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RESEARCH REVIEW

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# Reducing climate impacts of beef production: A synthesis of life cycle assessments across management systems and global regions

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## Abstract

The global demand for beef is rapidly increasing (FAO, 2019), raising concern about climate change impacts (Clark et al., 2020; Leip et al., 2015; Springmann et al., 2018). Beef and dairy contribute over 70% of livestock greenhouse gas emissions (GHG), which collectively contribute ~6.3 Gt $CO_2$-eq/year (Gerber et al., 2013; Herrero et al., 2016) and account for 14%–18% of human GHG emissions (Friedlingstein et al., 2019; Gerber et al., 2013). The utility of beef GHG mitigation strategies, such as land-based carbon (C) sequestration and increased production efficiency, are actively debated (Garnett et al., 2017). We compiled 292 local comparisons of "improved" versus "conventional" beef production systems across global regions, assessing net GHG emission data from Life Cycle Assessment (LCA) studies. Our results indicate that net beef GHG emissions could be reduced substantially via changes in management. Overall, a 46 % reduction in net GHG emissions per unit of beef was achieved at sites using carbon (C) sequestration management strategies on grazed lands, and an 8% reduction in net GHGs was achieved at sites using growth efficiency strategies. However, net-zero emissions were only achieved in 2% of studies. Among regions, studies from Brazil had the greatest improvement, with management strategies for C sequestration and efficiency reducing beef GHG emissions by 57%. In the United States, C sequestration strategies reduced beef GHG emissions by over 100% (net-zero emissions) in a few grazing systems, whereas efficiency strategies were not successful at reducing GHGs, possibly because of high baseline efficiency in the region. This meta-analysis offers insight into pathways to substantially reduce beef production's global GHG emissions. Nonetheless, even if these improved land-based and efficiency management strategies could be fully applied globally, the trajectory of growth in beef demand will likely more than offset GHG emissions reductions and lead to further warming unless there is also reduced beef consumption.

KEYWORDS
carbon sequestration, grass-fed, grazing, land-use change, soil management

# 1 | INTRODUCTION

On average, beef production emits 2–9 times the greenhouse gases (GHGs) of other animal products, and >50 times the GHGs of most plant-based foods per unit of protein (Clune et al., 2017; Poore & Nemecek, 2018; Searchinger et al., 2019). Beef production is also a major driver of global deforestation and land degradation (Bustamante et al., 2012; Cederberg et al., 2011). Globally, cattle produce ~78% of total livestock GHG emissions (including other livestock like goats, sheep, etc.), and enteric methane ($CH_4$) is the largest beef GHG source, contributing ~35% of total livestock emissions in carbon dioxide-equivalents ($CO_2$-eq; Herrero et al., 2016). The other top sources of total livestock GHG emissions include nitrous oxide ($N_2O$) from soils in fertilized feed production (~25% of livestock $CO_2$ eq emissions), $CO_2$ from soils in feed production (~15% of livestock emissions), $N_2O$ and $CH_4$ from manure management (~12%), and $CO_2$ from land-use/land cover change (~6%; FAO, 2019; Herrero et al., 2016; Hilborn et al., 2018). A recent Intergovernmental Panel on Climate Change (IPCC) report on Sustainable Land Management called for improved livestock management to mitigate climate change, with co-benefits for biodiversity, ecosystem services, and animal welfare (IPCC, 2019; Llonch et al., 2017). In addition, diet switching away from beef to plant-based diets could reduce total food GHG emissions by up to 70% at low cost and with health co-benefits (Springmann et al., 2016; Stehfest et al., 2009). However, given that the demand for beef has dropped very little per capita despite the climate and health impacts of beef (Searchinger et al., 2019), assessing and implementing best practices for beef production is necessary to help mitigate climate change.

Net GHG emissions from beef production vary fourfold globally, indicating that there is substantial room for improvement among a large proportion of producers (Poore & Nemecek, 2018). Opportunities for improvement in beef management and GHG emissions reductions also vary among global regions, depending on environmental factors such as soil type and degradation status, land-use history, vegetation cover, climate, cattle breeds, and socioeconomic factors (Conant et al., 2017; McSherry & Ritchie, 2013). To date, there has been no broad comparison of the potential reduction in beef GHG emissions that are possible by changing beef management systems across global regions. This study aimed to clarify the potential for management changes to minimize and/or offset beef GHG emissions across and within global regions.

Beef management strategies to reduce GHG emissions generally fall under two broad categories: (1) increased efficiency to produce more beef per unit of GHG emitted, and (2) enhanced land-based C sequestration to offset cattle GHG emissions. Increased efficiency approaches often focus on improving feed quality and/or genetic improvements to aid in digestion and increase rates of weight gain while reducing enteric $CH_4$ emissions per unit of beef (Henderson et al., 2015). Land-based strategies, by comparison, emphasize soil and plant C sequestration via improved management of grazed land, including planting trees, addition of C-rich organic compost, and changes in fertilization to increase plant growth, soil C sequestration, and/or reduce emissions of $N_2O$ from soils (Gravuer et al., 2019). Fundamental to both of these avenues for reducing beef GHG emissions is the need to dramatically diminish the rate of conversion of natural grassland and forest area into new pasture or grazing land, since avoided land conversion represents a climate change mitigation potential (3719 Tg $CO_2$-eq/year) roughly equal to past calculations of emissions reductions with improved agriculture and grassland management (4817 Tg $CO_2$-eq/year; Griscom et al., 2017). Within these two broad categories, there are specific management improvements that have been tested in different regions.

Life Cycle Assessments (LCA) are an increasingly popular method for accounting net GHG emissions across an entire beef production system, such as from cradle-to-farm gate or cradle-to-consumption. In particular, comparative LCAs that assess improved versus conventional beef management in nearby systems are useful for determining how much a given management shift might reduce GHG emissions in a given region. Some recent studies have found that beef GHG emissions can be reduced to net-zero or even negative emissions (i.e., net C sequestration) with improved management in temperate ecosystem grazed lands (Herrero et al., 2016; Paustian et al., 2016; Rowntree et al., 2016; Stanley et al., 2018; Teague et al., 2016), although management-related soil C sequestration rates may diminish over time, with added soil C storage potentially reversible under subsequent disturbances and/or climate change (Godde et al., 2020). Meanwhile, ongoing enteric methane emissions from cattle are unavoidable, and are likely to increase with increased beef production. Also, other recent management comparisons suggest no significant reduction in net beef GHG emissions in grassfed/grazed versus grainfed/feedlot systems (Clark & Tilman, 2017; Garnett et al., 2017). Thus, a formal assessment of a broader suite of management changes across global regions is needed to elucidate the potential for substantial reductions in beef GHG emissions.

Here, we present a meta-analysis of comparative LCA studies from different global regions to identify the most successful beef management strategies for reducing GHG emissions per unit of beef and/or per unit of land. We identified comparative LCA studies that evaluated local management changes aimed at reducing beef GHG emissions via increased efficiency, increased land-based C sequestration, or both. We calculated the potential GHG mitigation "Effect Size" for the management shifts in each study, and then explored broad patterns across management strategies, among global regions, and within regions. This approach also identified which management changes were most studied within and among different regions. Our results provide insight into the global and regional potential for a variety of beef management strategies to mitigate beef GHG emissions.

# 2 | METHODS

## 2.1 | Meta-analysis of comparative beef management LCAs

We compiled data from LCAs that compared total GHG emissions from at least two beef management systems within nearby/similar environmental settings to conduct a meta-analysis comparing results across studies. Broadly, LCAs attempt to identify and measure the total GHG flux for the entire production (and sometimes distribution and consumption) of a product; however, the methods embedded within individual LCA models vary across a number of dimensions, including the GHG fluxes accounted, the physical boundary of the study (e.g., cradle-to-farm gate, cradle-to-distribution, cradle-to-consumption; Table S1), and the proportion of on-the-ground data versus literature estimates (McClellande et al., 2018). Given the heterogeneity of LCA models, the resulting net GHG emissions, or C footprints, can vary substantially among studies, and generally are not directly comparable. Thus, we used a meta-analysis approach to control for this heterogeneity in total fluxes between studies by calculating a unitless parameter for each management comparison as:

$$\text{Effect size} = \ln\left(\text{improved}/\text{conventional}\right).$$

We relied on author identification within each study of the "improved" management system relative to the "conventional" system such that improved versus conventional was locally defined. Effect Sizes below zero indicate a net decrease in GHG emissions with improved management. Because the natural log of a ratio calculates the proportional shift, we present Effect Sizes as raw data values (fractions) in figures, and as percent change in the text for ease of interpretation. In a few cases, one or both emission values were negative (i.e., net C uptake into the system), so a positive number on the same order of magnitude as the measured fluxes was added to the control and treatment values to transform them into positive values, preserving the directional difference between control and treatment, before calculating Effect Size.

## 2.2 | Data collection

Our review of papers began in 2018 with collection and review of all citations of beef GHG LCAs from two recent reviews on the environmental impacts of food (Clune et al., 2017; Poore & Nemecek, 2018). Neither of these previous reviews attempted to assess differences among beef management strategies. We then conducted an additional search of the scientific literature using Web of Science and Google Scholar in English, Spanish, and Portuguese, using the search terms: "livestock," "cattle," "beef," "beef production," "beef management," "LCA," "life cycle assessment," "carbon," "greenhouse gas," "methane," and/or "grazing." We assessed all papers identified through these searches by reading title, abstract, and keywords to determine whether the study was a comparative beef production LCA (i.e., compared at least two management systems). We included studies that provided calculated net GHG emissions with errors associated, and statistical comparisons among treatments. We then conducted a forward citation search for all of the papers initially identified since the recent body of literature on beef LCAs has rapidly grown since 2006 (date of first paper found). We also assessed the gray literature, including government reports, dissertations, and conference proceedings from the conference: Life Cycle Assessment in the Agri-Food Sector. Assessment of the gray literature was intended to reduce publication bias, but because of our inclusion requirements (e.g., error, statistics), few gray literature studies were included.

We found a total of 57 comparative beef LCA studies across global regions (Figure 1), with most studies comparing numerous management changes relative to a control, or conventional, management system, generating a total of 292 comparisons of improved versus conventional management ($n$ = 292, Table 1; Table S1). Most studies provided GHG estimates from at least cradle-to-gate, and included input-related GHG emissions (e.g., related to the production and transportation of fertilizers, feed, and water), processing-related GHG emissions (animal maintenance, slaughter, packaging), and output-related GHG emissions (animals, soils, machinery use). From each study, we tabulated which GHG fluxes were included, the system boundaries, the type of LCA model used, the unit of measure (i.e., GHGs produced per head of cattle, per herd, per gram of protein/beef, or per land unit), and all aspects of management changes that were compared (Table S1). Finally, we recorded the net GHG flux for each improved and control management strategy within each paper, and used these to calculate the Effect Size for each management shift. In most cases, average data were provided in tables or text within the study, and in cases where data were only available in figures we extracted data using Data Thief III software (2018). Studies were all published between 2006 and 2018, with a linear increase in the number of studies per year over time (from 2 in 2006 to 10 in 2018), illustrating the growing use of LCA studies to assess and compare beef management strategies.

### 2.2.1 | Management comparisons

Across studies, management changes were generally targeted at reducing total beef GHG emissions. Because the improved versus conventional comparison was locally defined, studies varied somewhat in which specific management change was identified as "improved" (Table 1). We grouped studies into eight categories based on the primary management changes across studies (Tables 1 and S1). The eight categories included two strategies focused on land-based C sequestration to offset beef GHG emissions: (1) conventional field management versus **Integrated Field Management** (improved), which used application of C-rich organic compost, intercropping feed/fodder plants with trees, and/or agroforestry ($n$ = 48); (2) extensive versus **Intensive Rotational Grazing** as the improved practice (i.e., adaptive-multi-paddock grazing or high-intensity, short-duration grazing, $n$ = 58), which aims to promote greater plant growth, improved forage quality, and increase soil C sequestration during field recovery times between short (e.g., hours to days) and intense grazing periods (Rowntree et al., 2016; Stanley et al., 2018; Teague et al., 2016).

We included three efficiency strategies: (3) conventional versus **Improved Feed/Supplements**, achieved by providing feed with greater nutritional value, and/or vitamins to increase growth and

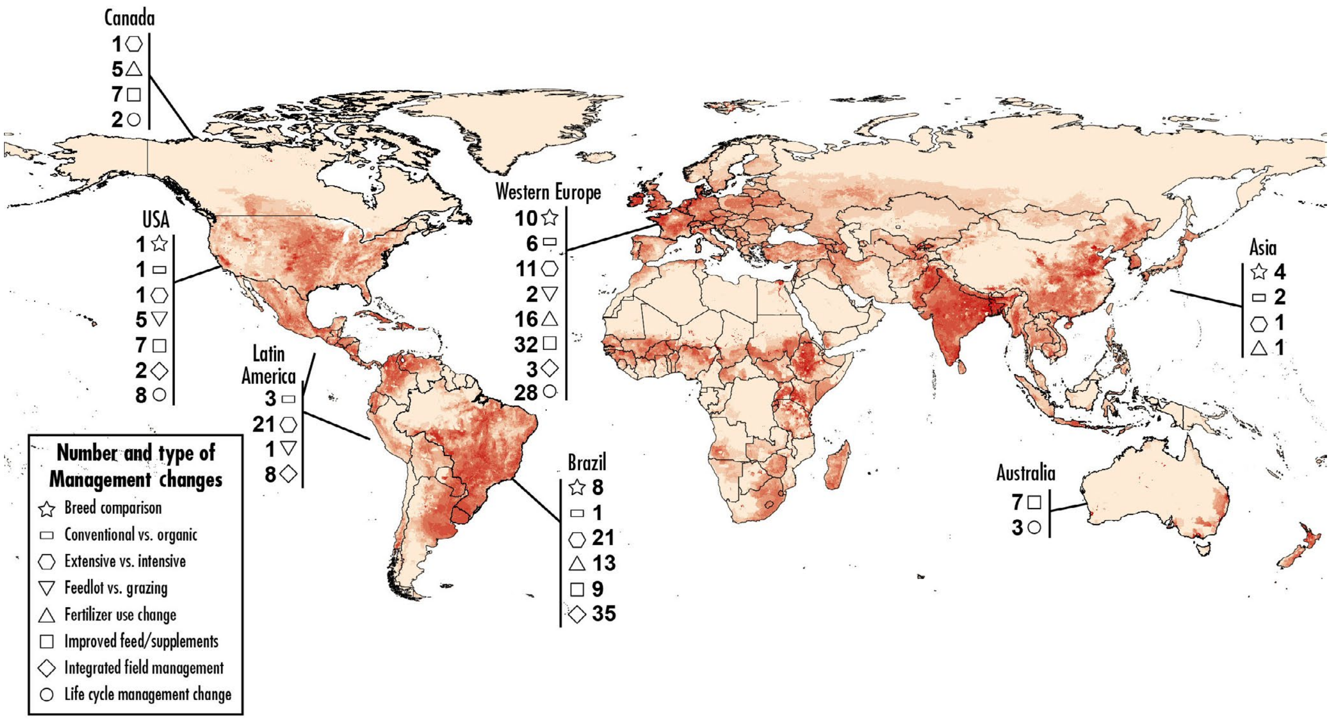


FIGURE 1 Map of the distribution of management changes considered in LCA studies by region. The number and type of management change for calculated Effect Sizes from LCA studies is shown for regions globally, with red shading showing the relative distribution of cattle globally (data source = FAO Global Livestock Environmental Assessment Model; GLEAM). Note that most regions with high density of cattle have comparative LCA studies, except Africa and India. In India, cattle density is very high but there is virtually no beef production from cattle.

TABLE 1 Management change strategies with examples from LCA studies. In all studies, management changes were from what was considered more conventional within the study area/region, toward what was hypothesized to be an "improved" practice for reducing beef GHG emissions

| Management strategy type | Treatment examples |
|---|---|
| Breed comparison | • Crossbreeding to reduce the calving interval, age at first calving, and increase beef yield per animal<br>• Selection for low inbreeding which allows for animals with better growth and efficiency |
| Conventional versus Organic beef production | • Eliminating the use of chemical fertilizers, pesticides, antibiotics, feed additives, growth hormones, and genetically engineered breeding |
| Extensive versus Intensive rotational grazing | • Switching from a non-irrigated, lightly stocked system to more heavily stocked, irrigated systems, often characterized by rotational grazing with short recovery times for plants to regenerate |
| Feedlots versus Grazing finished | • Conducting the finishing phase of cattle production in a pasture or rangeland, rather than a feedlot, with the goal to quickly fatten cattle |
| Fertilizer use change | • Reduction of mineral N fertilization with the aim of reducing GHG emissions from soils<br>• Increase in mineral N fertilization with the aim of increasing plant growth and nutrient content<br>• Addition of manure with the aim of increasing plant growth and nutrient content |
| Improved Feed/Supplements | • Dietary modifications aimed at reducing enteric $CH_4$ emissions and increasing growth efficiency, including changes in forage versus feed levels, pasture grass species with greater nutrient content, dietary supplementation with polyunsaturated lipids, and use of dried grains |
| Integrated field management | • Integrating trees and/or organic soil amendments and/or inorganic nutrients to enhance plant and soil C sequestration in degraded pasture and/or rangeland. |
| Cattle lifecycle management | • Weaning cows earlier so that they can spend additional time in the finishing phase as a means of more efficiently converting feed to weight gain<br>• Younger age at slaughter |

reduce enteric $CH_4$ emissions per unit of beef (*n* = 65); (4) **Breed Comparison** of conventional/common cattle breeds versus improved breeds, such as cross-bred or less-used strains (*n* = 23); (5) conventional versus improved **Cattle Lifecycle Management**, with management changes including shifts in age of slaughter, weight at slaughter, and/or age to pasture (*n* = 45), with the goal of maximizing weight gain per GHG emission at the time of slaughter.

We had two categories that blended efficiency and C sequestration to reduce overall beef GHG emissions: (6) **Feedlot versus Grazing** finished (i.e., grassfed as the improved strategy, *n* = 8), which compared growth efficiency on feedlots versus growth efficiency plus C sequestration on grazed lands; (7) **Fertilizer Use Change** (*n* = 33), with some studies increasing fertilizer application as the "improved" strategy, and other studies reducing fertilizer application as the "improved" strategy (Table 1). Because of this variation, we broke this category down into three subcategories based on the authors' definition within each study: (a) increased inorganic fertilizer application as an improved practice to increase plant growth and improve forage quality (*n* = 21); (b) manure additions as an improved practice to increase plant growth and improve forage quality (*n* = 3); and (c) reduced inorganic fertilizer application as an improved practice to reduce soil $N_2O$ fluxes and thus minimize overall beef GHG emissions (*n* = 9).

Our final category was (8) non-organic beef production versus **Organic Beef Production** (improved, *n* = 13), which was not strictly an efficiency or a C sequestration strategy, but rather a strategy for broader sustainable land use and food production.

### 2.2.2 | Regions

Countries and regions were grouped geographically, since local environmental factors such as climate, soil type, and soil degradation, as well as local beef production standards and cultural influences, like breeds and common feeds, could influence management outcomes. We subdivided some regions that included many studies (e.g., Brazil split from the rest of Latin America, and Canada and the United States separated from each other) resulting in the following regions: Asia, Australia, Brazil, Canada, Latin America, and the United States. The types of management shifts employed were not distributed evenly across regions. The vast majority of Integrated Field Management studies occurred in Brazil (73% of the studies in this category) and Latin America (17%). Western Europe had the majority of conventional versus Organic Beef Production studies (46%), Fertilizer Use Change studies (49%), Lifecycle Management (62%), and Improved Feed/Supplement studies (49%). The majority of Feedlot versus Grazing finished studies were in the United States (63%). In contrast, extensive versus Intensive Rotational Grazing comparisons were more evenly distributed among Brazil (36%), Latin America (36%), and Western Europe (19%; Figure 4). It is unclear whether this variation among regions is an artifact of random differences in scientific interest, or if this indicates the popularity of different sustainable management strategies among regions.

### 2.2.3 | Consideration of covariates

We assessed covariates that could bias results among studies. We tabulated all available covariate data presented within studies that could bias outcomes, including inclusion or not of soil C fluxes, unit of measure, system boundaries, duration of study, and type of LCA model used (Table S1).

First, we noted whether an LCA model included soil C sequestration and GHG emissions from soils and manure. Given that grazing can change C sequestration, loss, and storage levels in soil, inclusion of this flux could have a large impact on the net GHG footprint. All management change categories except Fertilizer Use Change had studies that included soil C in the LCA, with 10%–55% of studies within other categories including soil C sequestration. Thus, we excluded the Fertilizer Use Change in assessment of how inclusion of soil C fluxes altered net GHG calculations in LCAs. Notably, soil C fluxes were absent from a majority of the LCAs, so fewer Effect Sizes included soil C sequestration (*n* = 69) versus omitting this C flux (*n* = 221). Most studies that were focused on land-based C sequestration (Integrated Field Management and Intensive Rotational Grazing) included soil C fluxes.

We gave special consideration to the unit of measurement since some studies calculated GHG emissions per unit of beef, whereas others (or sometimes the same study) calculated GHG emissions per unit of land area. This distinction was assessed because with increased productivity, GHG emissions per unit of beef could decline if efficiency increases, whereas GHG emissions per unit of land could increase if stocking densities increase enough to offset efficiency gains. Most studies calculated GHG emissions per unit of beef or protein (*n* = 240), and some calculated GHG emissions per unit of land area (*n* = 42, Table 2; Table S2).

We also assessed the effect of the system boundary used in each study. Since competing agricultural products would require transportation and distribution C costs similar to those of beef, many livestock LCAs justify using only "on-site" production metrics (e.g., cradle-to-gate) to calculate net beef GHG emissions, often referred to as partial LCAs (Teague et al., 2016). In contrast, full LCAs track all beef GHG emissions, including inputs, production, processing, distribution, and consumption. The majority of beef LCAs identified here were partial LCAs and accounted for GHGs from cradle-to-gate, including all life stages of cattle (*n* = 229). Fewer studies focused on only the "finishing phase" (i.e., fattening period prior to slaughter; *n* = 23), and even fewer studies accounted from cradle-to-slaughter (*n* = 11) or cradle-to-consumption (*n* = 5), with the remaining studies including some variation of these three boundaries. One study included the C cost of Brazilian rainforest deforestation for new pasture within the boundary, comparing this versus improved management in existing pasture, which resulted in the most negative Effect Size measured (-3.25, or 325% reduction in beef GHGs) (Cederberg et al. 2011), but because of this unique boundary this was not included in the statistical analysis of the 8 groupings described above. Most studies included other off-site GHG production prior to the "cradle," like feed and fertilizer production and transportation to the site (*n* = 200). We tabulated the LCA boundary used in each study (Table S1), and we did not attempt to make any correction for different system boundaries aside from the normalizing calculation of the Effect Size.

**TABLE 2** Average Effect Sizes and numbers of management comparisons (*n*) per category. Averages are given for (a) all management change categories by unit of measure and (b) all regions by unit of measure. Negative Effect Sizes indicate a reduction in GHG emissions with "improved" management

| (a) Management change | Unit of measure | *n* | Effect size (mean) | Effect size (SE) |
|---|---|---|---|---|
| Extensive versus Intensive | per land area | 9 | 0.22 | 0.14 |
| Feedlot versus Grazing | per land area | 1 | 0.09 | |
| Fertilizer Use Change | per land area | 9 | 0.86 | 0.24 |
| Improved Feed/ Supplements | per land area | 12 | 0.01 | 0.01 |
| Integrated Field Management | per land area | 6 | −1.12 | 0.39 |
| Lifecycle Management Change | per land area | 5 | 0.01 | 0.01 |
| Breed Comparison | per unit beef | 23 | −0.30 | 0.14 |
| Conventional versus Organic | per unit beef | 13 | 0.06 | 0.04 |
| Extensive versus Intensive | per unit beef | 48 | −0.37 | 0.07 |
| Feedlot versus Grazing | per unit beef | 7 | 0.30 | 0.12 |
| Fertilizer Use Change | per unit beef | 24 | −0.26 | 0.06 |
| Improved Feed/ Supplements | per unit beef | 53 | −0.07 | 0.02 |
| Integrated Field Management | per unit beef | 42 | −0.62 | 0.09 |
| Lifecycle Management Change | per unit beef | 40 | −0.02 | 0.02 |
| **(b) Region** | **Unit of measure** | ***n*** | **Effect size (mean)** | **Effect size (SE)** |
| Brazil | per land area | 6 | −0.37 | 0.15 |
| Canada | per land area | 8 | 0.62 | 0.33 |
| USA | per land area | 4 | −1.17 | 0.66 |
| W. Europe | per land area | 24 | 0.22 | 0.06 |
| Asia | per unit beef | 8 | 0.06 | 0.08 |
| Australia | per unit beef | 10 | −0.18 | 0.03 |
| Brazil | per unit beef | 81 | −0.57 | 0.07 |
| Canada | per unit beef | 14 | 0.00 | 0.02 |
| Latin America | per unit beef | 29 | −0.25 | 0.04 |
| USA | per unit beef | 21 | 0.08 | 0.05 |
| W. Europe | per unit beef | 87 | −0.06 | 0.03 |

## 2.3 | Statistical analysis

Management change category, geographic region, inclusion of soil C fluxes, system boundary, and timespan of the study were all tested as predictors of Effect Sizes in ANOVA, running separate analyses for Effect Sizes based on the two units of measure (i.e., GHG per unit beef or GHG per unit land area). Effect Sizes for each management change category and each region were tested for significant difference from zero to indicate whether there was an overall negative, positive, or neutral effect on GHG emissions. Differences among management change categories and regions were then explored using post-hoc Fisher's least significant difference (LSD) tests. To assess how different management strategies performed within different regions, Effect Sizes for each management change category were also compared for each region separately using post-hoc Fisher's LSD tests. Post-hoc tests were also used to compare the influence of different LCA parameters on Effect Sizes, such as inclusion or not of soil C sequestration, soil and manure GHG fluxes, unit of measure, system boundary, and timespan. Assumptions of normality of data were tested and met. Statistical analyses were conducted in JMP Pro 14.0.0 (SAS Institute Inc., 2017). Significance was determined as $p < 0.05$, and data are shown as averages ±1 SE.

## 3 | RESULTS

Across all management comparisons explored in this meta-analysis ($n = 292$), 73% of studies found significant reductions in beef GHG emissions, indicating that there is broad potential for improving beef's climate impact across regions and producers. However, only 2% of comparisons indicated the potential for net-zero or negative emissions (i.e., C sequestration) over periods <10 years, with most beef management changes still producing net positive GHG fluxes (i.e., Effect Sizes ≥-1, Table S1), highlighting that improved beef production will still produce GHG emissions and contribute to global warming.

### 3.1 | Strategies for land-based carbon sequestration to reduce beef GHG emissions

Efforts to manage plants and soils explicitly for C sequestration on grazed lands, through Integrated Field Management and Intensive Rotational Grazing, had the greatest reductions in net beef GHG emissions, including examples of net-zero emissions, as described below. On average, these two strategies reduced beef GHG emissions by 46 ± 6% ($n = 105$).

#### 3.1.1 | Integrated field management

Integrated Field Management for C sequestration had the largest significant reduction in beef emissions among management strategies, reducing GHG emissions per unit of beef by 62 ± 9%, and reducing beef GHG emissions per unit of land by 112 ± 39% (Figure 2a,b). Thus, this was the only strategy with promise for net-zero or negative emission beef production. Across studies included here, Integrated Field Management included strategies such as organic compost application, silvo-agro-forestry, and seeding to increase plant cover on

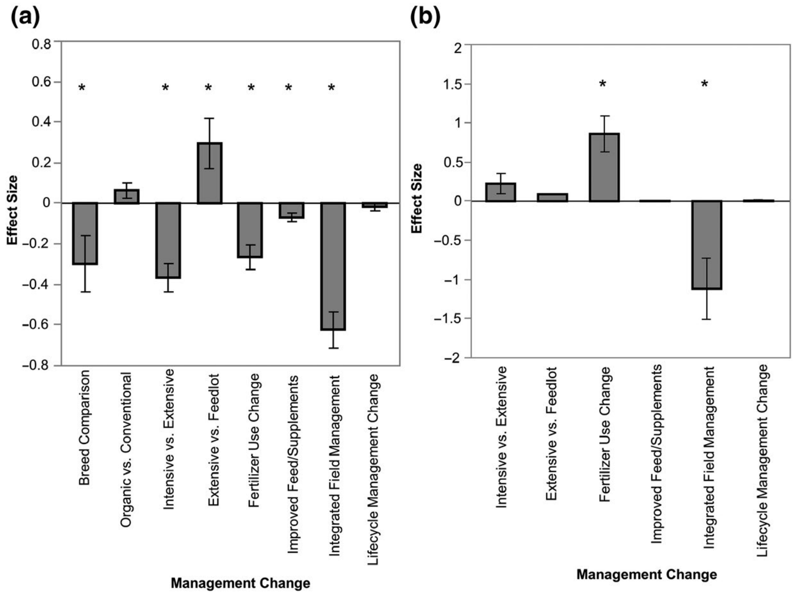


FIGURE 2 Impact of management changes on net GHG emissions from beef production life cycle analyses. Effect Sizes are shown for each management change category averaged across regions, shown (a) per unit of beef and (b) per land area. Comparisons, with $n$ for each unit of measure in parentheses, are shown for: Breed Comparison (unit beef $n$ = 23), conventional versus Organic Beef Production (unit beef $n$ = 13), extensive versus Intensive Rotational Grazing (unit beef $n$ = 48, unit land $n$ = 9), Feedlot versus Grazing finished (unit beef $n$ = 7, unit land $n$ = 1), Fertilizer Use Change (unit beef $n$ = 24, unit land $n$ = 9), Improved Feed/Supplements (unit beef $n$ = 53, unit land $n$ = 12), Integrated Field Management (unit beef $n$ = 42, unit land $n$ = 6), and Lifecycle Management Change (unit beef $n$ = 40, unit land $n$ = 5). Means are shown with one standard error, with significant differences from 0 indicated with *, with statistical details in Table 2a. Negative Effect Sizes indicate the proportion that improved beef management reduced GHG emissions (as indicated for: Breed Changes, intensive grazing, Improved Feed and Supplements, integrated field management), and positive Effect Sizes indicate the proportion that improved beef management actually increased GHG emissions (as shown for extensive grazing compared to feedlots)

grazed lands (Table 1), with most studies applying combinations of these strategies in response to local ecological conditions. The majority of these studies were from Brazil ($n$ = 35) and Latin America ($n$ = 8), and these management changes were also explored in the United States ($n$ = 2) and W. Europe ($n$ = 3; Figure 1).

#### 3.1.2 | Intensive rotational grazing

Intensive Rotational Grazing had the second largest reduction in GHG emissions per unit of beef, reducing emissions by 37 ± 7% compared with extensive grazing system, but there was no significant change in GHG emissions per unit of land for this management strategy (Figure 2a,b). One LCA for the Midwestern USA showed that an Intensive Rotational Grazing system had high enough soil C sequestration rates over 2 years to achieve net-zero GHG emissions (Rowntree et al., 2016), compared with net positive GHG emissions from nearby feedlots (Stanley et al., 2018), in one of the few studies to compare feedlots with alternative grazing practices. Extensive versus Intensive Rotational Grazing management studies were mostly in Latin America ($n$ = 21) and Brazil ($n$ = 21), and were also conducted across other regions, with comparisons from Asia ($n$ = 1), Canada ($n$ = 1), the United States ($n$ = 1), and W. Europe ($n$ = 11; Figure 1).

### 3.2 | Management strategies to increase production efficiency

Of the management changes aimed at increasing efficiency—Improved Feed/Supplements, Breed Changes, and Lifecycle Management Change—Improved Feed/Supplements and Breed Changes both showed significant opportunities for GHG reductions. None of the efficiency-based strategies led to net-zero or negative emissions from beef production (Table S1). On average, these three strategies reduced beef GHG emissions by 8 ± 3%.

#### 3.2.1 | Improved Feed Quality and supplements

Improved Feed Quality significantly reduced GHG emissions per unit of beef by 7 ± 2% (Figure 2a). For example, a Brazilian study showed that improved feed quality, achieved by seeding more nutrient-rich forage grasses into pastures, reduced enteric $CH_4$ production by 20% across seven different feed scenarios (Ruviaro et al., 2015). Improved Feed Quality practices commonly included adding nutrient-rich forage or feed to cattle diets, and were studied in Australia ($n$ = 7), Brazil ($n$ = 9), Canada ($n$ = 7), the United States ($n$ = 7), and W. Europe ($n$ = 32; Figure 1).

### 3.2.2 | Breed Changes

Breed Changes significantly reduced GHG emissions per unit of beef by 30 ± 14% (Figure 2a). Breed Changes generally aimed to increase the efficiency of beef production per enteric $CH_4$ emission of each individual cow. The types of breed comparisons used were variable across studies, but generally included comparisons of cross-bred cattle and/or less-used strains (improved) versus frequently used breeds (Table 1; Table S1). Breed Change comparisons were done in Asia (*n* = 4), Brazil (*n* = 8), the United States (*n* = 1), and W. Europe (*n* = 10; Figure 1). Because of the variability in how Breed Changes were applied, there were no clear groupings to indicate which breeds or cross-breeds were more efficient across regions.

### 3.2.3 | Cattle Lifecycle Management Changes

On average, changes in Lifecycle Management did not lead to significant reductions in beef GHG emissions per unit of beef or per unit of land area (Figure 2a,b), possibly because of the large variability in the management changes implemented in this category, and different conventions in each region. For example, Cattle Lifecycle Management studies variably changed the timing of different production phases, such as time cattle spent in the finishing/fattening phase, the age or weight at slaughter, and/or the age of weaning (Nguyen et al., 2013; Veysset et al., 2010). There were also variable changes in the proportions of heifers versus bulls versus calves, and the annual calving rate and replacement rate of heifers (Pelletier et al., 2010). Thus, while some Cattle Lifecycle Management studies showed potential for reductions in net beef GHG emissions (Taylor et al., 2016), other studies found that the conventional (i.e., baseline or pre-existing) lifecycle management had lower GHG emissions (Lupo et al., 2013). Cattle Lifecycle Management Changes were explored in Australia (*n* = 30), Canada (*n* = 2), the United States (*n* = 8), and W. Europe (*n* = 28; Figure 1).

## 3.3 | Strategies for both increased efficiency and C sequestration

### 3.3.1 | Feedlots versus Grazing

In this meta-analysis, beef produced on grazed pastures and rangelands emitted 30 ± 12% more GHGs compared with feedlot-finished beef per unit of beef (Figure 2a), with no difference per unit of land (Figure 2b). However, this comparison category contained the fewest data points (*n* = 8) among categories, and most studies compared feedlots to conventional, low-intensity grazing, rather than the high-intensity grazing strategy that here showed promise for reducing GHG emissions (see above). Therefore, the comparisons in this category likely underestimate C sequestration benefits from improved, intensive grazing practices relative to feedlots. Broader comparisons for feedlots versus different types of grazing management are merited, particularly in regions where both production systems are used. Comparisons in this category came from Latin America (*n* = 1), the United States (*n* = 5), and W. Europe (*n* = 2; Figure 1).

### 3.3.2 | Fertilizer Use Change for efficiency, C sequestration, and/or reduced soil GHG emissions

Overall, Fertilizer Use Change as a comparison of author-defined improved versus conventional decreased net beef GHG emissions by 26 ± 6% per unit of beef (Figure 2a), but increased GHG emissions by 86 ± 24% per unit of land (Figure 2b). For example, increased inorganic fertilizer application in Irish grazed lands increased GHG emissions per unit of land by 35% because of greater soil $N_2O$ emissions, yet decreased GHG emissions per unit of beef by ~9% because of improved efficiency (Foley et al., 2011).

Considering the sub-categories of Fertilizer Use Change, increased inorganic fertilizer significantly reduced GHG emissions per unit of beef by 33 ± 8%, and decreased inorganic fertilizer also reduced GHG emissions per unit of beef by 11 ± 3% (Figure 3a). Per unit of land, increased inorganic fertilizer significantly increased beef GHG emissions by 62 ± 11%, manure application significantly increased GHG emissions by 173 ± 2%, and there was no change with decreased inorganic fertilizer (Figure 3b).

Thus, gains in efficiency and/or C sequestration must outbalance increases in soil GHGs that commonly result from nitrogen fertilization (e.g., $N_2O$) (Liebig et al., 2010; Wang et al., 2015). Overall, this analysis suggests that gains in efficiency per unit of beaf that were achieved with increased fertilizer use were generally outbalanced by net increases in soil GHG emissions per unit of land. Fertilizer Use Change strategies were explored across Asia (*n* = 1), Brazil (*n* = 13), Canada (*n* = 5), and W. Europe (*n* = 16; Figure 1).

## 3.4 | Non-organic Beef Production versus Organic Beef Production

Overall, there was no significant difference in beef GHG emissions per unit beef between non-organic and Organic Beef Production in this meta-analysis (Figure 2a), and emissions changes per unit of land area were not assessed in the studies. There were relatively few studies comparing non-organic versus Organic Beef Production systems, with just 13 studies from across Asia (*n* = 2), Brazil (*n* = 1), Latin America (*n* = 3), the United States (*n* = 1), and W. Europe (*n* = 6).

## 3.5 | Regional differences in GHG reductions with beef management changes

Our regional analysis indicated that some regions, like Brazil, could broadly improve efficiency and land-based C sequestration to greatly

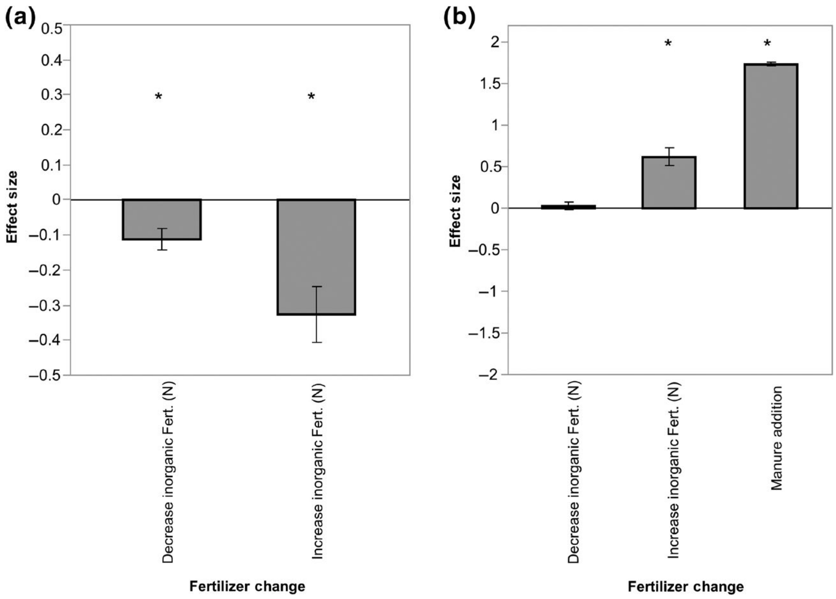


**FIGURE 3** Net effects of different Fertilizer Use Change strategies on GHG emissions from beef are shown. Effect Sizes are shown for different categories of fertilizer use change, including: (a) per unit of beef and (b) per land area. Fertilizer Use Change categories, with n for each unit of measure in parentheses, are shown for: decreased inorganic fertilizer (unit beef *n* = 7, unit land *n* = 2), increased inorganic fertilizer (unit beef *n* = 17, unit land *n* = 4), and manure addition (unit land *n* = 3). Negative Effect Sizes indicate that the improved beef management strategy reduced GHG emissions relative to the conventional strategy. Means are shown with one standard error, with significant differences from 0 indicated with *, with details about which countries were included in each comparison presented in Table S2

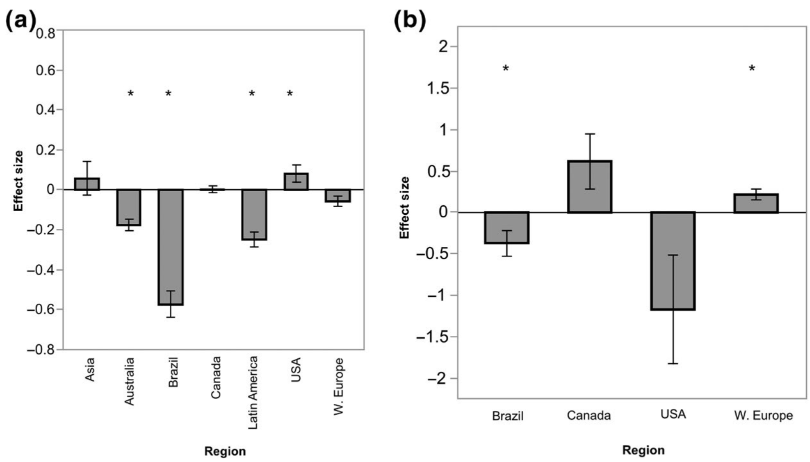


**FIGURE 4** Regional-scale differences in net effects of management changes on GHG emissions from beef production are shown. Average Effect Sizes are shown for each region across management change categories (a) per unit of beef and (b) per unit of land area. Regions, with n for each unit of measure in parentheses, include: Asia (unit beef *n* = 8), Australia (unit beef *n* = 10), Brazil (unit beef *n* = 81, unit land *n* = 6), Canada (unit beef *n* = 14, unit land *n* = 8), the rest of Latin America (unit beef *n* = 29), the United States (unit beef *n* = 21, unit land *n* = 4), and Western Europe (W. Europe, unit beef *n* = 87, unit land *n* = 24). Negative Effect Sizes indicate that the improved beef management strategy reduced GHG emissions relative to the conventional strategy. Means are shown with one standard error, with significant differences from 0 indicated with *, and statistical details in Table 2b

offset beef GHG emissions, while other regions could make substantial reductions with a narrower set of strategies, like increased efficiency in Australia and land-based C sequestration in grazed lands in the United States. Below, we present net changes among regions (Figure 4a,b), and the relative success of each management strategy within each region (Figure S1a–p).

#### 3.5.1 | Large reductions in beef GHG emissions are attainable in Brazil/Latin America

The largest potential for reducing beef GHG emissions per unit of beef was in Brazil, with overall 57 ± 7% reductions in beef GHGs, followed by the rest of Latin America with 25 ± 4% reductions

(Figure 4a). Per unit of land area, management improvements in Brazilian studies reduced beef GHG emissions by 37 ± 15% (Figure 4b). The large reductions in beef GHG emissions in Brazil resulted from successful management changes for both increased growth efficiency and land-based C sequestration. Specifically, Brazilian studies successfully reduced beef GHG emissions by implementing Breed Changes (Figure S1a), Improved Feed/Supplements (Figure S1b), and Fertilizer Use Change (Figure S1h). Also, both decreased and increased inorganic fertilizer treatments reduced GHG emissions per unit of beef (Figure S1i), indicating successful site-specific decisions to manage fertilizer either for better forage (efficiency) and C sequestration, or for reductions of soil $N_2O$ emissions.

For C sequestration strategies, Brazilian and other Latin American studies also successfully used Integrated Field Management, reducing GHG emissions per unit of beef (Figure S1l), and per unit of land (Figure S1m). Brazilian and other Latin American studies successfully implemented Intensive Rotational Grazing to reduce GHG emissions per unit of beef compared with extensive grazing, with the largest reductions in Brazil (Figure S1n). Tropical studies in these regions mainly occurred on lands where cattle are in broadleaf forest biomes that have been deforested (Figure S2a), and many of the large reductions in GHG emissions resulted from implementation of silvo-agro-forestry, with reforestation and integration of trees, forage plants, and livestock on pasture and rangelands.

### 3.5.2 | Successful increased efficiency in Australia

Australian studies achieved the third largest overall reductions in beef GHGs per unit of beef with 18 ± 3% reductions (Figure 4a). This was primarily related to successful implementation of efficiency strategies, which were the focus of all Australian studies (Table S2), and included Improved Feed/Supplements ($n$ = 7; Figure S1b) and changes in Cattle Lifecycle Management ($n$ = 3; Figure S1d).

### 3.5.3 | Carbon sequestration strategies most effective in the United States

In the United States, Integrated Field Management and Intensive Rotational Grazing LCA studies were rigorous as individual studies, albeit rare ($n$ = 2 and $n$ = 1, respectively) in the broader literature, and reflect an emerging interest of these approaches for offsetting beef GHGs in the United States. Data used in these LCA studies were derived from established emissions factors (e.g., IPCC, EPA, FAO, etc.) and from peer-reviewed field studies. Integrated Field Management and Intensive Rotational Grazing resulted in the largest reductions in beef GHG emissions among any strategy for one region, with a net negative change in emissions of 117 ± 66% (i.e., net C uptake into grazed lands) per unit of land area (Figure 4b; Figure S1m,o), compared with conventional grazing techniques. At the same time, US comparisons of Feedlot versus Grazed finished indicated overall increased GHG emissions per unit of beef with grazing (Figure 4a), with most studies using extensive, low-intensity grazing for this comparison (Table S1). This result parallels our results for comparison of feedlots versus grazing across regions (above). Per unit of beef, there were 40% lower GHG emissions from Feedlot versus Grazed finished cattle in the United States (Figure S1f), indicating that the greater efficiency in feedlots outweighed C sequestration benefits of these extensive grazing systems. This difference was much smaller (8%) per unit of land versus per unit of beef in the USA studies (Figure S1g), likely because of lower overall cattle density and thus diffuse GHG emissions per unit of land in grazed systems compared with feedlots. In contrast to the Australian results above, application of efficiency strategies in United States resulted in no significant effect on beef GHG emissions (Figure S1b,d).

### 3.5.4 | Effects of management change on beef GHG emissions for W. Europe, Canada, and Asia

In W. Europe, Canada, and Asia, management “improvements” overall tended to either increase beef GHG emissions, or have no significant effect, although some specific management changes resulted in the intended reductions in beef GHG emissions.

In W. Europe, there were overall increases in beef GHG emissions per unit of land with “improvements” (22 ± 6%, Figure 4b), and there was no overall change in GHG emissions per unit of beef across management change strategies intended to offer improvements (Figure 4a). Still, there were some significant reductions in beef GHG emissions per unit of beef for the region with Improved Feed/Supplements (Figure S1b), Integrated Field Management (Figure S1l), and Fertilizer Use Change (Figure S1h,i). Increased GHG emissions per unit of land for this region were primarily related to Fertilizer Use Change strategies that increased fertilizer application (Figure S1j,k). Intensive Rotational Grazing reduced beef GHG emissions per unit of beef in this region (Figure S1n), but increased emissions per unit of land (Figure S1o). Thus, while there were no overall improvements in W. Europe across strategies tested, there are still some promising avenues for reducing beef GHGs, particularly in relation to reducing use of inorganic fertilizers.

The largest increases in beef GHGs with “improved” management, on a per unit of land basis, were in Canada (Figure 4b), due almost entirely to large GHG emission increases with manure applications (Figure S1j,k).

In Asia, management changes had no overall significant effect on beef GHG emissions (Figure 4a,b), although Breed Comparisons reduced GHG emissions per unit of beef (Figure S1a), and Intensive Rotational Grazing reduced GHG emissions per unit of beef (Figure S1n), indicating the potential for reduced GHG emissions in this region. There were relatively few comparative LCAs for Asia ($n$ = 8 total), so conclusions about regional trends and potential to reduce beef GHG emissions in Asia require more LCA studies.

### 3.6 | Influence of LCA parameters on GHG effect sizes

There were some differences in Effect Sizes related to the parameters used within different LCA studies.

#### 3.6.1 | Inclusion of soil C sequestration

Overall, studies that included soil C fluxes (*n* = 69) had significantly more reductions in net GHG emissions with management change than studies that did not (*n* = 221). On average, studies that included soil C fluxes had 42 ± 10% reductions in GHG emissions, whereas studies that did not include soil C fluxes had 12 ± 3% reductions in GHG emission. While the direction of the effect of a given management change on GHG emissions (increase vs. reduction) was not altered by the inclusion or omission of soil C fluxes, calculating an accurate C footprint for a management strategy is the main goal of LCAs. Since soil C sequestration is one of the primary ways to offset cattle GHG emissions, future LCAs should explicitly include soil C fluxes. Inclusion of soil C sequestration was distributed across management change categories (Lifecycle Management *n* = 19, Improved Feed/Supplements *n* = 17, Extensive vs. Intensive grazing *n* = 9, Integrated Field Management *n* = 8, Conventional vs. Organic *n* = 5, Breed Comparison *n* = 4, Fertilizer Use Change *n* = 4, Feedlot vs. Grazing *n* = 3). Within management change categories, studies that included soil C fluxes had significantly larger reductions in beef GHG emissions for Breed Comparison, Extensive versus Intensive grazing, Fertilizer Use Change, and Integrated Field Management, whereas inclusion of this C flux did not influence average Effect Sizes for the other management categories.

#### 3.6.2 | Inclusion of soil and manure GHG emissions

Inclusion of soil or manure GHG emissions in LCA models was not a significant predictor of Effect Sizes in this study. In general, fewer studies included measures of GHG emissions from soil (*n* = 114) versus studies with neither of these measures (*n* = 179). Soil $N_2O$ fluxes were the most commonly included among soil GHGs ($CO_2$: *n* = 56, $CH_4$: *n* = 15, $N_2O$: *n* = 104). In contrast with soil GHGs, more studies included GHG emissions from manure (*n* = 218) versus no inclusion (*n* = 75), and again, manure $N_2O$ fluxes were the most commonly included ($CO_2$ *n* = 0, $CH_4$ *n* = 72, $N_2O$ *n* = 193).

#### 3.6.3 | Unit of measure

Effect Sizes for two management categories, Fertilizer Use Change and extensive versus Intensive Rotational Grazing, were sensitive to the unit of measure. There were increased beef GHG emissions per unit of land area, but decreased beef GHG emissions per unit of beef for both of these management categories (see above). That is, extensive grazing systems had greater GHG emissions per unit of land, but less GHG emissions per unit beef, compared with Intensive Rotational Grazing systems. Similarly, Fertilizer Use Change increased beef GHG emissions per unit of land, but decreased beef GHG emissions per unit of beef, which some authors explained as an increase in beef production efficiency, despite greater GHG emissions per unit of land. Thus, future LCAs should include beef GHG emissions both per unit of beef or protein, and per unit of land area, for a more comprehensive assessment of the warming effect of changes in beef management.

#### 3.6.4 | Boundary and timespan effects

The physical boundary of the LCA was not a significant factor in ANOVA. The vast majority of Effect Sizes were calculated from partial LCAs that considered beef GHG fluxes from cradle-to-gate (*n* = 229), followed by studies that considered only the "finishing" or fattening phase prior to slaughter (*n* = 23), while cradle-to-slaughter (*n* = 11) and cradle-to-consumption (*n* = 5) were much less common. Although there were no significant differences, all studies that used the first three of these boundaries had average negative Effect Sizes, whereas cradle-to-consumption studies found that management changes increased beef GHGs by 10 ± 16%. This trend might suggest that using partial LCAs that ignore distribution and consumption may over-emphasize the potential reductions in GHGs possible through management changes. More LCAs should consider a full GHG accounting from cradle-to-consumption.

Timespan of study was not a significant factor in our ANOVA, and did not vary greatly among studies. The period of most studies was either 1 year, or the lifespan of one generation of cattle (2–4 years). On average, studies were conducted over 2.3 ± 0.3 years, with only three studies considering timespans ≥10 years, which makes it particularly difficult to assess the longer-term success of C sequestration strategies.

## 4 | DISCUSSION

### 4.1 | Land-based carbon sequestration can help offset beef GHGs in the near-term

Our results indicate that improved pasture and rangeland practices that promote land-based C sequestration in plant biomass and in soil have the potential to contribute to climate change mitigation, at least on decadal timescales. On average, application of these strategies could reduce net beef GHGs by almost half (46%). Notably, we saw large regional variation in the magnitude of the success of these management changes, which could reflect differences in native ecosystem type (e.g., grassland vs. forest), plant community, climate, soil characteristics, land-use history, and the type of integrated field management or intensive grazing undertaken (McSherry & Ritchie, 2013). Thus, land-based C sequestration strategies must be finely tuned to local contexts to maximize their potential for climate change mitigation. Further exploration of these management strategies and how they can be fine-tuned to regional contexts over the longer-term deserves attention.

Reductions in beef GHG emissions in Brazil and Latin America would be of particular global significance, because these areas produce more beef than any other region globally, and have greater GHG emissions per unit of beef than other regions (FAO, 2019), in part because of the $CO_2$ emissions from ongoing deforestation of tropical rainforests for pasture and feed crops. Fertilizer Use Change was particularly successful in Brazil and Latin America in this meta-analysis, indicating successful local decisions balancing reduced inorganic fertilizer use in some studies/areas to minimize soils $N_2O$ emissions, with increased fertilizer use in other studies/areas to promote plant growth and soil C sequestration. Land-based C sequestration strategies were particularly successful in Brazil and Latin America. Silvo-agro-forestry systems can sequester more C than tree plantations or pastures alone because of greater plant biomass production in roots vertically beneath the soil surface (Sharrow & Ismail, 2004), and these systems can also be more productive and profitable than conventional grazed pastures (Murgueitio et al., 2011). These systems can also divert deforestation that could otherwise occur to create new grazing lands, particularly in rainforest regions (Schroth et al., 2004), with avoided forest conversion representing the largest mitigation potential for GHG production from tropical regions overall, and particularly in Latin America (Griscom et al., 2020). Globally, the climate mitigation potential of improved nutrient management in agriculture and grasslands (706 $TgCO_2$ eq/year) is nearly as much as the mitigation potential from agroforestry (1040 $TgCO_2$ eq/year; Griscom et al., 2017), yet even combined these two strategies are unlikely to provide the same level of climate change mitigation as avoided tropical forest conversion (2580 $TgCO_2$ eq/year) and reforestation of marginal grazed land in the tropics (1250 $TgCO_2$ eq/year; Griscom et al., 2020), which would likely require diet shifting away from beef. National policies to reduce deforestation are likely needed to support and promote Integrated Field Management, Fertilizer Use Change, and Intensive Rotational Grazing on existing pasturelands (Bowman et al., 2012).

Temperate grassland Integrated Field Management studies took the approach of diversifying forage species and applying C-rich organic soil amendments, with a few USA studies successfully doubling rates of soil C sequestration (Drinkwater et al., 1998), and reducing beef GHG emissions by over 100% with on-site waste management and compost production (DeLonge et al., 2013; Ryals & Silver, 2013). Thus, soil amendments that contain C and nutrients and promote plant growth without large increases in soil GHG fluxes represent an important potential strategy for reducing grazed beef GHG emissions in grassland regions, although nutrient runoff challenges must be addressed (Gravuer et al., 2019). Furthermore, while one-time applications of compost may not negatively impact some grassland plant communities (Ryals et al., 2016), nutrient addition can reduce natural grassland diversity (Bobbink et al., 1998; Suding et al., 2005), so more research on biodiversity impacts in native grasslands is necessary. It is promising that adoption of C sequestration management on grazed lands in temperate regions appears to be growing, as indicated by increased funding for and promotion of adding C-rich organic compost in Californian and adoption of soil health programs in US beef production (CalCAN, 2019; N4E, 2018), and projections of increased global adoption rates of improved grazing management and other land-based strategies for reducing GHG emissions, like forest and grassland protection, methane digesters, and nutrient management (ProjectDrawdown, 2020). A more comprehensive analysis of current and potential adoption rates of improved beef management strategies within existing beef production systems at national and sub-nations levels would help indicate how much more improvement is possible and likely.

Grazing-based strategies for climate mitigation have been shown to have varying effects on C sequestration rates among sites and over time (Henderson et al., 2015). In particular, the extent of soil degradation varied among regions (Figure S2b), leading to different baselines for comparison with increased soil C storage. Promotion of soil C sequestration is typically more successful on degraded lands that have lost large portions of their native soil C (Figure S2c), and it has been estimated that restoring depleted C stocks represents 47% of the potential for climate change mitigation on agricultural and grasslands (Bossio et al., 2020; Lal, 2004). A full spatial analysis of the extent to which beef management practices could increase soil C sequestration would require better data than is currently available about which strategies are being used on different degraded lands. Long-term dynamics of soil C sequestration on grazed lands must also be assessed, since C sequestration rates in soils typically decline after initial increases that can occur with improved management (Schmidt et al., 2011; Six et al., 2002). For example, soil C stocks increased rapidly for 6 years after conversion of degraded row cropland to intensive rotational grazing in three farms in the southeastern USA, but then C sequestration rates plateaued (Machmuller et al., 2015), and soil C stocks appeared to increase for the first 13 out of 20 years in a chronosequence study in similar sites in the southeastern USA using multi-species pasture rotation (Rowntree et al., 2020). Nonetheless, even the shorter-term recovery of previously existing soil C on grazed lands presents a feasible and substantial reduction in beef GHG emissions, and should be pursued to mitigate climate change.

## 4.2 | To what extent can efficiency strategies reduce beef emissions?

In this meta-analysis, improved efficiency practices provided an average 8% reduction in beef GHG emissions globally, with most of these GHG reductions related to Breed Change, which alone reduced beef GHGs by 30%, a smaller contribution from Improved Feed, and no change with Lifecycle Management. This result contrasts with previous global estimates that Improved Feed could mitigate roughly three times more $CO_2$-eq than Breed Changes and lifecycle management combined (Griscom et al., 2017). While these

GHG reductions related to efficiency gains present a substantial opportunity for climate mitigation, it seems unlikely that increased efficiency alone will reduce net global beef production GHG emissions on par with growing demand (Springmann et al., 2018). Consumption of meat products has more than doubled since 1961 (IPCC, 2019), and an 80% increase in global food GHG emissions is projected from 2009 to 2050 due to population growth and income-related dietary shifts toward more meat (Tilman & Clark, 2014). Even with increased efficiency, greater production to meet greater demand will increase net beef GHG emissions.

Also, in regions where growth efficiency is already nearly maximized, the potential for further gains appears small. For example, in the United States, where feedlots make up 97% of US cattle finishing phases (vs. 3% that are grass-finished; Cheung et al., 2017), efficiency techniques had no overall effect on beef GHGs, possibly because there is already low GHG emission intensity per unit of beef in the United States compared to other regions (Herrero et al., 2016). Large efficiency gains in US beef production in recent decades could actually open the possibility for restoration of some pasture lands back to natural forest and grassland, for further C sequestration opportunities related to United States beef (Fargione et al., 2018). In contrast with the results for the United States, Australia, Brazil, and Asia had significant reductions in beef GHG emissions in studies that implemented efficiency strategies. This regional contrast is probably linked to the lower baseline efficiency of beef production in Australia relative to the United States and W. Europe, and even lower baseline efficiency in parts of Latin America, SE Asia, and Africa, where beef demand is growing fastest (Herrero & Thornton, 2013; Searchinger et al., 2019). Thus, regions with relatively lower baseline efficiency and rapidly increasing demand for beef have a significant opportunity to reduce beef GHG emissions by broader implementation of efficiency management strategies like improved feed, breed and lifecycle changes. More information on which strategies are already saturating in different regions, and the rates of adoption of new strategies, would facilitate calculation of the remaining reductions in beef GHG emissions that are possible and likely.

Considering the strategies that blend efficiency and C sequestration, or trade off one for the other, whether finishing cattle in feedlots versus field grazing is more likely to reduce net beef GHG emissions has been a point of contention in the literature. Many studies show that feedlots are the more GHG-efficient beef finishing strategy because of reductions in enteric $CH_4$ emissions resulting from more digestible feed and greater stocking densities, compared to more fibrous diets and longer finishing times in grazed beef (Capper, 2012; Desjardins et al., 2012; Eldesouky et al., 2018; Lupo et al., 2013; Pelletier et al., 2010; Stackhouse-Lawson et al., 2012; Swain et al., 2018). Other studies argue that finishing cattle on pasture or rangeland, rather than in feedlots, is more beneficial to the climate because it promotes land-based C sequestration and requires less climate-intensive feed crops while also supporting natural grassland conservation and animal welfare (Chiavegato et al., 2015; Garnett et al., 2017; Llonch et al., 2017; Rowntree et al., 2016; Stanley et al., 2018; Teague et al., 2016). Also, greater growth efficiency on feedlots versus grazed lands is often counter-balanced by other negative environmental impacts, including greater water pollution (Hilborn et al., 2018), soil erosion (Janzen, 2011), and broader land degradation and GHG emissions from associated agricultural areas where feed is grown (USDA, 2015), which may or may not be included in LCA calculations. The majority of comparative LCAs on this topic assessed feedlots versus extensively grazed lands, rather than the Intensive Rotational Grazing strategies that presented the most potential for C sequestration. Also, iIntegrated Field Management and Fertilizer Use Change with Intensive Rotational Grazing during finishing phases have the potential to further improve fodder quality, increase growth efficiency, and promote land-based C sequestration. Thus, more LCAs should compare feedlot efficiency gains with efficiency plus C sequestration gains on lands withIntensive Rotational Grazing plus other improved management strategies.

## 5 | CONCLUSION

Overall, this meta-analysis suggests that substantial GHG emissions reductions are possible in beef production systems, both via increased efficiency and land-based C sequestration. To improve these estimates, LCA studies should uniformly include soil C sequestration fluxes, be conducted over longer timespans to assess the stability of added C storage, and expand boundaries to include cradle-to-consumption for a full accounting of beef GHG emissions. The broad-scale feasibility of large reductions in beef GHG emissions is difficult to assess because of a lack of data on the proportion of beef production in different management systems for most regions. Future research should assess which management shifts are saturating in different regions in terms of reduced beef GHG emissions, versus which strategies still present “low-hanging fruit” for increased broad-scale adoption. Emissions transition costs between beef management systems are also largely unknown, and such transitions would need to be considered within a larger sustainability context of local livelihoods, environmental impacts, food waste prevention, and animal welfare. Broad-scale implementation of more sustainable beef production practices would require political, economic, and institutional support, which have been intermittent and unreliable, particularly for many of the tropical regions that hold the greatest technical potential for reducing net beef GHG emissions. In conclusion, many of the efficiency and land-based C sequestration strategies assessed here hold broad-scale potential for mitigating the climate change impact of beef production, particularly if applied as suites of strategies tailored to particular regions. Nonetheless, given the unlikelihood that these strategies will be applied globally to maximum effect, beef management changes for increased efficiency and C sequestration should be considered as complements to efforts to curtail the growing global demand for beef in order to achieve large-scale, sustainable reduction in food GHG emissions.

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## AUTHOR CONTRIBUTIONS

DFC, ALC, AH, and KC conceived of the project and undertook the initial literature review. DFC undertook statistical analyses and productions of figures and tables. DFC, RR, JK, and CK wrote and edited the manuscript.

## DATA AVAILABILITY STATEMENT

Figures 1–4 have all associated raw data available as online Table S1. Data for Table S1 are also publicly available data from FAO GLEAM for cattle distribution globally (http://www.fao.org/gleam/en/). Supplementary Figures also uses the FAO Gleam dataset, plus publicly available data for Olson's global ecoregions distribution (https://www.worldwildlife.org/publications/terrestrial-ecoregions-of-the-world), soil C stocks from SoilGrid (https://data.isric.org/geonetwork/srv/eng/catalog.search), soil degradation from FAO (http://www.fao.org/soils-portal/soil-degradation-restoration/global-soil-health-indicators-and-assessment/soil-heath-physical/en/).

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## SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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