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Cattle diet and the carbon footprint of beef: a meta-analysis.

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Abstract

Grass-based beef cattle production systems are generally perceived as beneficial to the environment. However, the climate impact of grass-based systems compared to systems based on energy-dense feeds remains controversial. While grass-based systems require less feed from crops, the production of which emits carbon dioxide and nitrous oxide, they generate more enteric methane emissions. Here, we provide a meta-analysis of cradle-to-farm-gate life cycle assessments of beef cattle production systems to estimate the effect of cattle diet on the carbon footprint of beef. Panel regressions indicate that every 10-percentage-point increase in grazing (resp. hay intake) at the expense of concentrates in cattle diets, based on dry matter intake, increases the carbon footprint of beef by 0.9 ± 0.35 (resp. 1.1 ± 0.5) kg CO_2e per kg live weight. Lower feed efficiency and higher slaughter age are determinants of this effect. The findings highlight potential trade-offs between climate goals and other sustainability objectives (e.g., biodiversity, animal welfare).

Keywords: Life cycle assessments, beef cattle, GHG emissions, meta-analysis, grazing.

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1 Introduction

The beef production sector is a major source of greenhouse gas (GHG) emissions (Herrero et al. 2016; Xu et al. 2021), and beef is one of the most emission-intensive food products (Poore and Nemecek 2018; Clune et al. 2017). Due to population and economic growth, its production and consumption are rising (Godfray et al. 2018) and are expected to rise substantially over the next decades (Revell 2015; OECD/FAO 2021). This rise could significantly increase GHG emissions (Revell 2015; Springmann et al. 2018), with a dramatic impact on the global climate.

Reducing the quantity of animal-based foods in human diets — especially beef meat — has been suggested as a natural lever for GHG mitigation in this sector (Godfray et al. 2018). Several studies have shown that shifts towards more plant-based diets can considerably reduce emissions of the food system, especially when considering carbon sequestration through ecosystem restoration on spared land (Hayek et al. 2021; Sun et al. 2022; Theurl et al. 2020). However, reducing beef production to zero is unlikely. Beef contributes significantly to the availability of essential nutrients like vitamin B12, zinc, and some amino acids (Smith et al. 2022). In addition, changing the dietary behavior of populations is uncertain and slow (Godfray et al. 2018). Therefore, it is crucial to identify key mitigation options on the production side.

The present paper aims to determine whether grass-based beef production systems are more emission-intensive than systems using energy-dense feeds. Based on a systematic literature review of peer-reviewed life-cycle assessment studies of beef cattle production systems between 2000 and 2024, it provides quantitative and detailed data on cattle diet and the CF of beef. Then, from the data, the paper estimates the relationship between the carbon footprint (CF) of beef and cattle diets.

LCAs of beef production systems available in the literature show a large variation in the CF of beef, *from cradle to farm gate* (De Vries and De Boer 2010; De Vries et al. 2015; Pishgar-Komleh and Beldman 2022). In particular, cattle diet plays a pivotal role in the CF of beef (De Vries et al. 2015; Pishgar-Komleh and Beldman 2022). Cattle diet – mainly composed of grass, energy-dense forages like maize silage, and concentrates – determines the amount of enteric methane produced (IPCC 2006; Rosa and Gabrielli 2023), which is the main source of GHG from beef production (Poore and Nemecek 2018). However, determining whether grass-based production systems are more or less emission-intensive than systems based on concentrates and energy-dense forages is not trivial. Indeed, both types of systems have contrasted effects on GHG emissions. These effects are summarized in Table 1. Enteric

Table 1: Effect of cattle diet on the various sources of GHG emissions from beef production systems, on a productivity basis.

Source	GHG	More grass-based	More concentrate-based
Enteric fermentation	CH_4	+	-
Pesticide production and transport	CO_2	-	+
Mineral fertilizer production and transport	CO_2	-	+
Machinery and equipment (animal housing, field operations, feed processing and distribution, manure removal and transport)	CO_2	-	+
Mineral fertilizer application	N_2O	-	+
Manure management (storage, treatment, and spreading)	N_2O, CH_4	+/-	+/-

methane emissions increase with the share of grass in cattle ration.[1] In contrast, carbon dioxide emissions decrease due to lower input requirements for crops (pesticides, fertilizer, fuel, machinery) and animal housing (see, e.g., Lynch 2019). Nitrous oxide emissions from mineral fertilizers also decrease in more grass-based systems due to their lower use (De Vries et al. 2015). The effect of cattle diet on nitrous oxide and methane emissions from manure management is, conversely, unclear. Emissions from manure management depend mainly on the type of manure (solid manure vs. slurry) and the methods of storage, treatment, and spreading (Chadwick et al. 2011), which can vary between farms based on similar feed types. In addition, mitigation levers of emissions from manure exist in both grass-based and more concentrate-based systems, with some trade-offs between reducing CH_4 and N_2O emissions (Lombardi et al. 2021; Rivera and Chará 2021). Overall, the net effect on the CF of beef of moving from a concentrate-based beef production system to a more grass-based system is complex and depends on the magnitude of the variations in the various sources of GHG.

Several studies indicate that the increase in enteric methane emissions is greater than the variations in other sources of emissions when beef production systems are more grass- or roughage-based, resulting in an overall higher CF (De Vries et al. 2015; Mogensen et

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[1] In the IPCC guidelines, the methane conversion factor of feed intake is 3.0% for feedlot fed cattle and 6.5% for grazing cattle (IPCC 2006).

al. 2015; Pelletier et al. 2010). However, other results are more uncertain. Two recent systematic reviews of LCAs point out that beef from grass-based systems tends to have a higher CF than beef from non-grass-based systems but fail to find a statistically significant difference between the two (Lynch 2019; Pishgar-Komleh and Beldman 2022). There is also evidence that pasture-based systems without concentrate supplementation can be more emission efficient with an earlier slaughter age despite a lower growth rate (Herron et al. 2021), indicating again that the result is not straightforward.

Compared to previous reviews on the topic (De Vries et al. 2015; Lynch 2019; Pishgar-Komleh and Beldman 2022), the main contribution of this work is to provide an assessment of a *continuous* relationship between cattle diet and the CF of beef rather than a *discrete* comparison between grass-based vs non-grass-based systems, relying on an up-to-date database. This difference is crucial. Indeed, we suspect that the statistical insignificance of the difference in CF between grass-based and non-grass-based systems found in the literature so far (Lynch 2019; Pishgar-Komleh and Beldman 2022) comes from the comparison of similar systems in terms of diet that have been separated into two categories based on an arbitrary threshold.[2] Here, we overcome this issue by estimating the marginal effect of an increase in grass (grazing, hay, or silage) in cattle diet on the CF of beef.

The scope of the study excludes GHG emissions from land use and land use change (LULUC). Although grass-based beef production systems might benefit from carbon sequestration of grasslands, as suggested in the literature (see, e.g., Soussana et al. 2010), this reasoning has been strongly criticized (Smith 2014; Garnett et al. 2017). While carbon sequestration may occur in a static framework for a given year, it is unlikely to occur in a longer-term perspective. Indeed, grasslands can only sequester carbon temporarily until they reach a steady state, and the measured carbon sequestration generally results from previous poor management or cropland conversion (Smith 2014). Thus, agricultural soil carbon dynamics correspond only to stock variations with a zero long-term balance sheet and it is more consistent to assume that grassland and cropland carbon stocks are stable. Changes in cattle diets would also potentially lead to changes in land use. In more concentrate-based systems, more cropland and less grassland would be needed. As grassland has higher carbon

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[2] In De Vries et al. (2015), Lynch (2019), and Pishgar-Komleh and Beldman (2022), systems are considered grass-fed (resp. roughage-based) if at least 50% of their diet is grass (resp. roughage), and non-grass-fed (resp. non-roughage based) otherwise. Thus, a system with a 49% grass-based diet for cattle belongs to the group of non-grass-based systems, while the same system with a 51% grass-based diet is associated with the grass-based group. The difference between two groups built this way is unlikely to be significant. This reasoning is supported by the findings of Lorenz et al. (2019) in the case of dairy cattle. The authors do not find significantly different CF of milk between three categories of systems differentiated according to a threshold, but find however a significant effect of pasture intake on the CF of milk.

stock than cropland, this would result in a net carbon loss. However, extending the scope to LULUC emissions would also require taking into account the carbon opportunity cost of land, i.e. the potential for natural carbon removal through ecosystem restoration. With this system delineation, concentrate-based systems have been shown to be less emission-intensive because they use less land (Balmford et al. 2018; Blaustein-Rejto et al. 2023). For these reasons, our focus is on production emissions.

The paper is organized as follows. The method is presented in section 2. Results are shown in section 3. Section 4 discusses the results and concludes.

2 Method

2.1 Systematic review

A meta-analysis was undertaken following the up-to-date PRISMA[3] recommendations (Page et al. 2021). A bibliographic research was conducted in the Scopus and Web of Science databases on May 7, 2024, with the following instructions: [“emission*” OR “environment*”] and “beef” and [“life cycle” OR “farm* system*”] in abstract, title or keywords, over the period 2000-2024. All the documents matching the search criteria were retrieved in BibTeX files processed with the *JabRef* software. The duplicates were removed, and the title and abstract of each document were screened. The full text of relevant studies was finally reviewed.

To assess the effect of cattle feeding on the CF of beef, a sample of LCAs of beef production systems as homogeneous as possible was required to avoid capturing the effect of other factors. Therefore, the studies selected had to comply with a certain number of criteria:

- Beef from the dairy sector (culled dairy cows and fattened dairy calves) was excluded because of its significantly lower footprint due to an important allocation of GHG emissions to milk production (De Vries et al. 2015);
- LCAs had to be comprehensive, from calf birth to its sale at the farm gate, to account for emissions related to the suckler cow during the pregnancy and calf suckling periods. Thus, partial LCAs of the fattening period excluding the cow-calf phase (see for e.g. Herron et al. 2021) were not in the scope of this meta-analysis;
- Emissions from the three main gases, namely CO_2, CH_4 and N_2O, had to be considered. Emissions from crop production, including emissions from the production and use of

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[3] Preferred Reporting Items for Systematic reviews and Meta-Analyses.

fertilizers and fossil fuels, had to be within the system boundaries;

- The functional unit had to be a unit of beef weight (either carcass weight – CW – or live weight – LW);
- Quantities of feed intake over the life cycle, with data differentiating at least grass, energy-dense forages from crops, and concentrates, had to be provided.

A greater flexibility was applied to other criteria in order to have a sufficiently large sample. In particular, herd management parameters (calving rate, replacement rate, slaughter age) were not considered in the selection. However, as explained in the statistical analysis section, we control for these potential sources of heterogeneity in the models.

The methodology used to conduct the LCAs was not restricted. LCAs conducted with primary data from real farms or secondary data representing typical systems at the regional or national level were included, as well as large-scale input-output LCAs and models of whole farm systems.

2.2 Data collection

Data of interest from papers meeting the selection criteria were collected either directly or by calculation and organized in a database (see supplementary materials SM1). Data retrieved includes the CF of beef, grass intake, energy-dense forage intake (mainly maize and barley silage), and concentrate intake. For grass, the information provided in the selected papers made it possible to break down the intake into grazed grass, silage, and hay.

Additional data was collected on breed, calving rate, age at first calving, slaughter age, and replacement rate. Due to a lack of information on the breed in a significant number of studies and the presence of crossbreeds, this parameter was not analyzed.

The functional units met in the studies that are compliant with the selection criteria are the units of LW and CW. Since the most commonly used unit in the final sample is LW (93% of the observations), this unit was chosen to harmonize the LCAs' results. An average dressing percentage of 55% was applied to convert results expressed per unit of CW into a unit of LW.

2.3 Statistical analysis

Summary statistics were used to describe the sample. To assess the effect of cattle diet on GHG emissions from beef production, we had to account for the non-independence of observations from the same publication, the between-studies heterogeneity unrelated to cattle diet, and potential endogeneity bias. Following the recommendations of Nelson and Kennedy (2009), we estimated panel linear models integrating publication (fixed or random) effects. Single-observation studies were mechanically removed by these effects. The choice between random and fixed publication effects was made based on the results of the post-regression Hausman test (Hausman 1978). In the results section, the type of model used is systematically indicated in the regression tables. In all the models, the dependent variable is the CF of beef, and the independent variables are the different feed intakes expressed as a percentage of the total dry matter intake (DMI) per kg LW.

The four models estimated are:

- Model 1: $CF_{ij} = \alpha + \beta_1 G_{ij} + \mu_i + \epsilon_{ij}$;
- Model 2: $CF_{ij} = \alpha + \beta_1 G_{ij} + \beta_2 H_{ij} + \mu_i + \epsilon_{ij}$;
- Model 3: $CF_{ij} = \alpha + \beta_1 G_{ij} + \beta_2 H_{ij} + \beta_3 S_{ij} + \mu_i + \epsilon_{ij}$;
- Model 4: $CF_{ij} = \alpha + \beta_1 G_{ij} + \beta_2 H_{ij} + \beta_3 S_{ij} + \beta_4 F_{ij} + \mu_i + \epsilon_{ij}$.

where, for observation j from publication i, CF_{ij} is the carbon footprint, G_{ij} the grazed grass intake, H_{ij} the hay intake, S_{ij} the grass silage intake, and F_{ij} the energy-dense forages intake. For fixed effects models, $\alpha + \mu_i$ corresponds to the publication fixed effect and ϵ_{ij} to the error term. For random effects model, α is the constant and $\mu_i + \epsilon_{ij}$ is the composite error term.

Because the sum of grazing, hay, grass silage, energy-dense forages, and concentrates equals 1, at least one of the variables is excluded from the regressions. For each variable, the estimated coefficient must be interpreted as the effect of an increase of this variable at the expense of the variables not included in the model so that the sum is always equal to one. Thus, the variables excluded correspond to the counterfactual feed intake. For example, in model 1, β_1 measures the effect of an increase in grazing at the expense of all other non-grazed feeds on the CF of beef. In contrast, in model 4, β_1 measures the effect of an increase in grazing at the expense of concentrates on the CF of beef.

Diagnostic tests were used to detect the presence of heteroskedasticity. Inferences were corrected using heteroskedasticity-consistent standard errors (White 1980) based on the HC3 version adapted to small samples (Long and Ervin 2000). The same test was applied to all regressions, and robust standard errors were used whenever the null of homoskedasticity was rejected.

Calving rate, age at first calving, and replacement rate were not included in the models as control variables due to too little variation in the sample and within studies, but were controlled for by publication effects. Slaughter age was also not included because it is strongly correlated with grass intake and is a consequence of the type of diets (when animals are fed primarily on grass, their growth rate is lower and they are slaughtered at an older age).

To explore the determinants of the effect of cattle diet on the CF of beef, we analyzed the association between variables relative to cattle diet and (i) feed efficiency, expressed in kg LW per kg DMI, and (ii) slaughter age in months. The same specification as in model 4 was applied, but the dependent variable was either the feed efficiency or slaughter age.

All statistical analyses were executed in R, version 4.3.1.

3 Results

3.1 The sample

Figure 1 summarizes the different selection steps of the systematic review. Eighty-three individual CFs of beef from 22 peer-reviewed LCAs met the selection criteria. The main reason for excluding papers assessed for eligibility was the unavailability (or inability to calculate) of quantitative information on feed intake over the entire cradle-to-farm gate life cycle (n=78).

Table 2 describes the sample of LCAs used for the meta-analysis. The farm systems studied are located in Europe, North America, and South America. LCAs are generally based on primary or secondary inventory data, although some studies are based on optimization models of whole farm systems (calibrated from real data). The number of observations per study varies widely, from 1 to 13. Multiple observations in a single study correspond to the analysis of either various systems or one system under different practices. Global warming potential values (GWP) used for methane and nitrous oxide are mostly 25 and 298, respectively. However, other values were sometimes used, in particular in the oldest and most recent studies due to IPCC revisions. As already pointed out (Lynch 2019), data on disaggregated GHG emissions are rarely available. Therefore, it was not possible to standardize the calculation of emissions between studies. However, using panel regressions with publication effects allowed to account for between-studies heterogeneity, such as GWP values used.

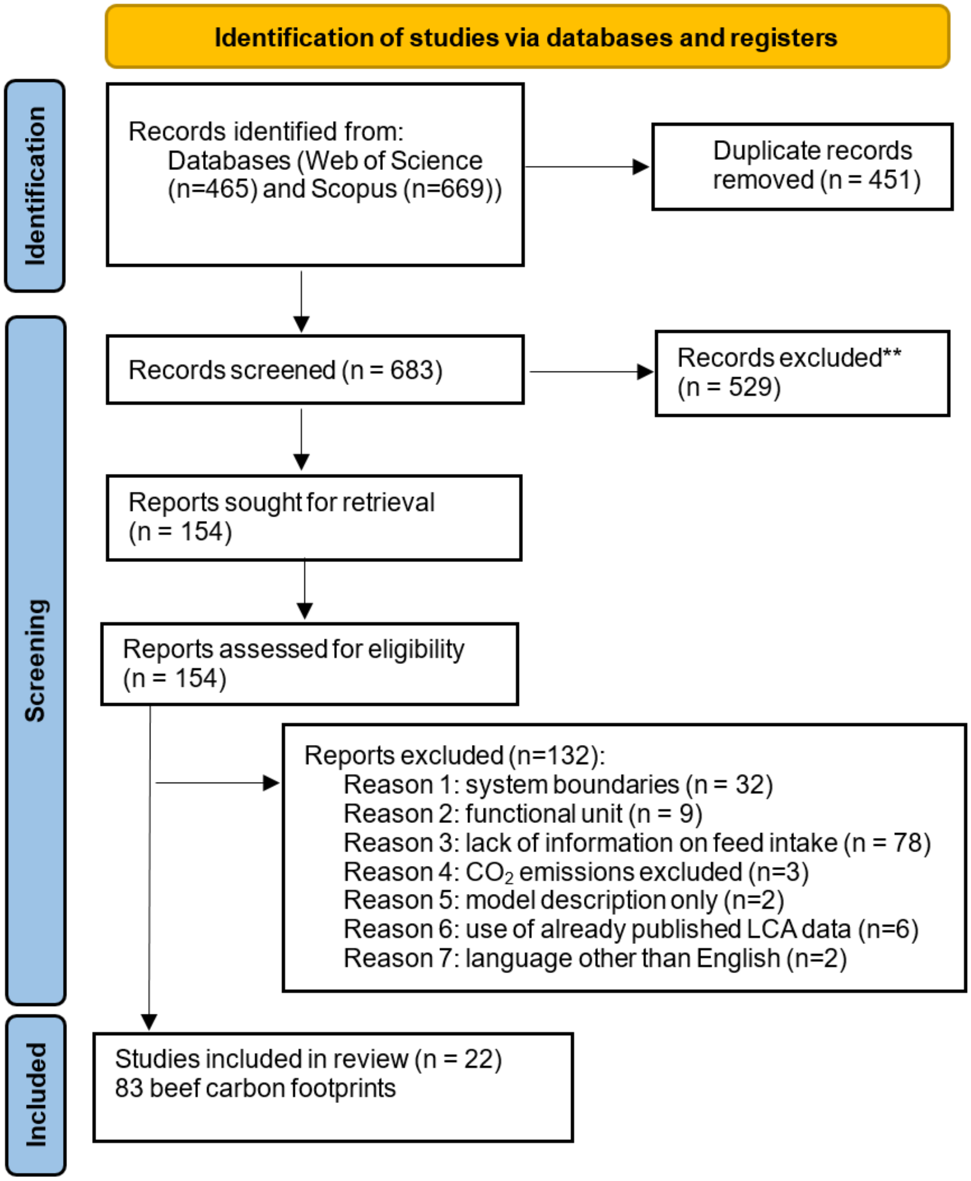

Figure 1: Systematic literature review flowchart, adapted from Page et al. (2021)

Table 2: Description of the studies selected for the meta-analysis

Reference	Region	Methodology	Farm	FU	No of obs.	GWP CH_4	GWP N_2O
Angerer et al. (2021)	Italy	LCA	Average of six farms studied	LW	1	34	298
Arrieta et al. (2020)	Argentina	LCA	Weighted average of Argentinean beef farms	LW, CW	1	34	298
Basarab et al. (2012)	Canada	LCA	Typical Western Canada beef farms	LW, CW	4	23	298
Casey and Holden (2006)	Ireland	LCA	Typical Irish beef farm	LW	5	21	310
Foley et al. (2011)	Ireland	Whole farm system model	Typical Irish beef farm	CW	5	25	298
Hammar et al. (2022)	Sweden	LCA	Typical Swedish farm	LW, CW	2	34/36	298
Herron et al. (2019)	Ireland	Whole farm system model	Typical Irish beef farm	LW, CW	4	25	298
Kamali et al. (2016)	Brazil	LCA	Typical Brazilian beef farms	LW	3	28	265
McGee et al. (2023)	Ireland	Whole farm system model	Experimental farm	LW, CW	4	28	265
McGee et al. (2024)	Ireland	Whole farm system model	Experimental farm	LW, CW	4	28	265
Mogensen et al. (2015)	Denmark and Sweden	LCA	Typical Danish and Swedish beef farms	LW, CW	3	25	298
Molossi et al. (2020)	Brazil	Whole farm system model	Cooperating farms in the Amazon and Cerrado biomes, Mato Grosso	LW, CW	8	25	298
Morel et al. (2016)	France	LCA	Extensive Charolais beef systems	LW	2	25	298
Nguyen et al. (2010)	EU	LCA	EU-representative system	CW	1	25	298
Nguyen et al. (2012)	France	LCA	Representative beef farm of the Charolais basin	LW, CW	4	25	298
Nguyen et al. (2013)	France	LCA	Representative beef farm of the Charolais basin	LW, CW	10	25	298
Pelletier et al. (2010)	United States	LCA	Representative beef farms of the Upper Midwest	LW	3	25	298
Pereira et al. (2018)	Brazil	Whole farm system model	Common pastured beef grazing farms, southern Brazil	LW	3	25	298
Rotz et al. (2013)	United States	Whole farm system model	Experimental farm	LW	1	25	298
Rotz et al. (2019)	United States	Whole farm system model	Weighted average of US beef farms	CW	1	28	265
Taylor et al. (2020)	Ireland	Whole farm system model	Average of commercial farms participating in a farm improvement programme	LW, CW	13	28	265
Tichenor et al. (2017)	United States	LCA	Representative Northeastern beef systems	LW, CW	1	25	298

Summary statistics are presented in Table 3. A diversity of systems in terms of cattle diet is represented in our sample; grazing varies from 26% to 100% of total dry matter intake (DMI), while the intake of energy-dense forage and concentrates varies from 0% to 41% and 0% to 67%, respectively. CFs also show an important heterogeneity in the sample: the largest CF is about three times larger than the smallest. Statistics of herd management practices indicate substantial differences in the sample. Calving rate, age at first calving, and replacement rate are mostly constant within studies and will be capture by publication effects in the statistical analysis. Slaughter age will be further analyzed as a potential explanatory factor for the relationship between cattle feeding and the CF of beef.

Table 3: Summary statistics of the sample

Statistic	N	Mean	St. Dev.	Min	Max
CF (kgCO2eq/kgLW)	83	14.12	3.28	9.48	27.30
Grazing (% of DMI)	83	60.23	17.04	26.39	100.00
Hay (% of DMI)	83	7.86	13.10	0.00	47.92
Grass silage (% of DMI)	83	17.19	14.56	0.00	55.58
Energy-dense forages (% of DMI)	83	3.55	9.19	0.00	40.98
Concentrates (% of DMI)	83	11.17	9.36	0.00	66.74
Feed efficiency (kg LW/ kg DM)	83	0.08	0.02	0.03	0.21
Age at first calving (months)	55	28.62	5.02	23.50	36.00
Calving rate	60	0.90	0.08	0.67	1.00
Slaughter age - heifers (months)	70	24.79	6.50	10.00	36.00
Slaughter age - steers (months)	81	19.66	6.68	9.00	36.00
Average slaughter age (months)	81	21.52	4.97	9.00	36.00
Replacement rate	69	0.19	0.05	0.05	0.32

3.2 Main regression results

Table 4 reports the estimation results for models 1 to 4. Publications with only one observation (n=6) were removed by including publication effects. Random effects were applied following the results of the Hausman test. In column 1, the counterfactual feed intake is a composite, including all non-grazed feeds. In contrast, the counterfactual in column 2 includes only grass silage, energy-dense forages, and concentrates since we control for hay intake. In columns 3 and 4, the effect of grazing on the CF of beef is relative to either energy-dense forages and concentrates or concentrates only, respectively. In all the regressions, the estimated coefficients on grazing and hay are positive and significant, indicating that increasing grazing or hay in cattle diets increases the CF of beef.

The effect of grazing is lower in column 1. This is because hay is in the counterfactual composite feed in this model, and hay intake is associated with an increase in the CF of beef, as shown in the other columns. The coefficients on grazing are similar in magnitude in columns 2, 3, and 4. They suggest that a ten-percentage-point increase in DMI through grazing at the expense of grass silage, energy-dense forages, and concentrates (column 2), energy-dense forage and concentrates (column 3), or concentrates only (column 4) increase the CF of beef by 0.85-0.90 kg CO_2e per kg LW.

Regressions 2-4 also suggest that hay intake increases the CF of beef. The estimated coefficients, similar in the three columns, indicate that a ten-percentage-point increase in hay intake at the expense of grass silage, energy-dense forages or concentrates increases the CF of beef by 1.0-1.2 kg CO_2e per kg LW. However, results indicate that replacing concentrates or energy-dense forages with grass silage (column 3) or concentrates with energy-dense forages or grass silage (column 4) in cattle diet does not impact the carbon footprint of beef.

Table 4: Effect of cattle diet on the carbon footprint of beef

	Carbon footprint (kg CO2eq/kg LW)			
	(1)	(2)	(3)	(4)
Grazing (% DMI)	0.070**	0.088***	0.085***	0.090***
	(0.034)	(0.034)	(0.033)	(0.035)
Hay (% DMI)		0.118***	0.104**	0.112**
		(0.031)	(0.046)	(0.051)
Grass silage (% DMI)			−0.015	−0.009
			(0.034)	(0.041)
Energy-dense forages (% DMI)				0.0004
				(0.0005)
Model	*RE*	*RE*	*RE*	*RE*
Observations	77	77	77	77
R^2	0.281	0.403	0.406	0.416

All estimates are based on ordinary least squares regressions with publication effects. RE = random effects; FE = fixed effects. Values in brackets are heteroskedasticity-robust standard errors. *p<0.1; **p<0.05; ***p<0.01.

3.3 Robustness checks

Several tests are performed to test the sensitivity of our main regression results. First, we suspect that the results were driven by regional differences and, in particular, observations from Brazil, where systems combine low productivity and high grass intake. Including country effects instead of publication effects (Supplementary Table 1) produces comparable results to those reported in Table 4. Second, although the publication effects capture the differences in GWP for CH_4 and N_2O, we re-estimate the models in Table 4 keeping only the observations based on a GWP of 25 for CH_4 and 298 for N_2O. Results are reported in Supplementary Table 2. Although qualitatively similar to our main results, the coefficient on grazing is 1.5 to 2 times higher, and the coefficient on hay intake varies more significantly between model specifications. Third, as some observations from different papers are based on the results of the same farm system model, we include a method effect in regressions 1-4 (Supplementary Table 3). Results remain similar in sign and significance to those in Table 4, but coefficients on grazing are higher. Fourth, we run simple cross-section OLS regressions (Supplementary Table 4). Results still hold, with higher coefficients on both grazing and hay. Finally, removing outliers (identified in Supplementary Figure 1) does not change the sign or the significance of the effects compared to those in Table 1, but the estimates suggest lower coefficients on grazing (Supplementary Table 5).

3.4 Potential explanatory factors

As summarized in Table 1, the effect of cattle diet on the CF of beef is qualitatively unclear. Our results suggest that higher methane emissions due to higher grass intake, in particular through grazing and hay, more than compensate for avoided emissions for the production and distribution of feed from crops. The zero effect of grass silage on the CF of beef may be due to a higher digestibility compared to hay and grazing (Baumont et al. 2009). However, more information on feeds would be needed to conclude on this point, as we would expect the opposite in a number of systems.

Associations between cattle diets and herd management are studied to analyze the determinants of beef CF beyond the methanogenic nature of the grass. We focus on feed efficiency and average slaughter age. Age at first calving, calving rate, and replacement rate of suckler cows are primarily constant for observations from the same publication. Therefore, they are captured by the publication effects in the regressions. Panel regressions with feed efficiency and slaughter age as dependent variables and variables on cattle diet as independent variables are estimated. Results are reported in Table 5.

Table 5: Associations between cattle diet and feed efficiency and cattle diet and slaughter age

	Feed efficiency (kg LW/kg DM) (1)	Slaughter age (months) (2)
Grazing (% DMI)	-0.001^{***}	0.142^{**}
	(0.0002)	(0.060)
Hay (% DMI)	-0.001^{*}	-0.062
	(0.0004)	(0.099)
Grass silage (% DMI)	-0.002^{***}	-0.029
	(0.0002)	(0.071)
Energy-dense forages (% DMI)	-0.00002^{***}	0.00001
	(0.00001)	(0.001)
Model	*FE*	*RE*
Observations	77	77
R^2	0.719	0.249

All estimates are based on ordinary least squares regressions with publication effects. RE = random effects; FE = fixed effects. Values in brackets are heteroskedasticity-robust standard errors. *p<0.1; **p<0.05; ***p<0.01.

Increasing grazing and hay at the expense of concentrates is negatively correlated with feed efficiency (column 1), suggesting that production systems based on grazing and hay require more dry matter intake. The lower energy density of grazed grass and hay compared to concentrates and the fact that grazing requires more energy expenditure related to the physical activity of animals are potential sources of the low feed efficiency of grass-based production systems. Since methane emissions are positively associated with dry matter intake (IPCC 2006), a lower feed efficiency may explain the higher CF of grass-fed beef. Grass silage and energy-dense forages are also negatively associated with feed efficiency compared to concentrates; the higher energy density of concentrates may explain this result.

We find a positive and significant association between slaughter age and grazing but no significant correlation for other forages (Table 5, column 2). A longer period may be needed to reach a given weight when animals are grazing and not supplemented with concentrates. As animals live longer, they emit more methane, which could explain the effect of grazing on the CF of beef (Taylor et al. 2020).

Overall, grazing appears to exacerbate the CF of beef by increasing enteric methane emissions through three channels: (i) the methanogenic nature of grass, i.e. the higher conversion rate of grass intake into methane compared to other feeds (IPCC 2006), (ii) the lower feed efficiency of grass-based cattle diet compared to diets with concentrate supplementation, inducing higher dry matter intake to satisfy animal needs, and (iii) a longer period to reach a given weight. The results are less clear for hay, in particular regarding slaughter age.

4 Discussion and conclusion

4.1 Methodological considerations

Comparing absolute CFs of beef from different LCA studies is a challenge because of the wide heterogeneity of methodological choices regarding system delineation, method of allocation, or method used to compute methane emissions (De Vries et al. 2015). By relying on a systematic and rigorous review of the literature and restrictive selection criteria, this study aimed to create a sufficiently large and homogeneous sample of LCAs of beef production systems to robustly analyze the effect of cattle diet on the overall CF of beef. Despite quite constraining selection criteria, the resulting size of the dataset (n=75) was comparable to other recently published meta-analyses (Lorenz et al. 2019; Lynch 2019), and satisfactory in terms of statistical power.

One limitation in comparing LCAs is the use of different allocation methods. Some studies use the method of system expansion for excess manure, regarded as a substitute to mineral fertilizers (see, e.g., Mogensen et al. 2015), or to estimate the environmental impact of oilseed cakes (Nguyen et al. 2010). Other studies use economic allocation to calculate GHG emissions related to feed based on co-products (Nguyen et al. 2012). Although these differences in the allocation methods affect the CF of beef, this effect is assumed to be marginal, concerning only some feeds, and is captured by the publication effects in the statistical models. In addition, removing beef production from dairy calves from the sample greatly limited the impact of allocation methods in the meta-analysis.

The way enteric methane emissions are calculated is another source of variation. Some studies in the sample rely on the IPCC tier 1 default factors or tier 2 model based on DMI (IPCC 2006), while others use equations available in the literature accounting for feed digestibility (see, e.g., Morel et al. 2016), which corresponds to the IPCC tier 3 method. However, the method to calculate enteric methane emissions is the same for all observations from the same study and is also captured by the publication effects.

The effect of cattle feeding on the CF of beef is addressed by simply distinguishing five categories: grazing, hay, grass silage, energy-dense forages, and concentrates. However, an important heterogeneity among grasses and forages and their management can explain variations in enteric methane emissions and are not accounted for. In their review, Thompson and Rowntree (2020) indicate that the inclusion of legumes in forages, tannin supplementation, lipid supplementation, rotational grazing rather than continuous grazing, as well as the use of grasses based on the C3 photosynthesis pathway (in contrast to the C4 one), are levers to mitigate methane emissions. In the sample, several systems mobilize one or several of these levers. Some systems are based on C4 grass pastures (Pereira et al. 2018). Others rely on lipid supplementation (Nguyen et al. 2012) or on pasture made up of a mixture of grasses and legumes (Kamali et al. 2016). The various feeding strategies encountered in the publications did not allow the building of simple indicators that could be included in statistical models. With a panel approach, we control for feed heterogeneity between studies through publication effects but potentially miss some heterogeneity within studies. However, this heterogeneity is expected to have second order effects on the carbon footprint and should not change our results qualitatively, especially given the limited number of observations in the sample for which specific grasses or forages are used, and given their robustness to numerous sensitivity tests. Similar limitations can be noticed regarding manure management, despite the effects of manure management practices on methane and nitrous oxide emissions (Chadwick et al. 2011).

4.2 Policy implications

What do our results imply for agri-environmental policies? They suggest that moving to more concentrate-based production systems may be a mitigation option for the beef sector. Given that more grass-based beef production systems are systematically more emission-intensive when accounting for LULUC emissions because of the carbon opportunity cost of land use (Balmford et al. 2018; Blaustein-Rejto et al. 2023), limiting the share of grass in cattle diets clearly emerges as a way to reduce the carbon footprint of beef. Promoting finishing cattle on concentrate-based diets, that is systems in which cattle are first grazed and then fed a grain-based diet, could be a significant mitigation lever for the beef cattle sector.

However, intensification raises other issues regarding animal welfare, societal expectations, biodiversity conservation, and other environmental problems such as soil and water acidification and eutrophication. Beef cattle have a preference for pasture rather than feedlot environments (Lee et al. 2013; Dickson et al. 2022), and the reduced space in feedlots can induce locomotion alterations and respiratory discomfort for beef cattle (Macitelli et al. 2020). People also have expectations regarding animal welfare (see, e.g., Bruers 2022; Clark et al. 2017) and a majority of consumers think that the welfare of farm animals is very important and should be better protected (in the EU, e.g., see European Commission 2015). The comparative advantage of concentrate-based beef production systems relative to grass-based systems on the acidification and eutrophication potential has not been established, and some trade-offs between the different environmental dimensions might exist (De Vries et al. 2015). Finally, grasslands may be more beneficial for biodiversity than the combination of intensification and natural ecosystem regeneration, especially if it leads to natural reforestation (Burrascano et al. 2016). This raises potential trade-offs between GHG mitigation and biodiversity conservation.

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