the 'Lower' group more often than in the 'Higher' group, make a more efficient management of forage land. In other words, these findings appear to suggest that more intensive suckler beef farms that support high stocking rates with low concentrate feed requirements can help reduce burdens at the inter-system-level even at lower levels of dairy farm diversification.

4. Discussion

For the first time, we present comprehensive LCA results for multiple environmental burdens (Figs. 3–4 and S1) based on a large panel dataset for commercial dairy and suckler-beef farms, and provide real-farm evidence on the environmental implications of dairy farm specialization in intensive milk production (Figs. 5–8 and S2–S8) that has so far been studied through limited farm (scenario) comparisons (Flysjö et al., 2012; Styles et al., 2018; Zehetmeier et al., 2012). We found that once beef and dairy burdens are fully accounted for, specializing dairy farms in milk production generally leads to higher burdens at the inter-system-level than more diversified dairy farms (i.e. farms producing a higher proportion of beef relative to milk). Our findings on GWP are in line with recent studies modelling dairy farming systems in different countries (e.g. Sweden, France, UK, the Netherlands and Germany; Flysjö et al., 2012; Puillet et al., 2014; Styles et al., 2018; Vellinga and de Vries, 2018; Zehetmeier et al., 2012), but we provide valuable new

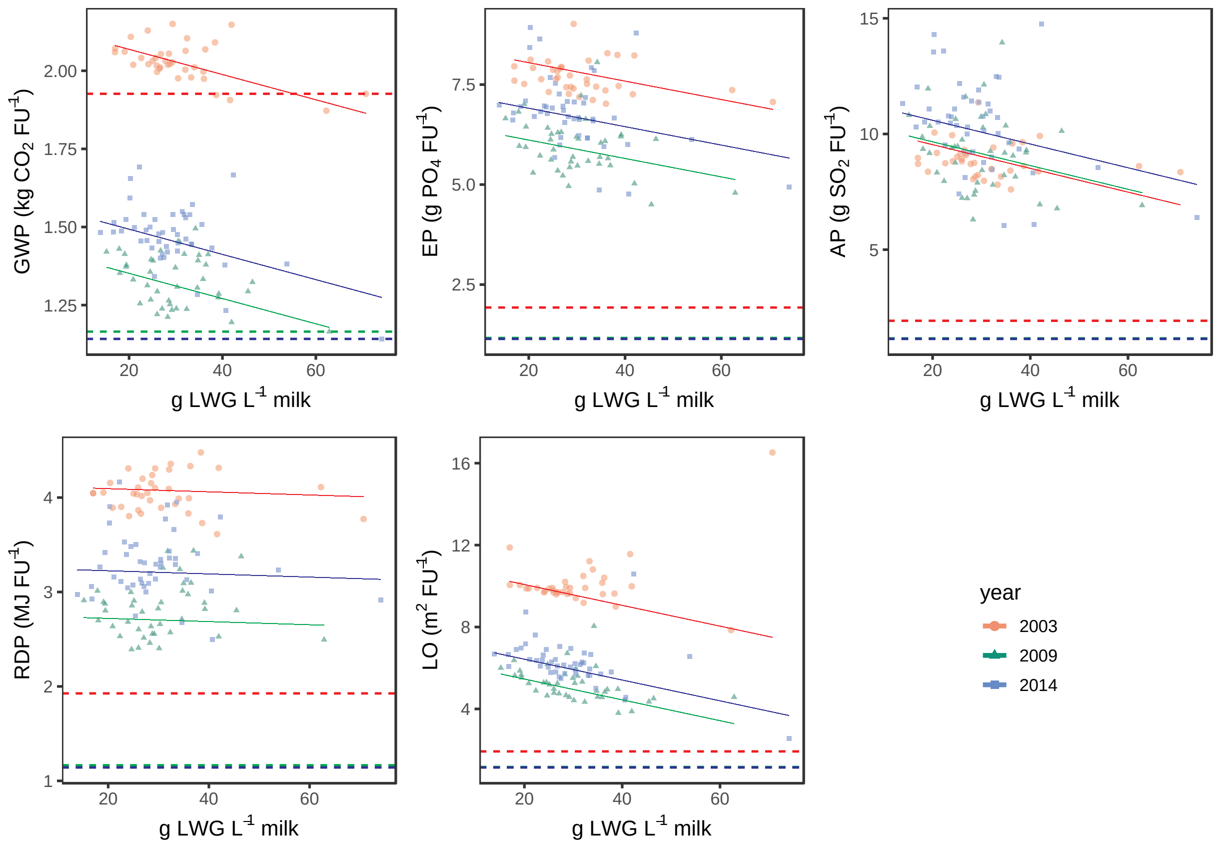

Fig. 6. Relationship between the beef:milk ratio and burdens per complex FU (see Eq. (1)) for the North West in selected years. FU: functional unit; LWG: live weight gain. GWP: global warming potential; EP: eutrophication potential; AP: acidification potential; RDP: resource depletion potential; LO: land occupation (on-farm + off-farm). The red, green and blue dashed horizontal lines pass through the dairy farm with the maximum beef:milk ratio in 2003 (71 g LWG L^{-1}), 2009 (63 g LWG L^{-1}) and 2014 (74 g LWG L^{-1}) respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

insights into effects across four additional burdens (Figs. 6–8 and S2–S8) and identify suckler-beef farm characteristics that can mitigate additional burdens arising from compensatory beef requirements (Table 1).

Our study reveals the considerable range in burdens per unit of output that is observed in practice (Figs. 3 and S1) but not captured in LCA studies of 'average' or 'representative' dairy and/or beef farms (Nguyen et al., 2010; Styles et al., 2018; Vellinga and de Vries, 2018). Such studies are normally confined to the creation of farm scenarios (e.g. low, medium or high farming intensity; Styles et al., 2018) based on data from a few commercial farms and on complementary data from national reports and databases (Flysjö et al., 2012; Ruviaro et al., 2015). By contrast, our dataset provides a much broader insight into the sustainability of dairy farming systems that (i) may be used to study the relationships between *continuous* variables of farming intensity, specialization and environmental performance, while accounting for variation between farms; (ii) may form the basis for upscaling[4] into distinct scenarios of farming and environmental intensity based on real-farm data (Gonzalez-Mejia et al., 2018; Soteriades et al., 2018) than 'average farm' scenarios; and (iii) confirms that the conclusions from modelled farm scenario studies hold for a wide range of stocking densities and intensities that are found in practice.

[4] With the assumption that the FBS survey is a representative sample of dairy and beef farms, a weighted combination of burdens gives an estimate of the performance of the sector in aggregate, and it would be interesting to compare this bottom-up estimate with, for example, a top-down national inventory estimate. In other words, does the accounting for the variability between farms affect estimates at the sector level?

4.1. Role of diversified dairy farms in mitigating burdens

A key aspect of our work is the use of the complex FU (Eq. (1)) to fully capture the environmental impacts of intensifying milk production of dairy farms (Figs. 5 and S2). Partial indicators of environmental efficiency that typically allocate burdens to milk and express them per L milk fail to capture the evidently significant contribution of the dairy farms' beef output to mitigating burdens at the inter-system level (Figs. 6–8 and S3–S8).

Comparatively efficient dairy-beef production, relative to suckler-beef production (Nguyen et al., 2010; Styles et al., 2018), has a key role to play in meeting the increasing global demand for beef (Alexandratos and Bruinsma, 2012) whilst reducing important local and global environmental impacts such as GWP, EP, AP, RDP and LO (Modernel et al., 2013). There is an urgent need to recognise important inter-system consequences, e.g. through simultaneous evaluation of multiple product outputs such as milk and beef, in order to identify genuine 'sustainable intensification' (i.e. increasing production in the least environmentally harmful manner; Foresight, 2011) pathways.

However, our conventional LCA milk footprints (i.e. Figs. 3–4 and S1) also shed light on important environmental trade-offs resulting from the ongoing trend in dairy farm intensification in the UK (Gonzalez-Mejia et al., 2018) and, more broadly, in other regions with intensive systems (e.g. Northwest Europe and North America; Vellinga and de Vries, 2018). Although increased reliance on imported concentrates for cattle feed can mitigate methane emissions from enteric fermentation per L milk (Fig. 4; Hristov et al., 2013), it was found to increase overall GWP per L milk in our analysis owing to higher upstream burdens from concentrate production (Fig. 3 and S1). A recent

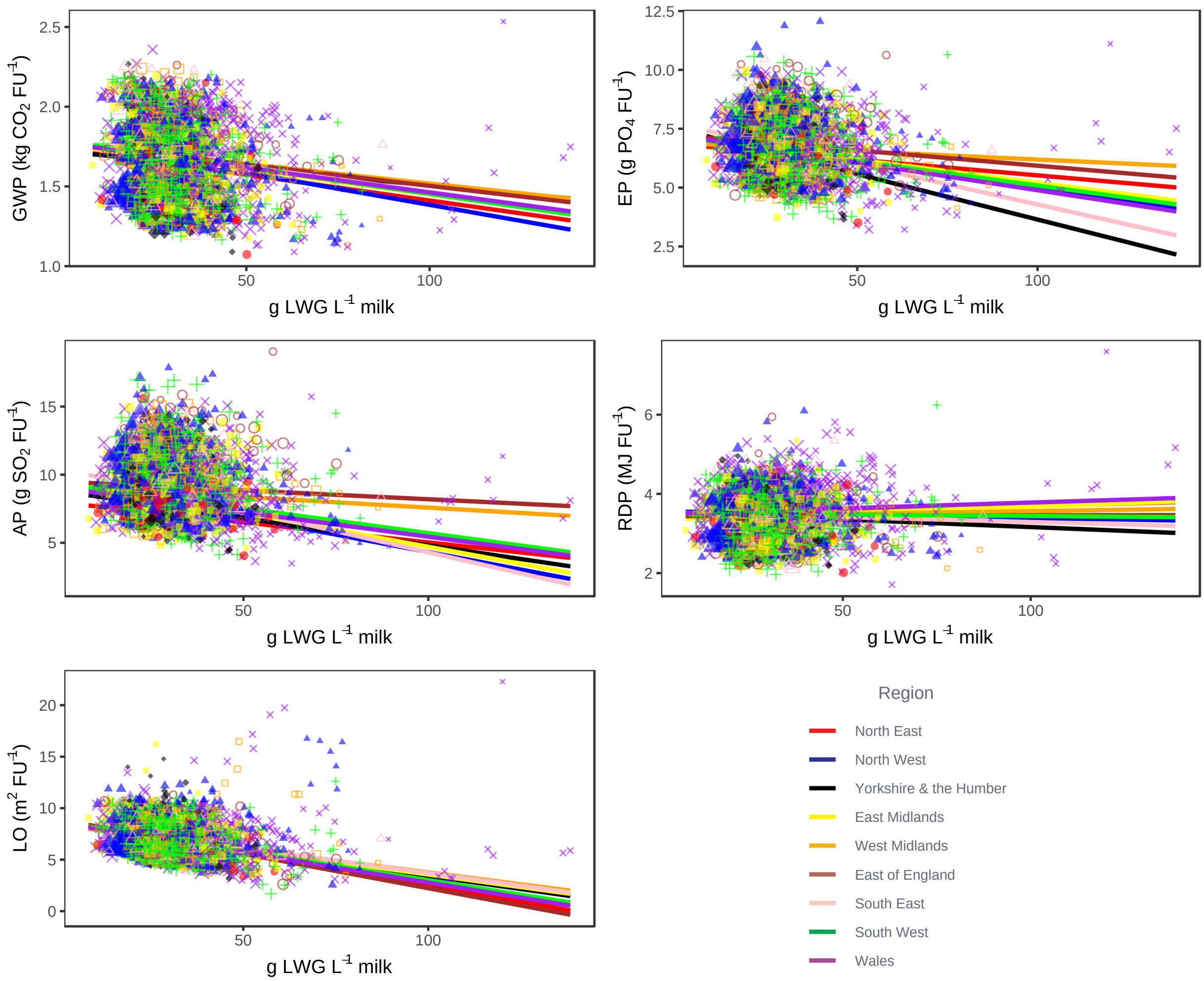

Fig. 7. Relationship between the beef:milk ratio and burdens per complex FU (see Eq. (1)) for all regions and years. Point size represents weight size in the regression models. FU: functional unit; LWG: live weight gain. GWP: global warming potential; EP: eutrophication potential; AP: acidification potential; RDP: resource depletion potential; LO: land occupation (on-farm + off-farm). (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

study with FBS data showed that the UK dairy sector continues on a long-term trend of intensification and specialization, with farms relying more heavily on concentrates (Gonzalez-Mejia et al., 2018), thus increasing indirect land occupation expressed in absolute terms, but also per L of milk and per kg LWG. Alongside land required to produce compensatory beef from suckler herds, this was found to be a major driver of greenhouse gas emissions from land use change in Styles et al. (2018).

Similarly, manure management emissions from manure storage and spreading (Fig. 4) appear to be increasing owing to increasing rates of animal housing across the UK dairy herd (March et al., 2014). Emissions of ammonia in particular are driving important local and regional burdens such as eutrophication and acidification (Modernel et al., 2013), as well as burdens not reported here such as human toxicity (European Commission, 2010). There is increasing attention on ammonia emissions as a significant source of air pollution across the European Union (European Commission, 2016). The increasing burdens per unit of output of dairy farms in terms of EP and AP (Figs. 3 and S1) is therefore a significant cause for concern and may require policy intervention to improve N-use efficiency at the cow-level (Foskolos and Moorby, 2018) and implementation of available manure management technologies, especially for indoor livestock systems (Soteriades et al., 2018). Mitigating these trade-offs needs to be considered along with minimizing the impacts from compensatory beef requirements to improve environmental efficiencies at the inter-system-level (Fig. 1).

4.2. Role of intensive suckler-beef farms in mitigating burdens

Suckler-beef farms were found to be environmentally inefficient compared with dairy-beef production, on average (Figs. 3 and S1), confirming results of recent studies (Nguyen et al., 2010). Indeed, cows giving birth to dairy-beef calves are primarily producing milk, therefore their emissions are apportioned primarily to milk production. Mother suckler-cow emissions are fully attributable to beef progeny as 'overheads'. Thus, whilst beef calves may fatten more quickly (efficiently) owing to breed and management specialization, this factor does not fully compensate these high overhead emissions (see Nguyen et al., 2010). If dairy farming continues to intensify by specializing in milk production (Gonzalez-Mejia et al., 2018), suckler-beef farms will have to expand more quickly than they otherwise would have had to do to meet growing demand for beef. Suckler-beef systems were the most prevalent beef system typology in the FBS data (Section 2.2), and are common across Europe (AHDB Beef and Lamb, 2016; Nguyen et al., 2010; Weidema et al., 2008). Thus, in practice, it is highly likely that displaced dairy-beef production will be compensated for by expansion of suckler-beef production.[5]

[5] It should be acknowledged that beef production could also be displaced

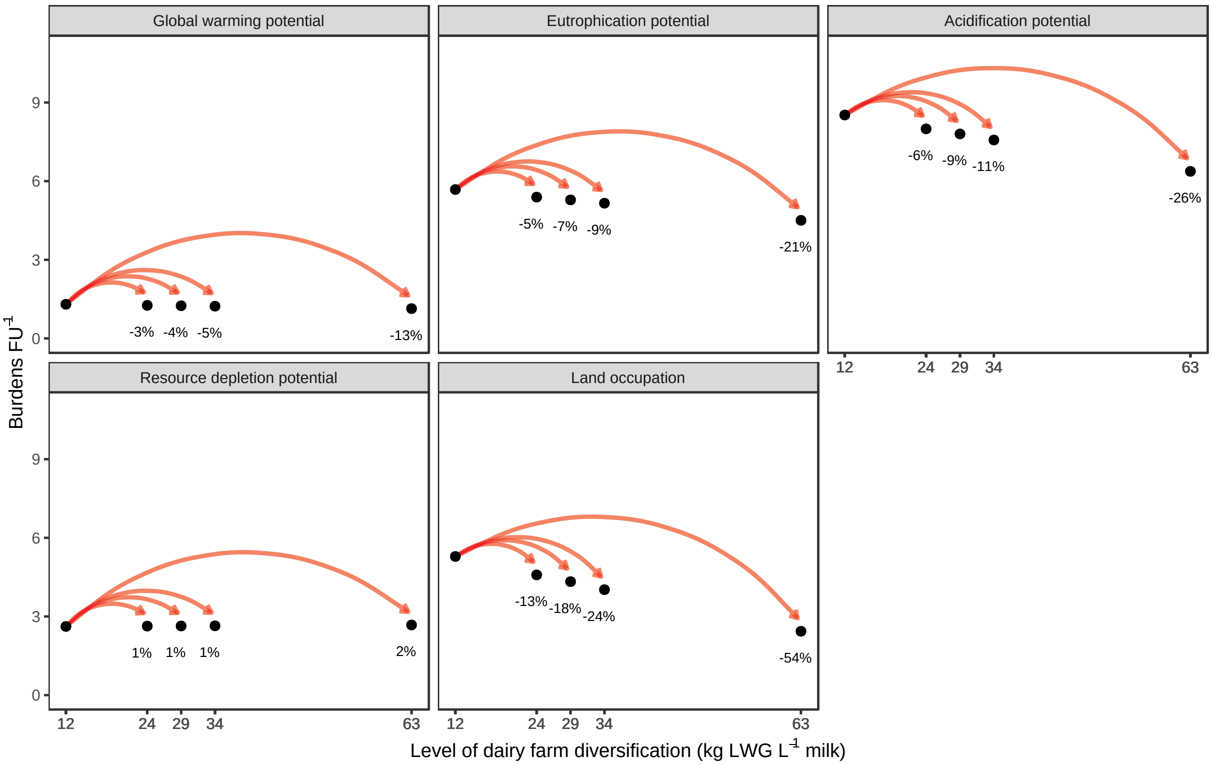

Fig. 8. Percent changes (text below each point) in burdens per complex FU relative to increasing dairy farm diversification levels for the top-5% sensitivity run. Values on the horizontal axis are the following five quartiles minimum; 1st quartile; median; 3rd quartile; and maximum. FU: functional unit; Global warming potential in kg CO_2 equivalents; Eutrophication potential in g PO_4 eq.; Acidification potential in g SO_2 eq.; Resource depletion potential in MJ; Land occupation (on-farm + off-farm): in m^2.

Table 1
Average intensity profiles of 'virtual' suckler-beef farms[a] for the different sensitivity runs.

	Top-5%		Top-2.5%		Top-10%	
	Higher[a]	Lower[a]	Higher	Lower	Higher	Lower
Stocking rate (LU[b] ha^{-1})	1.01	1.40	1.10	1.40	1.09	1.46
Concentrate use (t DMI[c] LU^{-1})	0.33	0.26	0.33	0.25	0.33	0.26
Animal-level beef production (kg LWG[d] LU^{-1})	167.60	171.45	167.64	171.73	167.67	171.23
Farm-level beef production (kg LWG ha^{-1})	203.23	275.29	204.27	277.08	202.48	293.01
On-farm area (ha)	94.21	77.52	93.80	70.01	94.27	74.65
Off-farm area (ha)	5.61	5.12	5.63	4.86	5.60	5.19

[a] These are the suckler-beef farms where the intensity variables of interest were averaged over all 'Higher' or 'Lower' occurrences. 'Higher' (similarly, 'Lower') refers to cases where a suckler-beef farm has higher (similarly, lower) burdens per complex functional unit than the farm with the maximum beef:milk ratio (see Sections 2.1.3–2.1.4).
[b] LU: livestock units.
[c] DMI: dry matter intake.
[d] LWG: live weight gain.

One potentially important mitigation action for dairy intensification is therefore the 'sustainable intensification' of suckler-beef systems. Our results from an extensive panel dataset corroborate a central finding derived from hypothetical scenario modelling by Styles et al. (2018), that intensification of suckler-beef production by increasing stocking rates and rates of LWG can mitigate the impacts of displacing beef output from dairy farms (Table 1). Suckler systems are generally more extensive (Nguyen et al., 2010), and our findings suggest that there is room for improving the utilization efficiency of the grass platform (Finneran et al., 2011), augmented by targeted use of concentrate feed where necessary to optimise growth rates (Hayek and Garrett, 2018). Existing suckler-beef farms may be constrained by location and climate in terms of how much intensification can be achieved. However, relatively productive grassland spared by dairy intensification and shifts towards concentrate feed could provide the ideal platform for sustainable intensification of suckler-beef systems, while leaving land for nature of trees, with potential benefits for biodiversity and from carbon sequestration (Styles et al., 2018).

4.3. Mitigation potentials

We found that allowing for a greater degree of dairy farm diversification can mitigate burdens for GWP, EP, AP and LO at the expense of minor increases in RDP (Figs. 8 and S7–S8). While the largest reductions in GWP, EP, AP and LO per complex FU could only be achieved

(*footnote continued*)
abroad (e.g. Brazil), likely with greater consequences (Styles et al., 2018). Therefore, our results are conservative.

through a large shift from highly specialized (i.e. farm with low beef:milk ratio) to highly diversified (i.e. farm with high beef:milk ratio) dairy farming systems, shifts to intermediate levels of diversification via moderate increases in the beef:milk ratio could help achieve significant burden reductions of up to 6–25% (Figs. 8 and S7–S8). These magnitudes are comparable with burden reductions achieved via managerial changes such as choosing alternative grazing swards (Soteriades et al., 2018) or adjusting the animals' productive life span and calving interval (Vellinga and de Vries, 2018).

The latter options may be more economically attractive than diversification for already-specialized dairy farms, as there is little economic incentive for farms to increase their beef:milk ratio at current milk and beef prices (Vellinga and de Vries, 2018). In particular, genetic differences between dairy and beef breeds mean that the economic efficiency and quality of meat are generally lower for dairy breeds (Clarke et al., 2009; Pfuhl et al., 2007). Rather than expect specialized farms to diversify, a potentially more economically viable management option for dairy farms would be to focus on reducing inputs (costs and upstream emissions) per animal and per litre of milk at current levels of specialization. Meanwhile, suckler suckler-beef farms should be intensified to help mitigate inter-system-level burdens from compensatory beef (Table 1).

There exist several examples of livestock systems exhibiting improved environmental and economic performance at lower intensity levels (van Grinsven et al., 2015). On the other hand, investment in technology can maintain production levels and improve environmental efficiencies in intensive systems, although such technologies can be capital-intensive (Dumont et al., 2013). Our results essentially indicate that it may be environmentally preferable not to further intensify and specialize already relatively intensive dairy systems, but instead to focus on intensifying typically extensive beef systems, within nutrient balance thresholds (van Grinsven et al., 2015). Our findings suggest that Research and Development and subsidy support hitherto focussed on dairy specialization, sustainable intensification and associated farm-level mitigation options should be revisited to consider counter-effects associated with beef system consequences.

However, it should also be noted that mitigation strategies in the dairy sector will strongly depend on the origin of the displaced (i.e. compensatory) beef, because burden intensities can vary substantially between pure beef systems (de Vries et al., 2015; Vellinga and de Vries, 2018). A recent review found several instances of concentrate-based systems exhibiting environmental efficiency advantages over roughage-based systems owing to lower animal emissions (de Vries et al., 2015). Future research could assess the inter-system-level burden intensities by considering intensive concentrate-based FBS beef systems (e.g. intensive cereal beef) that we did not examine owing to insufficient data coverage in our 15-year study period.

5. Conclusions

It is detrimental for overall environmental efficiency to continue specializing dairy farms in milk production, thus displacing beef production. Specialization results in both an increase in carbon footprint and an increase in more local burdens such as eutrophication and acidification. The effect of ongoing global trends in dairy farm intensification and specialization can be mitigated by (i) increasing beef output per unit of milk achievable without a large change in a dairy farm's management; and (ii) sustainable intensification of displaced beef production. As suckler-beef farms are by far the most prevalent beef system in Europe, burden intensities arising from displaced beef may be offset by increasing stocking densities of suckler-beef systems and improving grass utilization. A deemphasis on specialization of dairy farms is necessary in policy and management advice for sustainable intensification and burden mitigation.

Declaration of Competing Interest

No competing interests.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2019.05.031.

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