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Beef production represents a complex global sustainability challenge including reducing poverty and hunger and the need for climate action. Understanding the trade-offs between these goals at a global scale and at resolutions to inform land use is critical for a global transition towards sustainable beef. Here we optimize global beef production at fine spatial resolution and identify trade-offs between economic and environmental objectives interpretable to global sustainability ambitions. We reveal that shifting production areas, compositions of current feeds and informed land restoration enable large emissions reductions of 34–85% annually (612–1,506 $MtCO_2e\ yr^{-1}$) without increasing costs. Even further reductions are possible but come at a trade-off with costs of production. Critically our approach can help to identify such trade-offs among multiple sustainability goals, produces fine-resolution mapping to inform required land-use change and does so at the scale necessary to shift towards a globally sustainable industry for beef and to sectors beyond.

Beef production and consumption has a large environmental footprint, including substantial greenhouse gas (GHG) emissions[1], mainly through enteric fermentation[2] and land-use change[1], representing ~40% of all livestock emissions[3]. To reduce negative environmental impacts, many studies have called for beef consumption reductions[4,5]. However, despite the clear importance of diet shifts, a strategy focused solely on demand reduction is unlikely to produce rapid sustainability outcomes due to slow behaviour change[6], coupled with rising overall meat demand[7] spurred by population growth in many low- and middle-income countries. Beef is an economically important agricultural commodity, representing ~19% of total global livestock production value at a return of >US$245 billion globally in 2020[8]. In addition, livestock farming supports the livelihoods of nearly 600 million smallholder farmers in the developing world[9]. This is particularly important in the context of the Sustainable Development Goals (SDGs)[10] and global commitments towards reducing inequalities, responsible consumption and production and combatting climate change. The complexity of this challenge requires a multipronged approach, including promoting

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dietary change to reduce demand but also reaching the current and future demand with more sustainable beef production.

Improving 'sustainability' across the global beef supply chain is a complex balance of multiple objectives including reducing emissions, reducing the impact on natural ecosystems and maintaining or increasing incomes. The choice of where and how we produce beef to reach a level of demand involves trade-offs between these objectives. For instance, minimizing economic costs can entail producing beef in marginal land, such as rangelands and forested areas, with low land value and low production costs. However, lower forage yield and quality in extensive grazing systems lead to higher emission intensity and low production efficiency that can result in land clearing for pasture or cropland expansion[11]. Conversely, shifts to grain-based diets and pasture intensification tend to lower emission intensity of meat production, resulting from higher forage quality[12,13] but may also substantially increase production costs. In addition to lower emission intensity of non-CO_2 emissions from enteric fermentation and manure management, intensification of production allows for land sparing and carbon sequestration strategies, for instance, reforestation[14].

Sustainability shifts are driven at multiple scales by the choices of suppliers, national regulatory agencies and consumers and thus require mechanisms to assess the impacts of changes to livestock production across different objectives, at scales and resolutions that adequately support these choices. While there are reasonable farm-scale analyses of cattle production systems against multiple objectives[15,16], these lack scale that could drive the sustainable transition of an industry. There are also global analyses of livestock that simulate the food system to examine trade-offs between environmental and economic outcomes[17,18] under specific market conditions. However, these often provide outcomes at continental or broad regional geographic areas and thus lack the spatial granularity to inform actors across the beef sector on the land-use management needed to minimize trade-offs in economic and environmental goals. Here, we fill these gaps by taking a multidimensional lens to assess sustainable beef supply and spatially optimize where and how beef could be produced to meet global demand while minimizing production costs and GHG emissions at 5 arcmin (~9.26 km at the equator) resolution across the globe.

To estimate economic costs of production, we consider land-use transition, opportunity, feed production and transport costs. GHG emissions include: non-CO_2 emissions from enteric fermentation, manure management and fertilizer application; CO_2 emissions from the change in belowground and aboveground biomass; and postfarm emissions resulting from transport, export, processing and packaging. We also consider the 'carbon opportunity cost'[19]—the carbon sequestration potential through active or passive forest restoration if the current beef production ceases. We include the cost of restoration in total production costs and the aboveground and belowground biomass change resulting from reforestation in total GHG emissions.

For each grid cell, a weighted sum of production costs and GHG emissions is calculated and minimized for each feed mix, given the attribution of a weight on the two objectives. The grid cells with the lowest weighted sum are selected for beef production until beef demand is reached. Beef production, costs and emissions for these selected grid cells are then aggregated globally to generate a single Pareto-efficient solution. By changing the weights on production cost and GHG emissions, we trace out a set of efficient solutions (Pareto frontier[20]; Methods). Each solution along the frontier corresponds to an optimal spatial arrangement of feed compositions and locations that minimize a given weighted sum of production costs and GHG emissions. The steepness of the Pareto frontier indicates the gain of one objective at the loss of another, for instance, GHG reduction (gain) per dollar spent (loss).

We examine five solutions along the frontier in more detail where (1) only economic costs are minimized, (2) costs are minimized and the solution constrained to not increase GHG emissions, (3) GHG emissions are minimized and constrained to not increase production costs, (4) only GHG emissions are minimized and (5) GHG emissions are reduced by 45% from 2010 levels to approximate the GHG reduction identified by the Intergovernmental Panel on Climate Change (IPCC) to limit warming to 1.5 °C by 2030[21], assuming emissions in other sectors are reduced by the same proportion.

We first assess optimal beef production with a scenario where the location and feed composition within national borders can change but where the total current production for each nation is preserved (national beef). This spatial constraint capitalizes on higher reliability of country-level beef production information and is consistent with the spatial level of national agencies and sectorial bodies relevant to the industry. We also examine the removal of this national constraint and allow reallocation of production beyond national borders (beef without borders), to assess comparative regional advantages and explore broader insights into the potential benefits of a global-level sustainable redesign of beef production.

Efficient production of national beef within countries

Changing the feed composition of the ration fed to cattle and the location of its production within each country has the potential to provide substantial benefits in the form of production cost savings and reduced GHG emissions. Our results show that global GHG emissions from beef production could be reduced by 1,235 $MtCO_2e\ yr^{-1}$ (70% reduction) while still producing the same amount of beef at the simulated current production cost (Fig. 1a, lower GHG). It is possible to reduce production costs by US\$43 billion yr^{-1} (36% reduction compared to current) for the same amount of GHG emitted (Fig. 1a, lower cost). At this point on the Pareto frontier, important reductions of GHG emissions can be made at very low cost; US\$1 spent leads to a reduction of 387 $kgCO_2e$, which translates to a cost of US\$2.58 per tCO_2e.

The global GHG emissions reduction target for beef production of 790 $MtCO_2e\ yr^{-1}$ on 2010 levels could be achieved along with a reduction in production costs of US\$22 billion yr^{-1} compared to the current production (18% cost reduction). At this point on the frontier, US\$1 spent yields a 26.38 $kgCO_2e$ reduction, which translates to a cost of US\$38 per tCO_2e. Beyond this solution (towards lower GHG and minimizing GHG solutions), reducing emissions becomes more costly (Fig. 1c) due to the increasing cost of forest restoration and feed production (Fig. 1b). Along this portion of the Pareto frontier, further reductions in GHG emissions come from shifting production from low-cost grazing systems to more expensive grain-based mixed systems (Extended Data Fig. 1), for instance, with intensification of production in the Corn Belt region of the United States, Northeast China and Central Asia (Fig. 1a, map insets, and Extended Data Fig. 2). Production is also shifted away from areas with high carbon sequestration potential to make space for forest restoration, for example, Eastern United States and East China (Extended Data Fig. 2).

In the case where costs are minimized, opportunity and feed production costs are substantially reduced, while establishment costs show a slight increase (Fig. 1c). Feed mixes composed of grass and crop residues are chosen over grain in large extents of South America, Africa, India and Australia (Extended Data Fig. 2) because of their low production cost. Areas with low opportunity cost (that is, with low profit lost by shifting to cattle feed production) are prioritized; for example, Northeastern and Western Australia, Northern China and parts of the Amazon basin in Brazil (Fig. 1a, map insets). Prioritizing the reduction of economic costs results in a notable increase in emissions from aboveground carbon loss (Fig. 1b), associated with a larger proportion of beef produced in new areas (Extended Data Fig. 3). Under this solution, 28% of the emissions from the loss of carbon stock would occur in the United States, followed by 16% in Canada and 13% in China. Conversely, substantial carbon sequestration through forest restoration could offset all other emissions related to the production of cattle feed if emissions are minimized. A total of 2,809 $MtCO_2e$ could be

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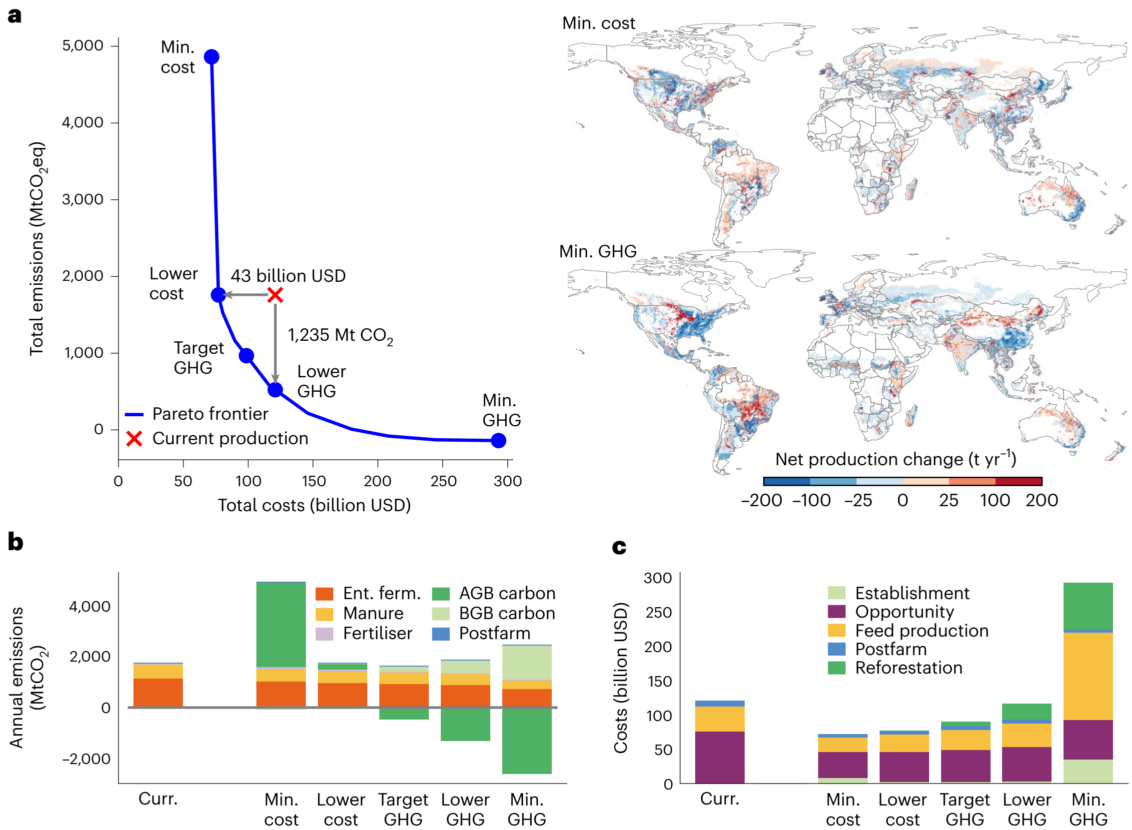

Fig. 1 | Efficient global beef production for the National Beef scenario. **a**, Pareto frontier of global beef production with the same quantity of beef produced in each country (national beef scenario). Five solutions along the frontier show feasible combinations of GHG emissions and production cost: minimize cost, achieves production at the lowest feasible production cost; lower cost, minimizes production cost constrained to not increase GHG emissions; GHG target, meets global GHG emissions reduction target at minimum cost; lower GHG, minimizes GHG emissions constrained to not increase cost; and minimize GHG, achieves production with the lowest feasible GHG emissions. Map insets show the change in spatial distribution of beef production when production costs are minimized versus current production (2018 levels) and when GHG emissions are minimized versus the simulated current production. **b**, Breakdown of emission sources among enteric fermentation (ent. ferm.), manure, fertilizer, aboveground biomass (AGB) carbon, belowground biomass (BGB) carbon from land clearing and reforestation, and postfarm (composed of transport, export and processing) emissions, for current production and the five solutions described above. **c**, Sources of economic costs, including establishment, opportunity, feed production, postfarm (transport and export) and reforestation costs. Economic costs are shown for the simulated current production and the five solutions described above.

sequestered annually on areas currently occupied by cattle feed, with 20.5% of this potential occurring in the United States, 20.1% in China and 18% in Brazil. We do not assess whether deforestation for cattle feed production or reforestation on existing cattle feed areas are viable given environmental regulations in those countries.

Impact of preferences and the potential of synergies

How we prioritize between minimizing GHG emissions and production costs can generate very different solutions along the Pareto frontier. If the sole preference is to minimize production costs, then over half (55%) of the demand is met through current production locations and feed compositions (Fig. 2a). Only reducing costs results in 18% of production from increases in productivity on current production areas, either through yield increases (12%) or changes in production systems (6%) (for example, from grazing to mixed system). Inefficient areas (31% of current production) either see a reduction in beef production (6% of current production) or a complete removal of production without forest restoration (25% of current production over 424 million ha) (light and dark blue grid cells in Fig. 2a, respectively). In this case, no cattle feed would be relocated for the purpose of reforestation given the additional restoration cost. Nearly a quarter of production (23%) comes from expansion into new areas, to a large extent on grasslands (Extended Data Fig. 3). Most of these areas are in regions with limited or no opportunity cost from other agricultural activities; for example, the Great Plains of the United States, Western Australia and Northern China and in 4.7% result in clearing of natural habitats (Extended Data Fig. 3).

If emissions are minimized, nearly a third (31%) of the efficient production relies on increased productivity in current production areas (25% yield increases and 5% production system change) and 46% of demand still gained from current unaltered production (Fig. 2b). Further, expansion accounts for 19% of total production feed (Fig. 2b). In this case, expansion is needed to relocate cattle feed from current areas that would be optimal for carbon sequestration through reforestation. Indeed, 28% of current production would be removed for restoration, mainly in Eastern United States, Southeast China, Southeast Asia and Brazil (dark green areas in Fig. 2b).

Over 40% of production can come from areas of agreement between strategies (listed in Fig. 2b) that prioritize cost or emissions reduction (agreement; Fig. 2c). Most of this production would remain identical to the current production (31.7% of total production, for example, in Mongolia, Uruguay and parts of Argentina, Western United States and large parts of Europe) or come from productivity increases (8.5% of total production, for example, in Brazil and Australia). Conversely, relocation of production through expansion (1.3% total production) or complete removal (1.8% of current beef production or 115 million ha)

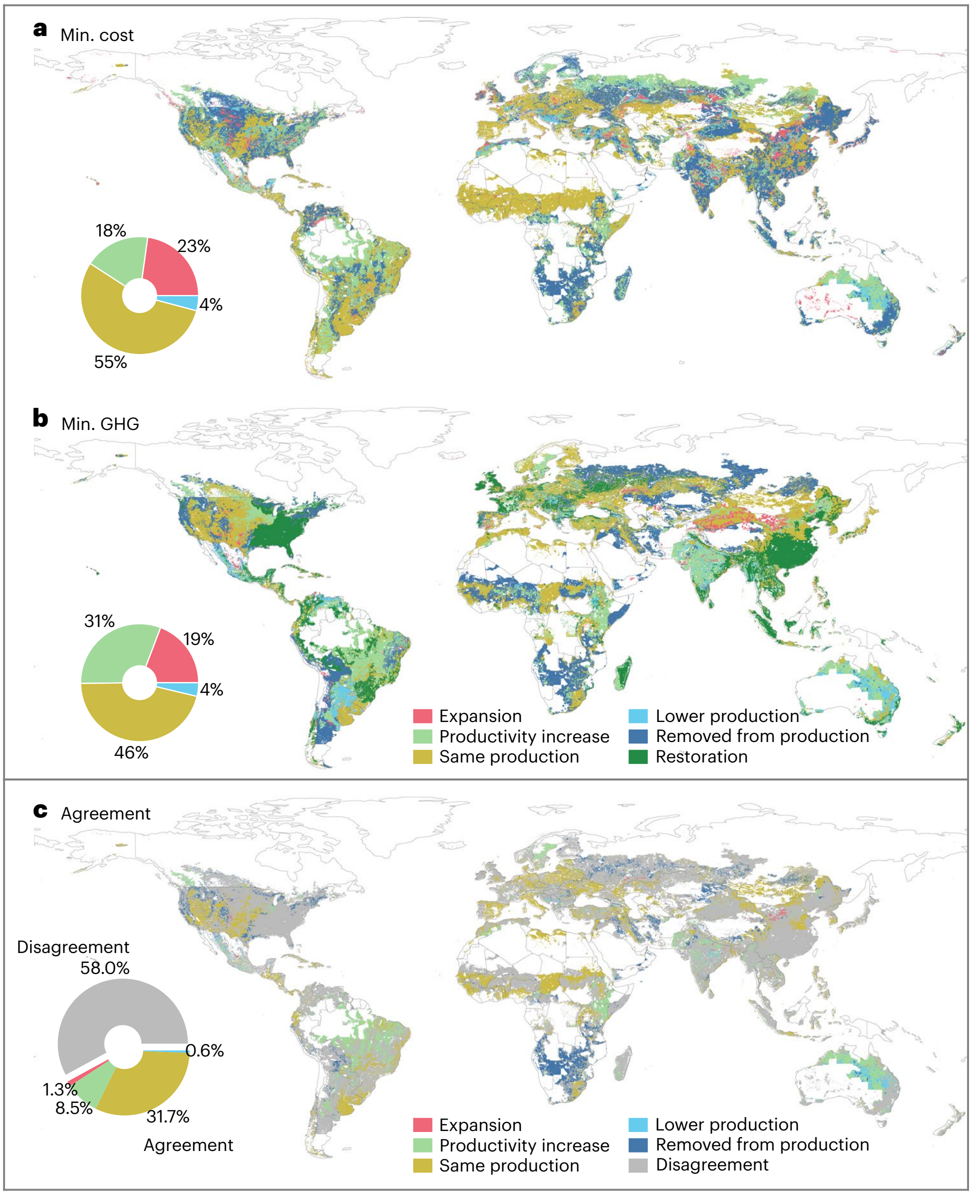

Fig. 2 | Land use strategies to achieve efficient beef production. a,**b**, Most efficient strategies and locations that minimize production costs (**a**) and minimize emissions for the national beef scenario (**b**). The pie charts (**a**,**b**) indicate the percentage of optimal beef production from different actions: increase production through land expansion or increase in production on current area; maintain current production; and decrease production or removal of current production with or without forest restoration. **c**, Map showing where and which actions agree and where actions disagree to produce the most efficient feed between the solutions minimizing costs and minimizing GHG for the national beef scenario. The pie chart shows the percentage of beef production in cells where the actions and locations agree or disagree and which actions are the same for the two solutions.

are rarely considered efficient win–win strategies (Fig. 2c). Adopting production strategies on the basis of this agreement, irrespective of preferences for economic or emissions concerns, may still provide a stepwise improvement within the beef sector. Indeed, implementing these agreed system changes whilst maintaining current production in other areas shows that global beef demand could be met with a 10.8% reduction in CO_2e (~191 MtCO_2e yr^{-1}) and a 2.4% costs reduction (~US\$3 billion yr^{-1}) (Extended Data Fig. 4).

Beef without borders

Reimagining where and how we produce beef around the globe, without the restriction that current national production is maintained, could bring about even greater efficiencies. Beef without borders results in 83% reduction in GHG emissions for the same economic cost as current beef production (1,454 MtCO_2e per annum reduction, lower GHG solution in Fig. 3). Even if emissions remain stable, considerable savings of 38% (US\$45 billion yr^{-1}) across global beef production could be made while still meeting the 2018 beef demand (Fig. 3, lower costs solution). The emission reduction target could be achieved while reducing total costs to the industry by US\$30 billion yr^{-1} (Fig. 3, target GHG solution).

When prioritizing cost reduction, beef production would shift from areas of high production costs (for example, land value and producer prices) such as North America, Europe and East Asia, to areas with lower costs of production such as parts of Latin America, Sub-Saharan Africa, Central and Southeast Asia and Oceania (Fig. 3, map insets). In this case, the fraction of beef produced in new areas would increase to 32% of total production (Extended Data Fig. 3). Conversely, giving a greater importance to minimizing GHG emissions would shift

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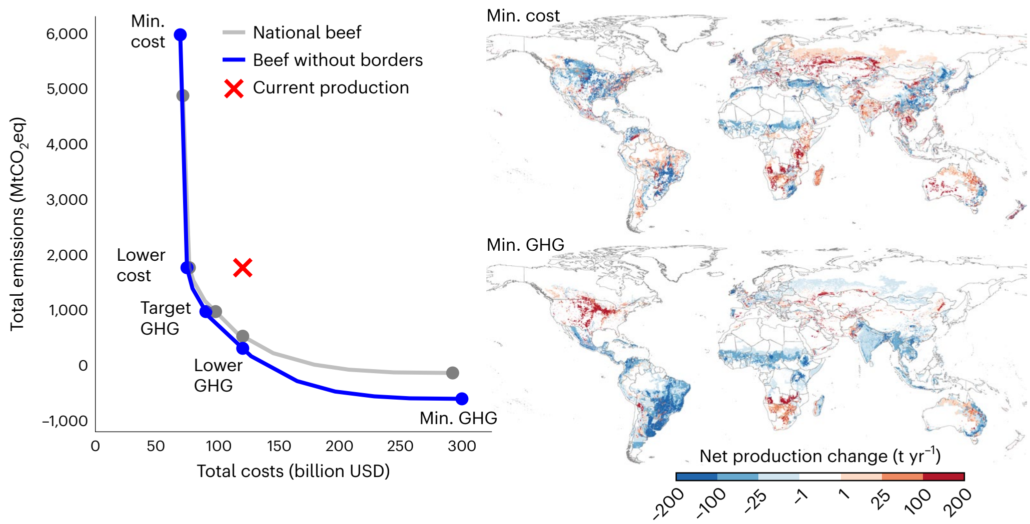

Fig. 3 | Pareto frontiers of beef without borders (blue) compared to national beef scenario (grey) and simulated current production. Map insets show the net change in the spatial distribution of beef production in beef without borders compared to the simulated current beef distribution.

production from Latin America, Oceania, the Sahel region and Asia to North America and Southern Africa where crop and grass yields tend to be higher and emissions intensity of beef production is lower. Across all solutions along the Pareto frontier, North America has the largest potential to increase beef production (up to 30 Mt or 45% of global production) whereas on average, production in Latin America and East Asia would be reduced compared to its current production (Extended Data Fig. 5). This increase in production in some regions would lead to substantial increases in exports, as up to 38% of total production could be exported compared to ~19% currently[8], leading to increasing postfarm emissions and costs (Extended Data Figs. 6 and 7). Similarly, shifts in the geographic location of key production areas could have important implications for biodiversity and cultural values that should be assessed as a matter of urgency.

Uncertainty implications from a global model

The complexity and scale of this model allows for multiple potential sources of uncertainty either through a lack of data at a global scale requiring estimation (for example, opportunity costs via agricultural commodity returns, field sizes and estimated profit margin; Methods) or through ranges in published data (for example, emission intensity of enteric fermentation[11] or soil carbon change[22]; Supplementary Table 4). We conducted Monte Carlo simulations and sampled values for the most uncertain parameters (Methods). Despite this uncertainty, the relative improvement compared to the current production remains substantial with a high confidence (90%) that at least savings of US$30 billion yr^{-1} (25% of current total costs) could be achieved in the national beef scenario with emissions constant at the 2018 levels (Fig. 4). Further, we estimate at 90% likelihood a reduction in emissions between 612 and 1,506 $MtCO_2eq\ yr^{-1}$ (34% to 85% reduction compared to 2018 emissions) if current economic costs were to be kept constant.

Several datasets are required for our optimization and some of these datasets are only available from model outputs[11,23]. The use of such datasets increases the potential for accumulating uncertainty and further honing would improve the reliability of these inputs. For example, land value, estimated here as opportunity cost of agricultural land and area currently used for cattle feed production have a large contribution to total global costs (Extended Data Fig. 7). Furthermore, enteric fermentation is a large factor in cattle emissions (Extended Data Fig. 6) and improving information on different beef production systems[11], for example, types of feed consumed, location of feed production and animals and emission intensities related to enteric fermentation

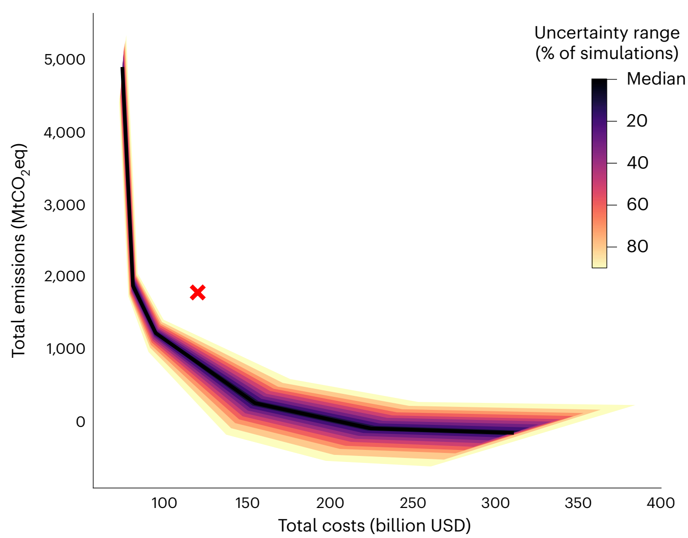

Fig. 4 | Uncertainty range of optimization results for national beef scenario. Monte Carlo sampling using uniform distributions was conducted for 11 parameters that were deemed to be most uncertain and most likely to affect the results. The 5th–95th and 25th–75th percentiles of economic costs and emissions are chosen to create a range for each solution along the Pareto frontier, in this case using six solutions. The range of efficiency is compared to the current production (red cross).

could help to increase the reliability of inputs to assess sustainable beef production. The limitation of such information is ubiquitous for global assessments of livestock production and, therefore, further research to improve such critical information could have considerable benefits to policy and industry decisions to support a sustainable beef future.

Given the large contribution of the change in aboveground and belowground biomass from land clearing and reforestation to total emissions, the time horizon used to estimate the change in carbon stock can substantially influence total emissions. For instance, considering a time horizon of 50 yr rather than 30 yr leads to greater total carbon sequestration but this carbon stock is annualized over a longer period, thus resulting in a lower annualized stock from reforestation and lower reduction in total emissions (Extended Data Fig. 8). The uncertainty related to carbon sequestration can vary widely depending on forest restoration strategies. However, even if no restoration occurs on current cattle feed areas, substantial cost savings and emission reductions are still attainable (Extended Data Fig. 9).

In addition, the IPCC temporal horizon used to determine the global warming potential of emissions[24] may lead to an underestimate of short-lived climate pollutant emissions such as methane resulting in probable conservative estimate of mitigation potential from reducing enteric fermentation emissions. Further, the temporal scale does not capture the potential lags in achieving benefits from relocating beef production (for example, acquiring different breeds or supply chain disruptions) leading to potential underestimation of the costs of transition for shifts in feed systems.

Improvements in one or the other of the objectives, for instance, the reduction of production costs, could affect prices and demand for food commodities and have a different impact on environmental performance of beef production. Different approaches to modelling global livestock production are better suited to capture such economic feedbacks resulting from changes in feed demand[25]. Combining these two modelling approaches could provide the opportunity to explore sustainability improvements in livestock production at high spatial resolution while accounting for changes in demand and prices resulting from these land-use changes.

Potential sustainability lessons from a global perspective

The important economic and emissions reduction gains observed in this study from relocating where we produce beef and what cattle are fed, highlight not only complexities inherent in shifting towards a globally improved industry but also potential lessons that could guide such a shift.

Our beef without borders scenario presents sector changes that would require unprecedented global cooperation among producing countries to reach the full extent of potential benefits. Although substantial GHG emissions reductions could be achieved (minimize GHG solution in Fig. 3), unconstrained global reallocation could lead to lower protein availability in regions with food insecurities and a regress in achieving other SDG, for instance, eliminating hunger. Therefore, the consideration of the impact of beef relocation on other SDGs is crucial for policy development. Nonetheless, the inclusion of this scenario not only serves to envision the potential envelope of benefits from a reimagined global beef industry but also highlights the comparative advantages of different regions for either minimizing production costs (for example, Oceania and Central and South Asia) or reducing global emissions (for example, North America, Europe and Southern Africa).

Restricting beef production changes to within country borders (national beef scenario) is a more realistic scenario but is not without complexity. Taking inefficient areas out of production would probably face opposition without active national-level policies to provide incentives and supports to shift to alternative livelihoods and may take time to realize its full potential. However, by examining land-use decisions and their environmental and economic outcomes at fine spatial resolution, this study assesses the biophysical and economic feasibility of land-use change needed for sustainable transformation of the beef sector[26]. As such, our results could help policy-makers to identify areas or types of feed with the potential to improve efficiencies and enable further articulation of local level dynamics that can inform more nuanced approaches based on social and institutional conditions to support sustainable land management in the beef sector.

We also see that a large share of the efficient production identified in the national beef optimization consists of changes in feed productivity in a location as opposed to moving away from current production areas (Fig. 2). For such changes, the results from our model could help governments to identify policy interventions to improve efficiency irrespective of preferences (for example, Brazil, Australia, India and East Africa in Fig. 2c), for instance, by incentivizing the improvement of grazing management to increase yields through agricultural extension programmes[27]. Land-use zoning[28] and the implementation and expansion of protected areas[29] could help to limit beef production in inefficient areas. Further, payments for ecosystem services can be successful at fostering change in land use and achieving multiple benefits; for example, by promoting forest restoration without imposing additional costs on cattle farmers[30]. Identifying efficient production systems and where they lie may also provide valuable insights to non-governmental actors within the beef sector. For instance, environmental certification and the behaviour of large purchasers of beef products can influence the adoption of more efficient practices and even where production occurs[31]. Consistent patterns of more sustainable production approaches and locations could guide purchase decisions that support corporate commitments to increased sustainability in beef supply chains[32]. Moreover, these patterns could support land conservation and restoration efforts of non-governmental organizations[33].

Trade-offs beyond costs or emissions

As a first step towards optimizing the global production of beef for multiple competing sustainability objectives, we focussed on minimizing economic impacts and GHG emissions. The potential gains identified here suggest current inefficiencies in the system regarding these two aims but other objectives and constraints in the current beef supply chain were not captured within our study. The importance of alternative goals also comes to the fore considering the increasing share of mixed systems and grain in feed composition as we prioritize the reduction of emissions (Extended Data Fig. 1). Such intensification will probably come with trade-offs beyond economic costs, potentially compromising the sustainability of the beef sector (for example, pollution from fertilizer nutrient leaching, loss of biodiversity, animal welfare and disease risks[34]). Externalities outside of the beef system may also influence sustainability outcomes; for example, increases in grain consumption and production costs as the reduction of emissions is prioritized may lead to a shift in bovine meat demand towards less emission-intensive and thus cost-efficient meats, such as poultry, pork and fish.

Mitigating future environmental impacts from beef production and consumption will probably require not only the improvement of the efficiency of production but continued technology advances[35] coupled with approaches to curbing the growing demand of animal-based protein[36]—that is, a focus on supply and demand. Changes in our consumption of food and subsequent production requirements for sustainability, both for beef and beyond, require an outlook that accounts for both the synergies and trade-offs amongst the goals we are trying to achieve. By explicitly considering multiple objectives we can potentially find strategies that lead to acceptable outcomes in multiple dimensions. Indeed, we show that, within the beef sector, environmental gains may not necessarily mean economic loses. However, we must first determine where these opportunities exist to find these opportunities and guide negotiation of acceptable outcomes for multiple sustainability goals. This study not only facilitates the understanding of trade-offs and opportunities to achieve economic and emissions outcomes from beef production but also provides a scaffold that can be extended to explore a larger array of multidimensional trade-offs within the global food system, such as those societal and environmental objectives globally endorsed in the SDGs.

Methods

Modelling approach

We developed a spatial multi-objective optimization model to find the most efficient feeds, locations and restoration options to produce beef globally considering economic costs and GHG emissions at 5 arcmin resolution (~10 km at equator). This approach enabled us to achieve three things not previously implemented: (1) to directly optimize land use to achieve objectives without the need to convert environmental impacts into monetary units, (2) to evaluate these land uses at fine spatial resolution and (3) to

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represent these trade-offs as preference between objectives shifts and identify the spatial land uses that achieve these outcomes.

We first estimated the area available to produce feed and the amount of meat that can be produced on each grid cell. We then calculated total economic costs and GHG emissions associated with different feed options. This information allowed us to calculate costs and emissions per unit of beef produced. At each grid cell, we selected the most efficient feed option using a weighted sum optimization. The cells with the lowest combined costs and emissions that produce enough meat to reach the demand were then selected for production. One set of weights applied to cost and emissions provides one efficient solution with a specific spatial allocation of beef production. This process is therefore repeated for a range of weight combinations to create a set of efficient solutions. The results of the optimization were then compared with properties of the current beef production; for example, aggregated costs and emissions and spatial allocation. The optimization was coded with Python v.3.7.3, with the following libraries: Numpy v.1.20.2, Pandas v.1.2.5, Rasterio v.1.0.21, managed with Anaconda v.4.8.3. The methodology is described in more detail in Supplementary Information.

Area available for optimization

The area that could be repurposed for beef production is based on current land cover and land use. We defined the suitable area on a cell as the sum of all areas excluding urban areas and water bodies[37]. We therefore considered land cover that is not currently under agricultural activities (for example, tree cover) but accounted for economic costs and GHG emissions from land-cover change. We then defined available area as the suitable area that is not currently used to produce food crops and non-cattle feed. The area of cropland currently used to produce cattle feed on a cell was estimated on the basis of the grain biomass consumed by beef cattle[11], composition of grain produced as feed[8] and crop yields[38]. This cropland area currently used to feed beef cattle was subtracted from the total cropland area[38], which was in turn subtracted from the suitable area to exclude the croplands used for food crops and non-cattle feed while still including the current cropland area used to produce beef cattle feed (Supplementary Section 1.2.2).

On each grid cell currently producing cattle feed[11], we distinguished between the current area occupied by cattle feed and the possible expansion area—the available area that is not currently producing feed. This information is used to calculate establishment costs (Economic costs section) and the change in aboveground and belowground biomass, as well as available area for reforestation (Greenhouse gas emissions section).

Feed options for optimization

The model has a total of 13 feed options for beef cattle that consist of nine grazing management levels, three land uses of mixed feeds and the current feed composition[11] (Supplementary Table 1). We opted for an approach that focuses on feed production rather than beef production; that is, we did not consider feed imported into a grid cell for beef production but assumed that feed produced on a cell can be exported to be fed to cattle in trade partner countries. As such, we distinguished between: (1) feed produced and consumed by cattle on the same cell and (2) feed produced on a grid cell but consumed by cattle abroad on the basis of FAOSTAT detailed trade matrices[8] (Supplementary Section 1.2.4). The export of feed only applies to grain biomass.

Biomass and energy consumption

Grazed biomass was based on nine grazing biomass options obtained from ORCHIDEE-GM v.3.1 simulations[23] (Supplementary Section 1.2.3). Feed crop biomass consumption was estimated with the available area on a grid cell, the area allocated[38], yield ceilings[39] and yield gap[40] for seven major feed crops. Biomass from crop residues was based on current and potential crop production, a residue-to-product ratio for each of the feed crops[41] and a removal rate of crop residues of 40% (ref. [42]). Biomass production was then converted to metabolizable energy consumption using feed quality[11] for each type of biomass.

Meat production

We calculated liveweight gain by multiplying metabolizable energy consumed with a liveweight gain conversion factor for each production system (mixed and grazing), climate (temperate, arid and humid) and region[11]. For grazing options, we used the liveweight gain conversion factor for grazing systems and used the conversion factors for mixed systems for all feed options that include grain or crop residue. We then applied a dressing percentage[3] to obtain meat production in carcass weight for each cell and feed option.

Economic costs

Economic costs of each feed option include establishment, opportunity, production, postfarm and restoration cost.

We estimated a cost for establishing new pasture or cropland if feed is produced outside current feed locations. We used a different transition cost for establishing a pasture and cropland[43] and multiplied this cost by the transition area on a cell (the sum of areas for which land cover is not cropland or grassland)[37]. If beef production expands outside its current location and the feed composition includes grain, we calculated a feedlot cost per head, that includes equipment, machinery and building costs[44]. Additionally, if a feed option produces more beef than the current production, we assumed that calves need to be bought and transported from the nearest city to be fed on the grid cell. We annualized this initial cost with an annuity factor composed of a discount rate for each country[45] and a time horizon of 30 yr, based on common practices in agricultural investments[46].

Opportunity cost accounts for the profit forgone from other potential agricultural activities on a cell and represents a proxy for land value. We considered total returns from crops and forestry[39] and grass-fed ruminants other than beef cattle[11] as competing economic activities and multiplied this total return by a profit margin. Profit margins have been found to depend on farm sizes[47] with smaller sized farms recording smaller profit margins than larger farms. We, therefore, associated profit margin on a cell with information on global field sizes[48] (Supplementary Fig. 8).

We calculated production costs of grazing biomass on the basis of fertilizer input. We used nitrogen application rate, defined by the grazing management scenario (0, 50 or 200 kg ha^{-1}), the grazing area on a cell and the nitrogen (N) fertilizer price in the country. Due to the lack of available information on fertilizer prices, we inferred the price for each country on the basis of quantity and value of fertilizers traded in each country[49]. The production costs for feed crops was calculated using producer prices in each country[8]. Crop residues were assumed to have no production cost as the crops are grown for other uses.

Postfarm costs consist of transport cost of cattle meat to consumers. We assumed that after the production stage, cattle are transported to the nearest urban centre for slaughter. If beef production is intended for local consumers (if the country's supply has not yet reached its demand (Trade section)), the cost of this transport is calculated from the travel time to the nearest urban centre[50], payload capacity, average speed and fuel efficiency of heavy trucks[51] and price of diesel per country[52].

If beef supply in the country has already reached its demand, beef produced grid cells are assumed to be exported to trade partners of the country. In this case, cattle are transported to the nearest port (adapted from the travel time to cities methodology[50]) and a trade margin is added onto the transport cost, on the basis of quantity of meat traded, distance between trade partners[53] and trade margin between trade partners[54].

On areas that currently produce cattle feed, we assume that three land management options are possible if feed is remove from production: (1) land is actively restored to its original biome, (2) land is passively restored to its original biome and (3) land use is kept unchanged. Land restoration is only considered where the historical biome is forest[55] to avoid potentially perverse impacts on biodiversity in grassland biomes. For active restoration, we estimated three different costs: (1) a cost of forest restoration using an initial cost for land preparation[56], annualized with the same annuity factor as for establishment cost, (2) maintenance and monitoring costs assuming long rotation plantations[56] and (3) the same opportunity cost of agricultural activities as previously described. For passive restoration, only opportunity cost was considered since no maintenance or preparation is assumed. If land use is kept unchanged, we assumed that there is no restoration cost and no change in carbon stock.

Greenhouse gas emissions

GHG emissions from feed and beef production comprise: non-CO_2 emissions from enteric fermentation; manure management and fertilizer application; CO_2 emissions from the change in belowground and aboveground biomass; postfarm emissions resulting from transport, export, packaging and processing; and change in belowground and aboveground biomass from forest restoration.

Emissions from enteric fermentation and manure were estimated from an emission factor that varies by production system, climate and region[11]. The emission factor for grazing systems was used for feed options entirely composed of grass and the emission factor for mixed systems was used for feed options composed of grain or crop residues.

Emissions from applied N fertilizers were calculated with crop-specific N–N_2O emission factors[57]. The quantity of N fertilizer for grasslands is set by the grazing management scenario (0, 50 or 200 kg N ha^{-1})[23], whereas N application rate for grain production on a cell was modelled as a function of intensifying yields for each of the seven crops[40]. Crop residues were assumed to require no additional fertilization. To estimate CO_2 equivalents from N_2O emissions, we used the 100-yr global warming potential (GWP_{100}) conversion factor for consistency with the conversion factors used for enteric fermentation and manure management[11].

Changes in carbon stock in current vegetation resulting from producing new feed were calculated from: (1) the clearing of vegetation on new feed areas and (2) carbon in remaining grass biomass after grazing. Land clearing was assumed to occur where feed is produced in a new area (where no beef cattle feed is currently produced) and calculated by multiplying the available area for feed with current aboveground carbon density[58]. For grazing feed options, we converted the remaining biomass to carbon on the basis of the carbon content in the standing biomass[59]. The balance of aboveground carbon stock was then converted to CO_2e (ref. [60]) and annualized over a 30 yr time horizon.

Changes in soil carbon were calculated on the basis of the relative change (%) in soil carbon density when land transitions occur, for example, from forest to pasture[22]. This relative change was multiplied by the current belowground carbon density[58] and the C–CO_2e conversion factor[60] and annualized over a 30 yr time horizon.

Postfarm emissions consist of transport emissions and processing and packaging emissions. Similarly to transport costs, transport emissions included the weight of cattle transported to the nearest urban centre for slaughter, payload capacity, average speed and fuel efficiency of road transport and a road emission factor for heavy trucks[61]. If meat production is exported, transport emissions were calculated with travel time to the nearest port[62] instead of nearest urban centre. Meat was then exported from the nearest port to trade partners proportionally based on the fraction of meat traded between the exporting country and each of its trade partner[8]. For each trade flow, the quantity of meat was multiplied by the distance between the exporting country and its trade partner[53] and an emission factor for deep-sea container shipping[61]. Emissions from processing and packaging were calculated using a global parameter for energy consumption for meat processing and a country-specific emission factor for energy consumption[63].

We calculated the potential for change in aboveground biomass if current cattle feed is removed from production using stemwood growth equations[64] and maximum carbon in potential vegetation[65]. Parameters of the stemwood growth model vary on the basis of the type of forest (boreal, temperate and tropical) and type of restoration (active or passive)[64]. We estimated and annualized stemwood growth over the same time horizon used for the annualization of establishment and restoration costs (30 yr). If no restoration takes place, we assumed no change in carbon stock.

Soil carbon change in restored areas was calculated the same way as soil carbon change in expansion area—areas not currently used to produce cattle feed. However, we only estimated land restoration in grid cells located in a forest biome[55], thus the change in belowground biomass from forest restoration is calculated on the basis of the transition of current pasture and cropland used to feed cattle to forest. For active restoration, we assumed that the new land use was considered to be a plantation, whereas passive restoration was assumed to transition to secondary forest, to match forest types for relative change in soil carbon[22] and stemwood growth curves[64].

Trade

We used a simple model to incorporate trade costs and emissions in the optimization. If the sum of beef from converted grid cells in a country is lower than the country's demand, costs and emissions for each feed option were assumed to include domestic transport costs and emissions only (transport of cattle to the nearest urban centre for slaughter). Once the sum of beef production in a country has met the country's demand, the costs and emissions of all land-use options in the remaining unconverted cells were modified by removing transport cost and emissions to the nearest urban centre and adding instead transport cost and emissions to the nearest port, in addition to costs and emissions of container shipping based on the distance between the producing country and its trade partners.

Optimization of beef production

The optimal feeds and locations to produce beef were determined by selecting land use and cells with the lowest summed relative cost that meet beef demand (67 Mt at year 2018 (ref. [8]).

For each cell i, feed option k and restoration strategy s, a weighted sum ($Z_{i,k,s}$) was calculated from the relative production costs ($\frac{C_{iks}}{B_{iks}}$, US$ per tonne of beef per year) and relative emissions ($\frac{G_{iks}}{B_{ik}}$, tCO_2e per tonne of beef per year) and minimized to obtain the optimal score (Z^*_i) to produce beef across feed options and restoration strategies:

$$Z_{iks} = \lambda \frac{G_{iks}}{B_{ik}} + (1 - \lambda) \frac{C_{iks}}{B_{ik}}$$

$$Z^*_i = \min_{k,s} Z_{iks}$$

where λ is a weight given to emissions per unit of beef produced.

Once the lowest score has been calculated and the optimal feed option selected for each grid cell, cells with the lowest scores were selected for beef production until beef demand was reached, per country (national beef scenario) or globally (beef without borders).

We ran the optimization with ten different λ weight values ranging from 0 to 1 to obtain solutions at different intervals and thus generate a set of Pareto-efficient solutions. For each solution, we aggregated costs and emissions over all selected grid cells. Lastly, we linked all Pareto-efficient solutions to trace the Pareto frontier.

Current production

We assessed the current beef production as of 2018 as a reference to compare with the optimization results and Pareto frontier. Current beef production on a given grid cell for year 2000[11] was adjusted to fit country-level production at year 2018 using the change in production in each country between 2000 and 2018[8].

Current emissions

Current emissions from beef production consist of enteric fermentation, manure management, fertilizer emissions and postfarm emissions. For current production, we did not consider past changes in carbon stocks from land-use change, for instance, from past deforestation, reforestation or soil carbon change. As such, the total emissions from current production may appear lower than results from previous studies[1,3] that considered CO_2 emissions from land-use change.

We used emissions from enteric fermentation and manure management at year 2000[11] and adjusted the two layers to 2018 emissions using the same method as for beef production. Emissions associated with the use of fertilizer were divided between fertilizer use in grasslands and cropland. For grasslands, N application rates[66] were used to estimate fertilizer application. For cropland, grain consumed by beef cattle[11] was decomposed on the basis of the fraction of the seven major grains used for feed in each country from the Food and Agriculture Organization (FAO) balance sheets[8] and fertilizer application in cropland was estimated as a function of increasing crop yields. Emissions from N fertilizer application and postfarm emissions (transport, export, processing and packaging emissions) were calculated with the same method as for the potential feed options detailed above in the Greenhouse gas emissions section.

Current costs

We simulated current costs associated with beef production on the basis of opportunity cost, production cost and postfarm cost, using the same equations as for the feed options in the optimization, as described above in the Economic costs section. For current production, we did not consider past establishment cost for crop or pasture preparation.

Uncertainty assessment

We conducted an uncertainty analysis to assess the range of values that can be obtained on the basis of the variation in input parameters. We first identified the most uncertain parameters and sampled values from uniform distributions (Supplementary Table 4). We ran 1,000 simulations for five weights and generated a range for each weight showing percentiles of total costs and emissions along the Pareto frontier. In addition, we assessed uncertainty related to model structure and assumptions. We examined variation in the Pareto frontier by simulating different selections of suitable land covers, grazing options, feed crops available for cattle feed and time horizons to annualize establishment and restoration costs, as well as change in biomass (Supplementary Section 2.2).

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

The datasets used to obtain results in this study are publicly available as referenced within the article and Supplementary Information and from the corresponding author upon request. The land-cover layer was obtained from https://www.esa-landcover-cci.org/. Current crop areas and yields were obtained from http://www.earthstat.org/. Annual net primary productivity was obtained from https://lpdaac.usgs.gov/products/mod17a3hv006/. Fraction of grain in cattle diet, fraction of feed exported, producer prices and beef demand were obtained from https://www.fao.org/faostat/en/. Quantity and value of fertilizer traded were retrieved from https://comtrade.un.org/data. Beef production, liveweight gain, emissions from enteric fermentation, emissions from manure management and feed consumption from beef cattle at year 2000 were obtained from https://data.csiro.au/collection/csiro:29893. Metabolizable energy in feed was obtained from https://www.feedipedia.org/ and residue-to-product ratio of grains were retrieved from https://doi.org/10.1016/j.wasman.2010.04.016 and https://doi.org/10.1111/gcbb.12305. Monthly air temperature and wind velocity were obtained from http://www.worldclim.com/version2. Average liveweight of calves, dressing percentage, energy use for meat processing and packaging and emission intensity of energy use were retrieved from https://www.oneplanetnetwork.org/sites/default/files/from-crm/gleam_2.0_model_description.pdf. Global field sizes were obtained from https://geo-wiki.org/Application/. Travel time to cities was retrieved from https://figshare.com/articles/dataset/Travel_time_to_cities_and_ports_in_the_year_2015/7638134. The location of major ports was obtained from https://geonode.wfp.org/layers/esri_gn:geonode:wld_trs_ports_wfp. Fuel prices were obtained from https://sutp.org/download/10008/. Nominal hourly wage was retrieved from https://www.ilo.org/ilostat-files/Documents/Excel/INDICATOR/EAR_4MMN_CUR_NB_A_EN.xlsx. Road transport payload capacity, average vehicle speed and average fuel efficiency were obtained from https://www.globalfueleconomy.org/media/404893/gfei-wp14.pdf. The country-specific discount rate was obtained from https://data.worldbank.org/indicator/FR.INR.LEND. Costs of land restoration were retrieved from https://www.jstor.org/stable/23297079. Trade margins for exported beef in each country were retrieved from https://www.gtap.agecon.purdue.edu/databases/archives.asp. Sea distance between countries were obtained from https://zenodo.org/record/240493. Aboveground and belowground carbon densities were retrieved from https://doi.org/10.3334/ORNLDAAC/1763. The carbon in potential vegetation layer was obtained from https://doi.org/10.1594/PANGAEA.893761. The preprocessed datasets used to conduct the analysis and the output datasets generated and used to generate figures in this article are available at https://doi.org/10.5281/zenodo.7085816.

Code availability

The software used to find solutions to this multi-objective optimization problem was Python v.3.7.3, with the following libraries: Numpy v.1.20.2, Pandas v.1.2.5, Rasterio v.1.0.21, as well as Anaconda v.4.8.3. The code used in this analysis is available from the following link: https://github.com/accastonguay/beef_simulation. The code used to analyse outputs of the optimization and generate figures is based on Python v.3.7.3 and Jupyter Notebook v.6.4.8 with the following libraries: Matplotlib v.3.5.1, Numpy v.1.20.2, Pandas v.1.2.5, Rasterio v.1.0.21, Cartopy v.0.20.2, Geopandas v.0.10.2 and Sklearn v.1.0.2. Results of the optimization can also be visualized online at https://accastonguay.shinyapps.io/beef_app/.

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Author contributions
E.M.M., E.G., S.P., M.H.H. and A.C.C. developed the concept and designed scenarios. A.C.C. ran the analysis with feedback from E.M.M., S.P., M.H.H., M.H., D.M.D. and K.L. M.H., J.C., J.G. and D.M.D. contributed data required for the analysis. A.C.C. drafted the manuscript and E.M.M., S.P., M.H.H., M.H., D.M.D, B.A.B., C.G., G.B.W, J.C., J.G., E.G., B.W., K.L. and P.B. contributed to the interpretation of findings and provided revisions to the manuscript.

Competing interests
The authors declare no competing interests.

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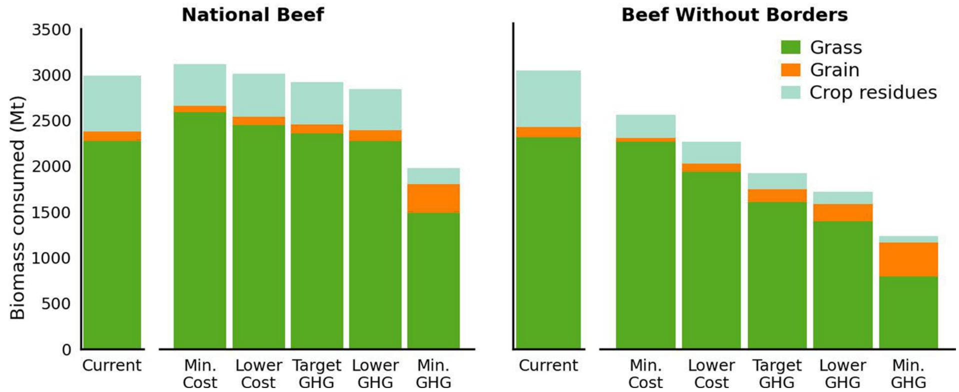

Extended Data Fig. 1 | Total feed consumption for five solutions along the Pareto frontier for the two spatial scenarios (National Beef and Beef without Borders). Total feed consumption (grass, grain and crop residues) for five solutions along the Pareto frontier compared to simulated current biomass consumption for the two spatial scenarios (National Beef and Beef without Borders).

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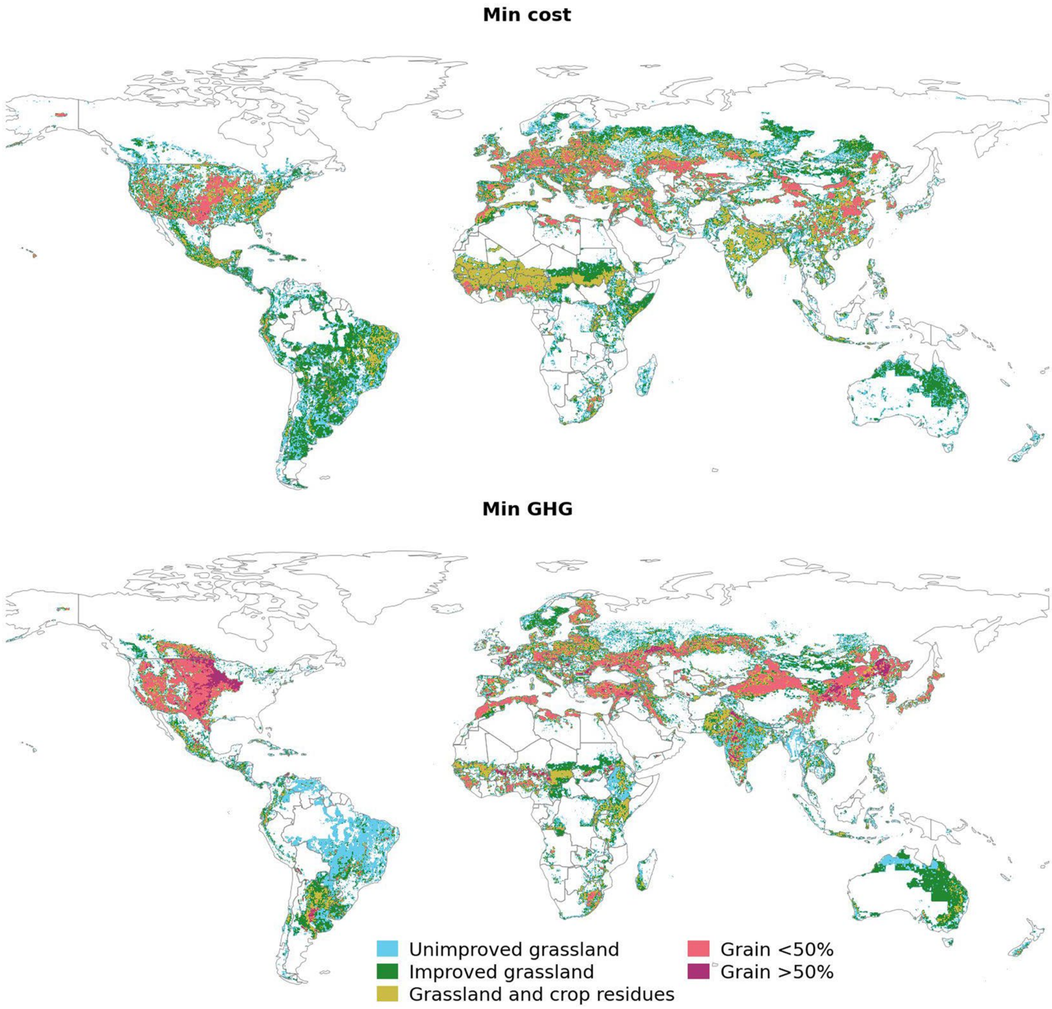

Extended Data Fig. 2 | Distribution of feed for two solutions along the Pareto frontier for the National Beef scenario. Distribution of feed for two solutions along the Pareto frontier for the National Beef scenario. Feed options were grouped into five categories: 1) diet is composed of grass from unimproved grassland without N application, 2) diet composed of grass from improved grasslands with N application, 3. Diet composed of a mix of grass and crop residues, 4) diet with grain contributing to less than 50% of total biomass consumed, 5) diet with grain contributing to more than 50% of total biomass consumed.

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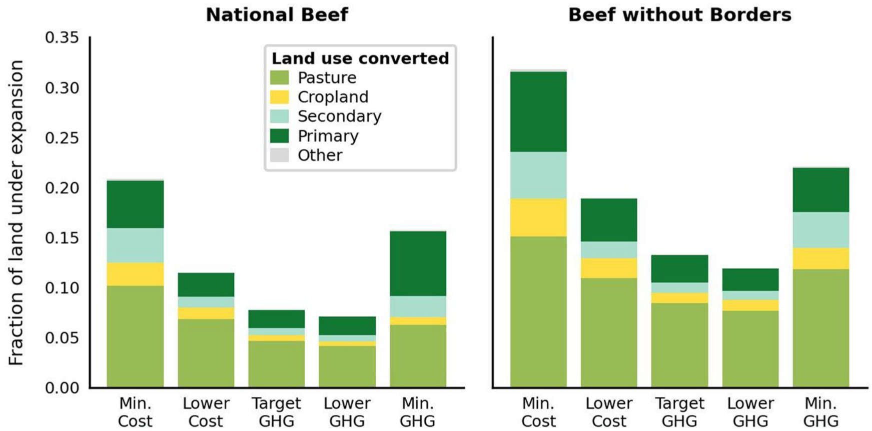
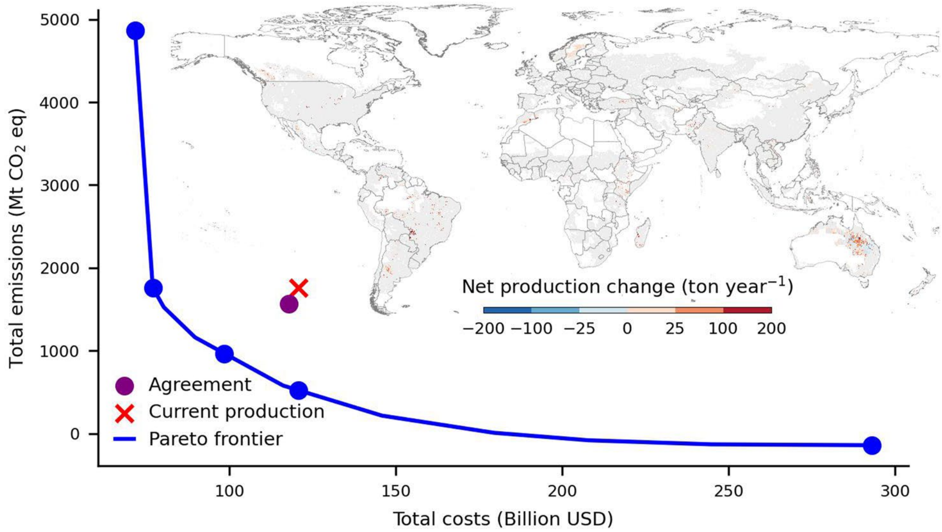


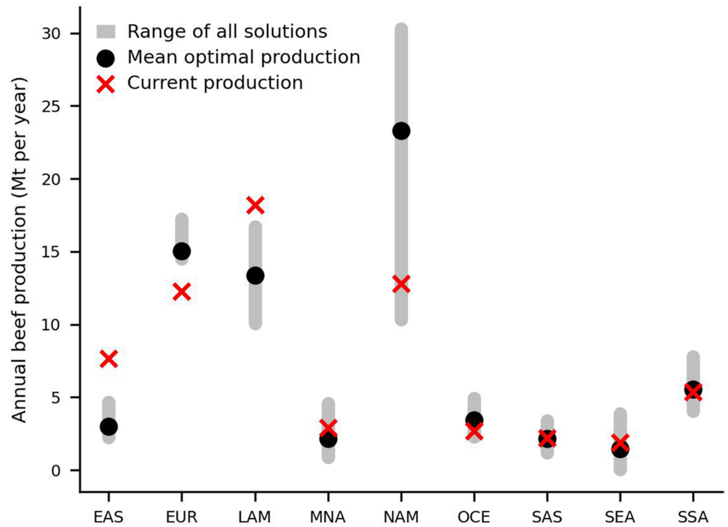
Extended Data Fig. 3 | Fraction of new area used for feed production, and type of land use lost from expansion for the two spatial scenarios. Fraction of new area used for feed production, and type of land use lost from expansion for the two spatial scenarios. The land use classification is based on the land use types from Hoskins et al.[67]: Primary (undisturbed natural habitat), Secondary (recovering, previously disturbed natural habitat), Cropland (land used for crop production), Pasture (land used for the grazing), Other (dense urban settlement).

 https://doi.org/10.1038/s41893-022-01017-0



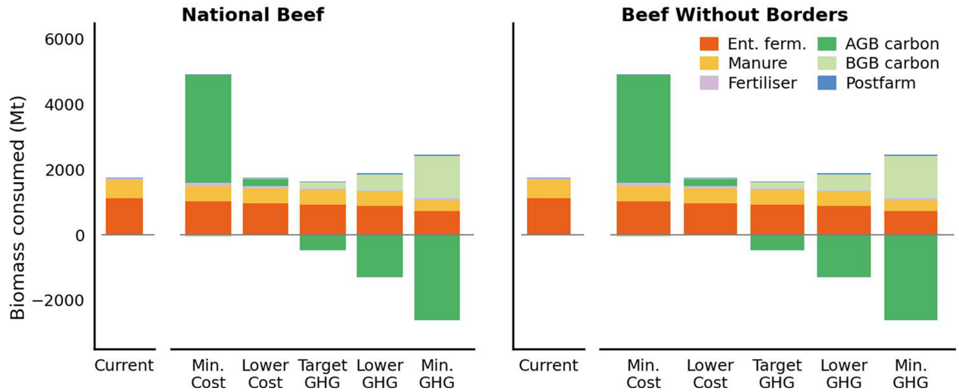
Extended Data Fig. 4 | Pareto frontier and production where changes that occur in both minimizing costs and minimizing emissions solutions were implemented with the associated GHG reduction and costs saving. Pareto frontier of the National Beef scenario in comparison with current production and production where changes that occur in both minimizing costs and minimizing emissions solutions were implemented, that is, strategies shown in Fig. 2c, with the associated GHG reduction and costs saving. The map shows the spatial distribution of net production changes if these strategies were implemented. This scenario ensures low- and middle-income nations see no reduction in current beef production levels in the interest of avoiding perverse impacts on national food security.

https://doi.org/10.1038/s41893-022-01017-0



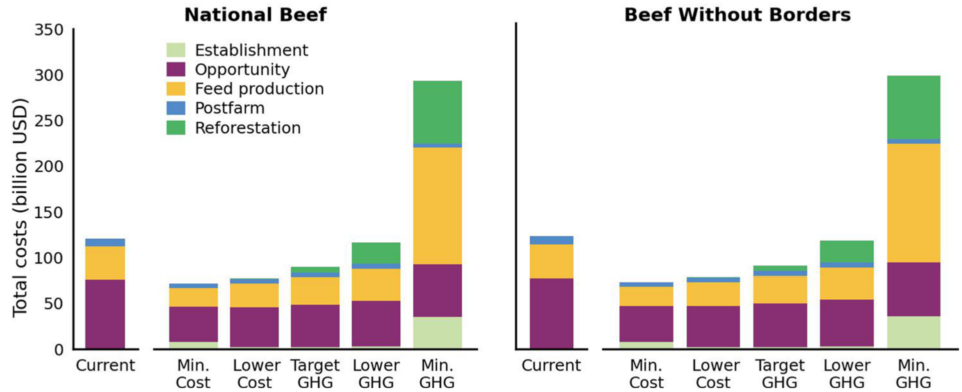
Extended Data Fig. 5 | Range and mean beef production at regional level for the Beef Without Border scenario. Range (grey bar) and mean beef production (black point) compared to current production (red cross) at regional level for all solutions across the Pareto frontiers for the Beef Without Border scenario.

https://doi.org/10.1038/s41893-022-01017-0



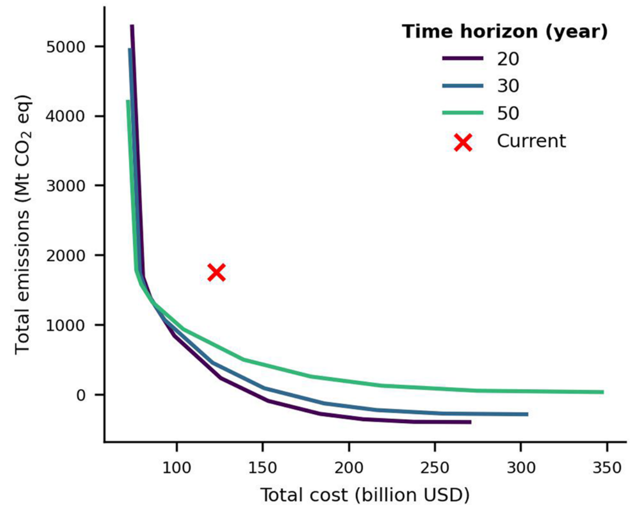
Extended Data Fig. 6 | Sources of emissions. Sources of emissions for the simulated current production and two spatial scenarios. AGB and BGB stand for aboveground biomass and belowground biomass, respectively and include biomass change from land clearing in new area and reforestation.

https://doi.org/10.1038/s41893-022-01017-0



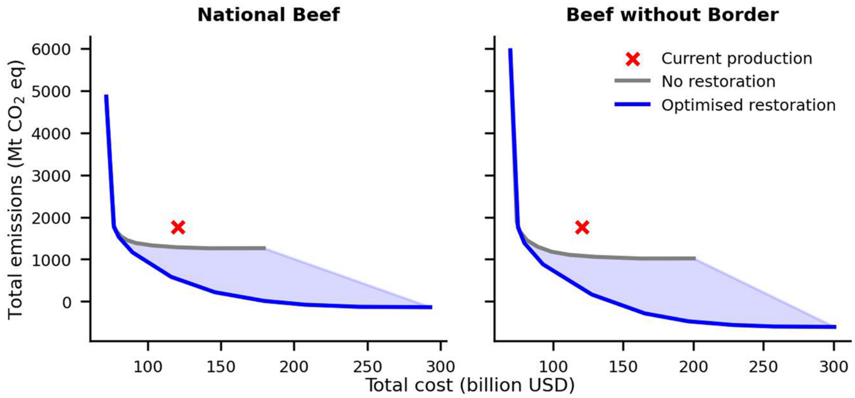
Extended Data Fig. 7 | Sources of economic costs. Sources of economic costs for the simulated current production and two spatial scenarios.

https://doi.org/10.1038/s41893-022-01017-0



Extended Data Fig. 8 | Uncertainty from using different time horizons. Uncertainty resulting from different time horizons used for annualizing change in biomass (from soil carbon, land clearing and reforestation), transition costs and land preparation costs for active reforestation.

https://doi.org/10.1038/s41893-022-01017-0



Extended Data Fig. 9 | Difference in Pareto frontiers if forest restoration options are considered and optimized, or if restoration is not considered. Difference in Pareto frontiers if forest restoration options are considered and optimized, or if restoration is not considered, in comparison with simulated costs and emissions of current beef production.

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Reporting Summary

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For all statistical analyses, confirm that the following items are present in the figure legend, table legend, main text, or Methods section.

n/a	Confirmed	
☐	☒	The exact sample size (n) for each experimental group/condition, given as a discrete number and unit of measurement
☒	☐	A statement on whether measurements were taken from distinct samples or whether the same sample was measured repeatedly
☒	☐	The statistical test(s) used AND whether they are one- or two-sided *Only common tests should be described solely by name; describe more complex techniques in the Methods section.*
☒	☐	A description of all covariates tested
☒	☐	A description of any assumptions or corrections, such as tests of normality and adjustment for multiple comparisons
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☒	☐	For null hypothesis testing, the test statistic (e.g. F, t, r) with confidence intervals, effect sizes, degrees of freedom and P value noted *Give P values as exact values whenever suitable.*
☒	☐	For Bayesian analysis, information on the choice of priors and Markov chain Monte Carlo settings
☒	☐	For hierarchical and complex designs, identification of the appropriate level for tests and full reporting of outcomes
☒	☐	Estimates of effect sizes (e.g. Cohen's d, Pearson's r), indicating how they were calculated

Our web collection on statistics for biologists contains articles on many of the points above.

Software and code

Policy information about availability of computer code

Data collection	Grazing biomass layers were generated with the ORCHIDEE-GM model available at https://doi.org/10.14768/20190319001.1.
Data analysis	The software used to find solutions to this multi-objective optimisation problem was Python version 3.7.3, with the following libraries: Numpy 1.20.2, Pandas 1.2.5, Rasterio 1.0.21, as well as Anaconda version 4.8.3. The code used in this analysis is available from the following link: https://github.com/accastonguay/beef_simulation. The code used to analyse outputs of the optimisation and generate figures is based on Python version 3.7.3 and Jupyter Notebook version 6.4.8 with the following libraries: Matplotlib 3.5.1, Numpy 1.20.2, Pandas 1.2.5, Rasterio 1.0.21, Cartopy 0.20.2, Geopandas 0.10.2 and Sklearn 1.0.2. Results of the optimisation can also be visualised online at https://accastonguay.shinyapps.io/beef_app/.

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors and reviewers. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Portfolio guidelines for submitting code & software for further information.

Data

Policy information about availability of data

All manuscripts must include a data availability statement. This statement should provide the following information, where applicable:

- Accession codes, unique identifiers, or web links for publicly available datasets
- A description of any restrictions on data availability
- For clinical datasets or third party data, please ensure that the statement adheres to our policy

The datasets used to obtain results in this study are publicly available as referenced within the article and Supplementary Information, and from the corresponding author upon request.
The land cover layer was obtained from https://www.esa-landcover-cci.org/. Current crop areas and yields were obtained from http://www.earthstat.org/. Annual net primary productivity was obtained from https://lpdaac.usgs.gov/products/mod17a3hv006/. Fraction of grain in cattle diet, fraction of feed exported, producer prices and beef demand were obtained from https://www.fao.org/faostat/en/. Quantity and value of fertiliser traded were retrieved from https://comtrade.un.org/data. Beef production, liveweight gain, emissions from enteric fermentation, emissions from manure management and feed consumption from beef cattle at year 2000 were obtained from https://data.csiro.au/collection/csiro:29893. Metabolisable energy in feed was obtained from https://www.feedipedia.org/ and residue-to-product ratio of grains were retrieved from https://doi.org/10.1016/j.wasman.2010.04.016 and https://doi.org/10.1111/gcbb.12305. Monthly air temperature and wind velocity were obtained from http://www.worldclim.com/version2. Average liveweight of calves, dressing percentage, energy use for meat processing and packaging, and emission intensity of energy use were retrieved from https://www.oneplanetnetwork.org/sites/default/files/from-crm/gleam_2.0_model_description.pdf. Global field sizes were obtained from https://www.geo-wiki.org/pages/data. Travel time to cities was retrieved from https://www.map.ox.ac.uk/accessibility_to_cities/. The location of major ports was obtained from https://geonode.wfp.org/layers/esri_gn:geonode:wld_trs_ports_wfp. Fuel prices was obtained from https://sutp.org/download/10008/. Nominal hourly wage was retrieved from https://www.ilo.org/ilostat-files/Documents/Excel/INDICATOR/EAR_4MMN_CUR_NB_A_EN.xlsx. Road transport payload capacity, average vehicle speed and average fuel efficiency were obtained from https://www.globalfueleconomy.org/media/404893/gfei-wp14.pdf. The country-specific discount rate was obtained from https://data.worldbank.org/indicator/FR.INR.LEND. Costs of land restoration were retrieved from https://www.jstor.org/stable/23297079.Trade margins for exported beef in each country was retrieved from https://www.gtap.agecon.purdue.edu/databases/archives.asp. Sea distance between countries were obtained from https://zenodo.org/record/240493. Above- and below-ground carbon density were retrieved from https://doi.org/10.3334/ORNLDAAC/1763. The carbon in potential vegetation layer was obtained from https://doi.org/10.1594/PANGAEA.893761.
The pre-processed datasets used to conduct the analysis and the output datasets generated and used to generate figures in this article are available at https://doi.org/10.5281/zenodo.7085816.

Human research participants

Policy information about studies involving human research participants and Sex and Gender in Research.

Reporting on sex and gender	*Use the terms sex (biological attribute) and gender (shaped by social and cultural circumstances) carefully in order to avoid confusing both terms. Indicate if findings apply to only one sex or gender; describe whether sex and gender were considered in study design whether sex and/or gender was determined based on self-reporting or assigned and methods used. Provide in the source data disaggregated sex and gender data where this information has been collected, and consent has been obtained for sharing of individual-level data; provide overall numbers in this Reporting Summary. Please state if this information has not been collected. Report sex- and gender-based analyses where performed, justify reasons for lack of sex- and gender-based analysis.*
Population characteristics	*Describe the covariate-relevant population characteristics of the human research participants (e.g. age, genotypic information, past and current diagnosis and treatment categories). If you filled out the behavioural & social sciences study design questions and have nothing to add here, write "See above."*
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Ethics oversight	*Identify the organization(s) that approved the study protocol.*

Note that full information on the approval of the study protocol must also be provided in the manuscript.

Field-specific reporting

Please select the one below that is the best fit for your research. If you are not sure, read the appropriate sections before making your selection.

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For a reference copy of the document with all sections, see nature.com/documents/nr-reporting-summary-flat.pdf

Ecological, evolutionary & environmental sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	In this study, we developed and applied a multi-objective optimisation framework to identify the most efficient locations and feeds to produce beef in the world while minimising economic costs of production and greenhouse gas emissions. To do so, we estimated: i) the potential beef production on a given cell and for a type of production (i.e., 13 different feed combinations or forest restoration); (ii) the economic costs associated with this production and (iii) the greenhouse gas emissions associated with this production. Using this information, we calculated an efficiency score for each grid cell and feed combination given preferences or weights attributed to costs per tonne of beef and GHG emissions per tonne of beef. We then selected the feed combination (and associated beef production) yielding the lowest impact score on each grid cell. Finally, we selected the grid cells with the lowest scores that produced enough beef to meet the demand. We explored two scenarios of spatial constraint; (1) where each country is required to produce the same amount of beef as they currently produce (as of 2018) and (2) where the global beef production (i.e., approximately 67 million tons as of 2018) can be produced anywhere on the planet without country-level constraint. Finally, We compare the cost and emissions associated with the current beef production and costs and emissions associated with optimal production to assess potential costs savings and GHG emissions reduction for each preference along the pareto frontier.
Research sample	No primary data was collected and no sampling was performed.
Sampling strategy	No primary data collection was performed, and the secondary datasets used are listed above.
Data collection	We used secondary data as input for the optimisation described in the Method section and in more detail in Supplementary Information. All input parameters (Table 5 in Supplementary Information), state variables (Table 6 in Supplementary Information) and equations are described and, when applicable, referenced in Supplementary Information.
Timing and spatial scale	No data collection was performed.
Data exclusions	No data were excluded from the analyses.
Reproducibility	The findings can be reproduced using the datasets and codes developed, all either publicly available or available upon request.
Randomization	No data collection was performed.
Blinding	No data collection was performed, and blinding was not applicable to the modeling approach used.

Did the study involve field work? ☐ Yes ☒ No

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems

n/a	Involved in the study	
☒	☐	Antibodies
☒	☐	Eukaryotic cell lines
☒	☐	Palaeontology and archaeology
☒	☐	Animals and other organisms
☒	☐	Clinical data
☒	☐	Dual use research of concern

Methods

n/a	Involved in the study	
☒	☐	ChIP-seq
☒	☐	Flow cytometry
☒	☐	MRI-based neuroimaging