nature food

Article

https://doi.org/10.1038/s43016-022-00661-1

A 12% switch from monogastric to ruminant livestock production can reduce emissions and boost crop production for 525 million people

Received: 1 June 2022

Accepted: 4 November 2022

Luxi Cheng[1,2], Xiuming Zhang[1,3], Stefan Reis[4,5,6], Chenchen Ren[2,7], Jianming Xu[1,8] & Baojing Gu[1,2] ✉

Ruminants have lower feed use efficiency than monogastric livestock, and produce higher reactive nitrogen and methane emissions, but can utilize human-inedible biomass through foraging and straw feedstock. Here we conduct a counterfactual analysis, replacing ruminants with monogastric livestock to quantify the changes in nitrogen loss and greenhouse gas emissions globally from a whole life cycle perspective. Switching 12% of global livestock production from monogastric to ruminant livestock could reduce nitrogen emissions by 2% and greenhouse gas emissions by 5% due to land use change and lower demand for cropland areas for ruminant feed. The output from released cropland could feed up to 525 million people worldwide. More ruminant products, in addition to optimized management, would generate overall benefits valued at US$468 billion through reducing adverse impacts on human and ecosystem health, and mitigating climate impacts.

The global livestock sector emitted 65 $\mathrm{TgN\ yr^{-1}}$ in 2010, accounting for one-third of total anthropogenic reactive nitrogen (Nr) emissions[1]. The whole livestock production chain generated approximately 15% of global anthropogenic greenhouse gas (GHG) emissions, with ruminants and monogastric livestock contributing 5.7 and 1.4 $\mathrm{PgCO_2e}$ GHG emissions per annum, respectively[2]. Livestock feed production uses approximately two-thirds of global total cropland area[3] and increases in livestock-derived protein demand could accelerate food–feed competition[4].

Feed use efficiency is lower in ruminants than in monogastric livestock[1], leading to relatively higher Nr and GHG emissions per unit of protein production for ruminants. Reducing ruminant product consumption can help limit the environmental impacts of meat production[5], yet fulfilling animal protein requirements from monogastric livestock, especially poultry, comes with trade-offs. Grain accounts for ~95% of the feed in intensive poultry farms, and poultry consume comparatively more human-edible grains than ruminants[6]. In contrast, about 60% of ruminant feed is human-inedible cellulose, for example, grass, crop residues and leaves[7]. Thus, ruminants can contribute to maximizing the usage of otherwise unusable plant biomass, benefiting food security and reducing the environmental impact of farming[8,9].

We argue that maximizing cellulose use as livestock feed may reduce pressure on grain feed production, which is associated with high environmental costs and food security risks. Here we perform a

---

[1]College of Environmental and Resource Sciences, Zhejiang University, Hangzhou, China. [2]Policy Simulation Laboratory, Zhejiang University, Hangzhou, China. [3]School of Agriculture and Food, The University of Melbourne, Melbourne, Victoria, Australia. [4]UK Centre for Ecology and Hydrology, Penicuik, UK. [5]University of Exeter Medical School, Knowledge Spa, Truro, UK. [6]The University of Edinburgh, School of Chemistry, Edinburgh, UK. [7]Department of Land Management, Zhejiang University, Hangzhou, China. [8]Zhejiang Provincial Key Laboratory of Agricultural Resources and Environment, Zhejiang University, Hangzhou, China. ✉e-mail: bjgu@zju.edu.cn

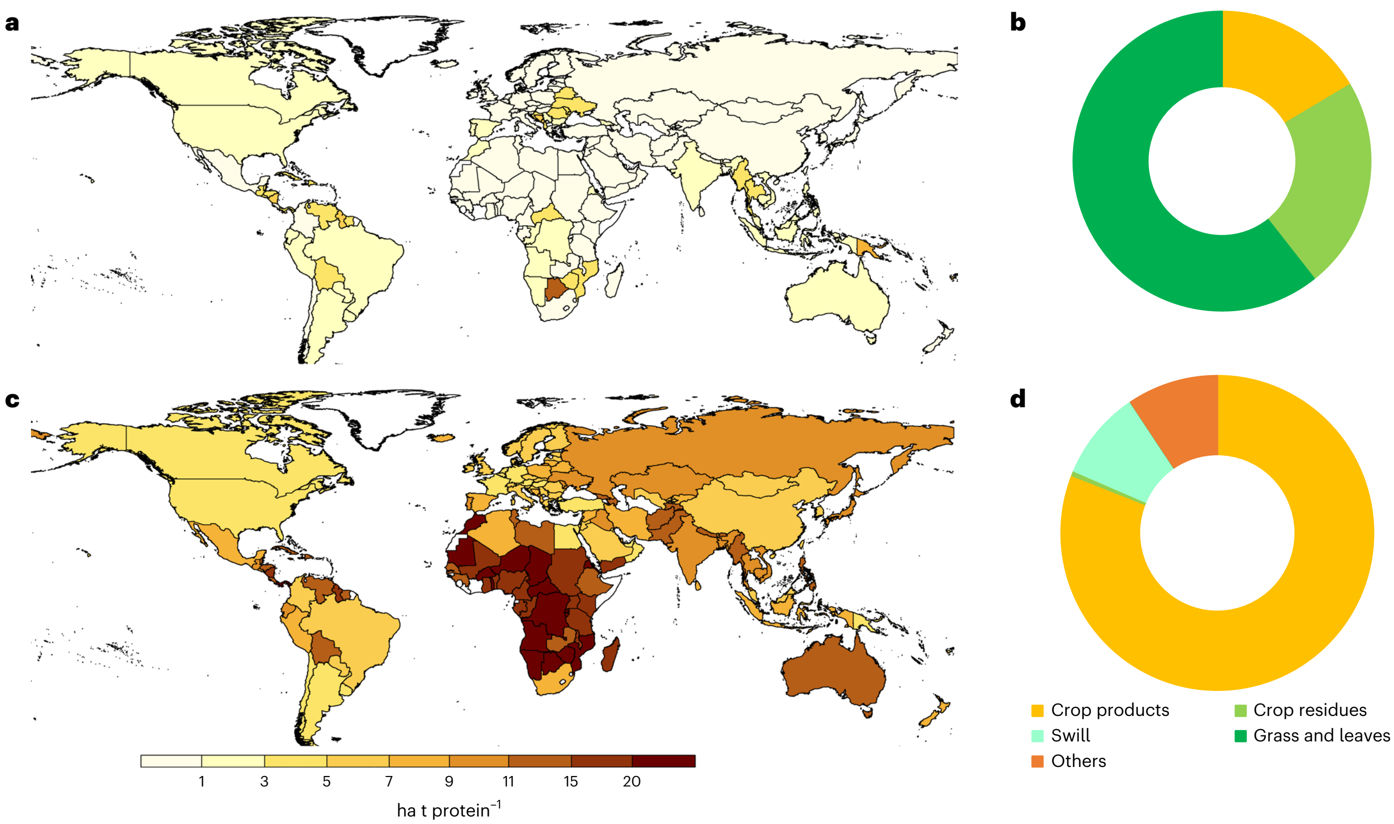


Fig. 1 | Cropland area for producing feed required by per unit livestock protein and feed ratio for ruminant and monogastric livestock. a, Cropland area required to produce per unit of ruminant protein. **b**, Feed ratio of ruminant livestock; this value represents the percentage of nitrogen content. Ruminant feed comprises grass (61%), crop residues (23%) and crop products (16%). **c**, Cropland area required to produce per unit of monogastric protein. **d**, Feed ratio of monogastric livestock. 'Others' represents synthetic amino acids, fishmeal and limestone. Monogastric livestock mainly feed on crop products (81%), followed by swill (9%) and other feed (9%). The base map was applied without endorsement using data from the Database of Global Administrative Areas (GADM; https://gadm.org/).

counterfactual analysis, replacing ruminants with monogastric livestock, to quantify changes in Nr and GHG emissions in 166 countries, taking a full life cycle perspective. We then calculated the efficiency aspects of producing equivalent amounts of protein and the resulting Nr and GHG emissions from ruminants and monogastric livestock across different countries, considering local constraints. Based on these global analyses, we developed an optimized livestock protein production scenario by maximizing the proportion of ruminants to reduce Nr and GHG emissions, thus increasing the availability of croplands for grain-based human food production. Managing ruminants for low-emission food production could safeguard food security, reduce environmental impacts and mitigate climate change.

Results

Cropland area and total emissions

Ruminants mainly feed on human-inedible cellulose (Extended Data Fig. 1), although they have larger feed requirements (14.8 $\mathrm{kgN_{feed}}$ per $\mathrm{kgN_{ruminant}}$) than monogastric livestock (6.3 $\mathrm{kgN_{feed}}$ per $\mathrm{kgN_{monogastric}}$). Monogastric livestock production requires around four times more cropland than ruminant production to produce an equivalent per unit protein (Fig. 1a,c and Extended Data Figs. 2 and 3) (8.0 ha per t protein for monogastric livestock versus 1.9 ha per t protein for ruminants). Global ruminants produced approximately 7 Tg protein-N in 2019. Producing the same level of proteins solely by monogastric livestock would result in 15% (7 Tg) more nitrogen losses to the environment over the whole production chain. Ammonia (NH_3) emissions to the air and nitrate (NO_3^-) released to water bodies would increase under such a scenario by 13% (3 Tg) and 18% (5 Tg), respectively, while N_2O and NO_x emissions would decrease by 14% (−0.3 Tg) and 17% (−0.04 Tg), respectively (Fig. 2a,b). The substantive increases are associated with grain feed production for monogastric livestock, which requires more cropland area and synthetic fertilizer input.

Monogastric livestock has a higher nitrogen use efficiency (NUE) at the animal-raising stage (16%) compared with ruminants (7%). However, the NUE of feed production for monogastric livestock (33%) is much lower than that of ruminants (69%), leading to the overall NUE of the livestock production chain being fairly similar for both monogastric livestock and ruminants, at around 6% globally. Furthermore, at the livestock raising stage of ruminants, more manure nitrogen is produced due to low NUE, which could be used for crop ration production for humans. More recycling opportunities and natural-based processes were available in the ruminant production chain (Fig. 2), such as straw and manure recycling and natural biological nitrogen fixation in grasslands, illustrating that ruminants can recycle more nutrients into food production, reducing overall Nr emissions.

Emissions would be higher by about 3 $\mathrm{PgCO_2e}$ if ruminants replaced monogastric livestock at global levels (Fig. 2c,d). The increase in croplands needed for grain feed production (270 Mha) was modelled to be converted from forest, leading to an increase of 5.4 $\mathrm{PgCO_2e}$ emission from land use change, field operations, processing and fertilizer manufacture. In contrast, about 2.5 $\mathrm{PgCO_2e}$ emission reduction would result from avoided CH_4 enteric fermentation and manure management.

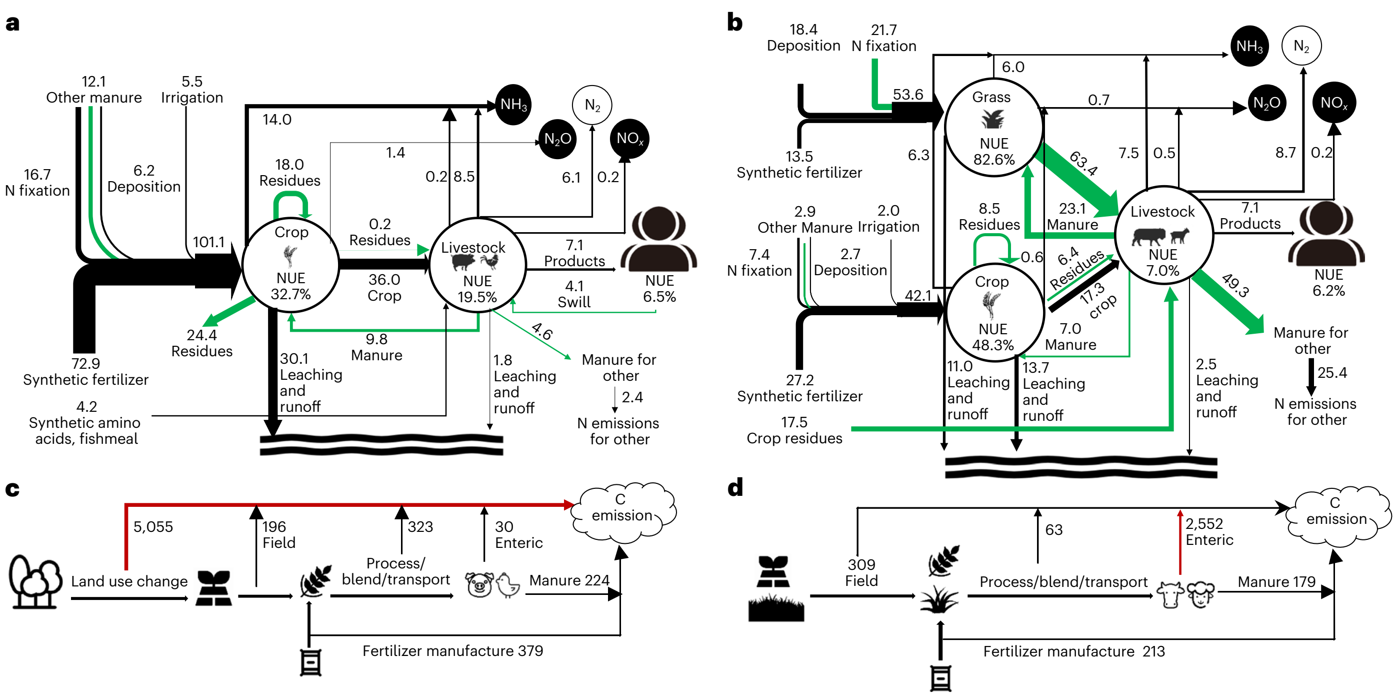


Fig. 2 | Nitrogen budget and carbon emissions in global ruminants and monogastric livestock systems with the same amount of protein produced. **a**, Global nitrogen flows in monogastric livestock. 'Manure for other' represents the manure applied to croplands for human nutrition or crop feed for other animals. **b**, Global nitrogen flows in ruminant livestock. 'Manure for other' here comprises two parts: (1) manure deposited on other grassland (12 Tg); (2) manure applied to croplands for human nutrition or feed for other animals (37 Tg). **c**, Global carbon emissions from monogastric livestock (comprising emissions of CO_2 and CH_4). **d**, Global carbon emissions from ruminant livestock. The dark green flow represents green inputs, such as recycling of straw, returning manure to the field, natural nitrogen fixation and utilization of swill, etc. All numbers are in Tg yr^{-1}.

Livestock species

The Nr emission intensity of ruminants (1.07 kgN per kg protein) was calculated to be lower than that of monogastric livestock (1.24 kgN per kg protein) across the whole production chain globally. Feed production accounts for 81% and 78% of total emissions in monogastric livestock and ruminants, respectively (Fig. 3a). Replacing ruminants with monogastric livestock would increase Nr emission from feed production by about one-third. Among all livestock, backyard chickens had the highest feed Nr emission intensity due to their lower feed conversion ratio (1/4–1/2 that of industrial chickens)[4], followed by industrial pigs. In contrast, non-dairy small ruminants (sheep and goats) had the lowest feed Nr emission intensity since their feed typically contains a large ratio of crop residues (10–40%) and only a small ratio of grain (0–7%)[6]. There was no notable difference in Nr emission intensity of livestock raising between ruminants (0.23 kgN per kg protein) and monogastric livestock (0.24 kgN per kg protein) globally.

The GHG emission intensity of ruminants (93 kgCO_2e per kg protein) is much lower than that of monogastric livestock (159 kgCO_2e per kg protein), but variations tend to be substantial at the feed-production and livestock-raising stages (Fig. 3b). The feed GHG emission intensity of monogastric livestock systems was calculated to be far higher than for ruminants due to substantial emissions from land use change. The feed GHG emission intensity from processing, transport, blending, field operation and fertilizer manufacture was also higher for monogastric livestock (36 kgCO_2e per kg protein) than for ruminants (26 kgCO_2e per kg protein). The CH_4 emission intensity of dairy production is lower than that of meat production, due to higher protein production efficiency and a higher share of digestible diet content. For instance, dairy cattle CH_4 emission intensity (22 kgCO_2e per kg protein) is much lower than that of beef cattle (173 kgCO_2e per kg protein). Chickens had the lowest livestock raising GHG emission intensity due to the lack of enteric fermentation and overall CH_4 emissions from manure.

National variations

Nitrogen and GHG emission intensity vary notably between ruminants and monogastric livestock and across countries due to differences in technology, facilities in livestock farming, farmers' knowledge and practices and climatic conditions (Extended Data Figs. 4 and 5). Moreover, there are considerable differences in the change ratio of nitrogen and GHG emissions when replacing ruminants with monogastric livestock (Extended Data Fig. 6).

Most countries and regions showed increased Nr emissions when replacing ruminants with monogastric livestock, predominantly those in East and South Asia, Africa, Oceania and North America due to relatively low NUE in grain feedstock production for monogastric livestock (Fig. 3c,d). India was the country that showed the largest increase in Nr emissions, estimated at 2.5 Tg (+44%). On a continental scale, Africa has the largest increase ratio (+66%, 2.2 Tg), followed by South Asia (+50%, 4.3 Tg). However, in most South American and European countries, Nr emissions of monogastric livestock were lower than emissions of ruminants, especially in Brazil, which showed a reduction of about 2.7 TgN (−57%) if replacing ruminants with monogastric livestock. This is because Brazil's grain feed production has a comparatively high NUE (69%) because it is based on soybean production with low rates of synthetic nitrogen fertilizer application resulting in an overall low Nr emission rate.

Except for most countries in South America and several countries in Africa, all remaining countries showed increased GHG emissions if no ruminant livestock production was undertaken due to substantial demand for grain feed and the resulting land use conversion of forest to croplands (Fig. 3e,f). India, Pakistan and China showed the most substantial increase in GHG emissions with 524 Tg (+99%), 289 Tg (+155%) and 273 Tg (+102%) CO_2e, respectively. Oceania (+206%, 329 Tg) had the highest increase ratio due to low enteric CH_4 emissions of ruminants and high land use change emissions. In contrast, in central and eastern

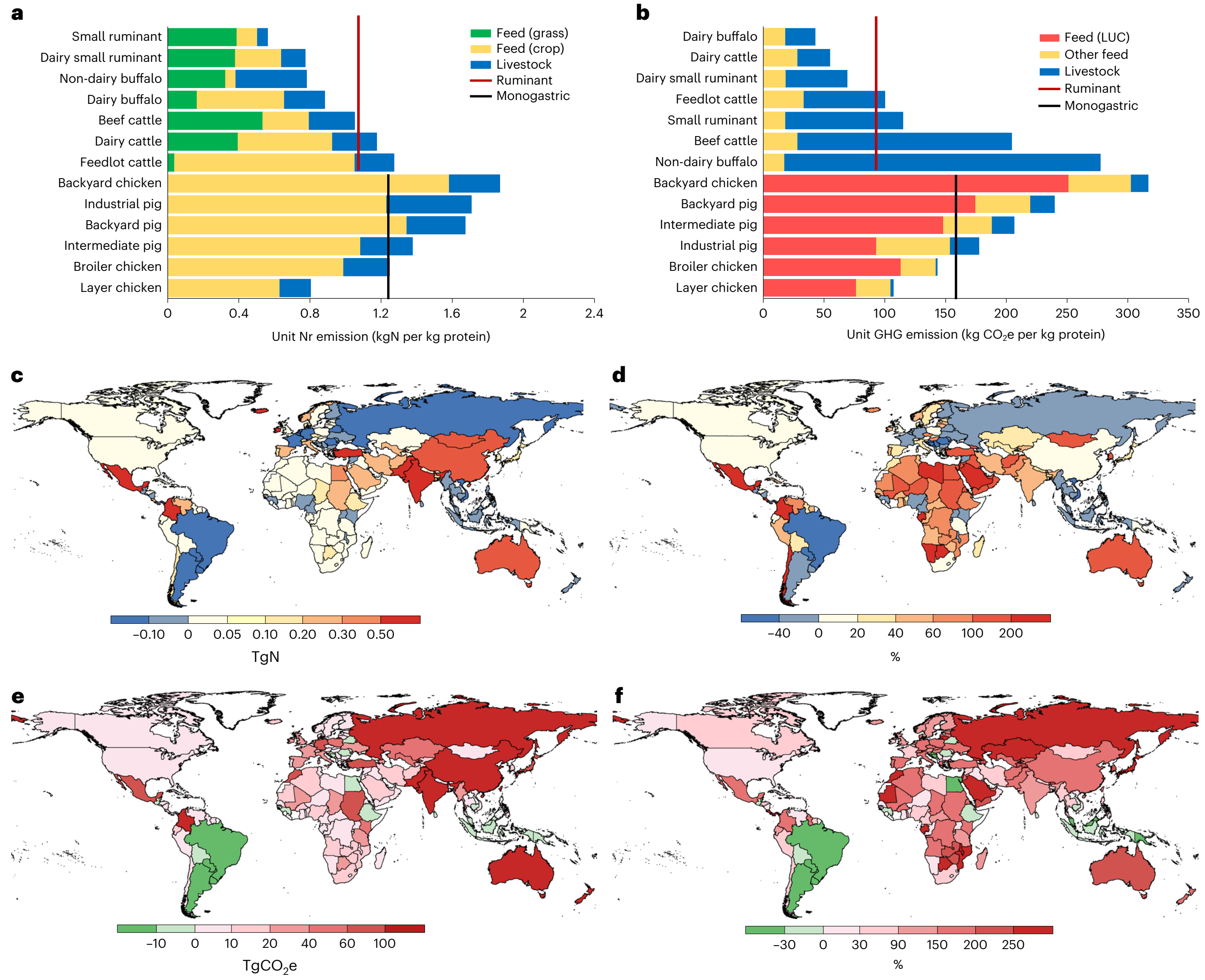


Fig. 3 | Global changes in Nr and GHG emissions when replacing ruminants with monogastric livestock by region and by livestock systems. a, Nr emission intensity (includes NH_3-N, NO_x-N, NO_3^--N) of all livestock systems. Green (grass feed) and yellow (crop feed) represent feed Nr emissions, and blue represents Nr emissions from livestock breeding. **b**, GHG emission intensity (including CO_2, CH_4, N_2O) of all livestock systems. The red bars represent the feed carbon emissions caused by land use changes, the yellow bars are the total carbon emissions from other feed production processes such as field operations, processing and blending, and the blue bars represent GHG emissions from livestock breeding. The red and black lines represent the average unit emission for ruminants and monogastric livestock, respectively. **c**, Total changes in Nr emissions from replacing monogastric with ruminant livestock, including NH_3-N, NO_x-N, NO_3^--N from livestock supply chains. **d**, Proportion of changed Nr emissions calculated by dividing total changed supply chains from **a** by ruminant Nr emissions. **e**, Total changed GHG emissions (including CO_2, CH_4, N_2O) from replacing ruminants with monogastric livestock. **f**, Proportion of changed GHG emissions from replacing ruminants with monogastric livestock, calculated by dividing total changed GHG emissions from **c** by ruminant GHG emissions from feed production and livestock raising. The base map was applied without endorsement using data from the Database of Global Administrative Areas (GADM; https://gadm.org/).

South America, such as Brazil, Argentina, Paraguay and Uruguay, GHG emissions decreased by 255 Tg (−45%), 66 Tg (−60%), 16 Tg (−61%) and 13 Tg (−45%) CO_2e, respectively. High crop yield decreased the total cropland area required for monogastric livestock feed and high gross energy intake by ruminants induced high enteric CH_4 emission in these countries.

Optimized scenario setting and analysis

Four scenarios were designed to mitigate livestock Nr and GHG emissions through optimizing livestock production systems: a BAU scenario (business as usual) and three mitigation scenarios (SYS, FED, ALL) (Fig. 4), with related environmental welfare and food security benefits (Fig. 5). The SYS scenario assumed maximizing ruminant production with consideration of grassland carrying capacity and maximum available straw feed for countries where ruminant Nr emissions are lower than Nr emission from monogastric livestock (Methods). The SYS2 scenario (an extreme variant of the SYS scenario) aims at maximizing ruminant production based on the current maximum total cellulose production potential, assuming the straw is not returned to the field and ruminants make maximum use of straws. The FED scenario was set to optimize feed and manure management in line with a global average emission intensity (decreasing the higher level to global average emission intensity while maintaining the original lower emission intensity). Finally, the ALL scenario integrated the SYS and FED scenarios.

Under the SYS scenario, we found that increasing ruminant production by 24% (Extended Data Fig. 7) could maximize the use

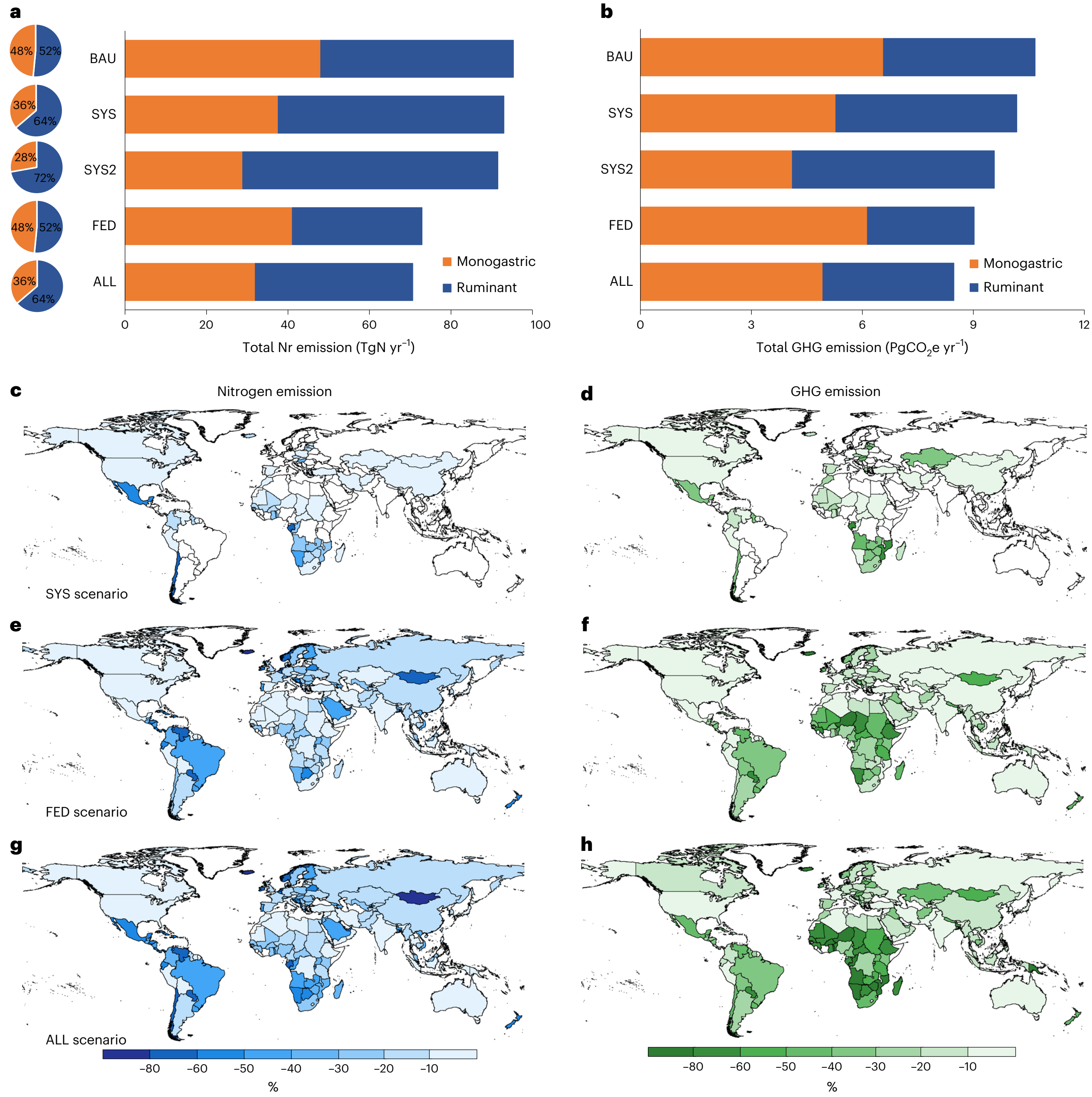


Fig. 4 | Optimizing livestock system to reduce Nr and GHG emissions under different scenarios. a, Total Nr emissions from ruminants and monogastric livestock under various scenarios. The ALL scenario represents a combination of the SYS and the FED scenario and is not related to SYS2. **b**, Total GHG emissions from ruminants and monogastric livestock. **c**, Total Nr emission (NH_3-N, NO_x-N and NO_3^--N) reduction ratio. **d**, GHG emission (including CO_2, CH_4, N_2O) reduction ratio under SYS scenario compared to BAU. White areas depict no change. **e**, Nr emission reduction ratio. **f**, GHG emission reduction ratio under the FED scenario compared to BAU. **g**, Nr emission reduction ratio. **h**, GHG emission reduction ratio under the ALL scenario compared to BAU. The base map was applied without endorsement using data from the Database of Global Administrative Areas (GADM; https://gadm.org/).

of cellulose and reduce by 2.3 TgN (3%) losses to the environment (Fig. 4c), reducing feed grain demand by 2.9 TgN (Extended Data Fig. 8a) compared with the BAU scenario globally. As a consequence, 39 Mha of cropland could be released, with the potential to feed up to 525 million people (Extended Data Fig. 8c,e) worldwide or sequestrate 862 TgCO$_2$e emission through reforestation. In total, 495 TgCO$_2$e emissions per year could be reduced under the SYS scenario. Surprisingly, 40% more ruminants would be produced under SYS2, and there would be 4 TgN emissions reduced and 73 Mha of cropland released, which means 940 million more people could be fed (Extended Data Fig. 8d,f). However, the amount of carbon sequestration resulting from reforestation is estimated to be larger than the total GHG reduction in the SYS scenario, that is, there is a trade-off between reducing emissions and supporting more people. This mainly occurs because the increased ruminant

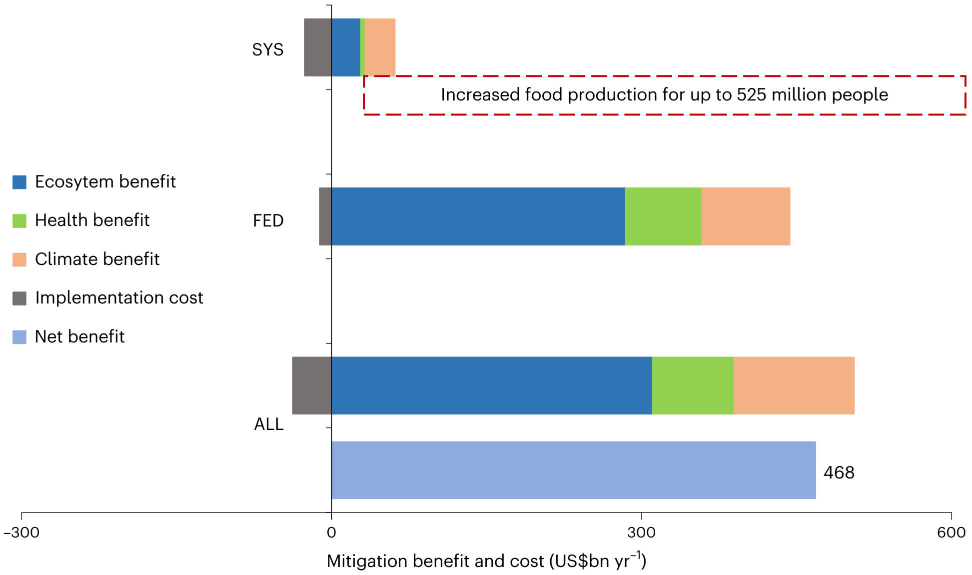


Fig. 5 | Costs and benefits under assumed scenarios. The benefits of reducing Nr and GHG emissions are superimposed in this figure. The benefits arising from GHG emission reduction are included in the climate impact.

production would generate large amounts of CH_4 emission, and thus the simultaneous implementation of targeted abatement measures is also essential.

Nr emissions from feed production and livestock raising are projected to be decreased by 20 Tg and 3 Tg under the FED scenario, respectively (Fig. 4e), as a consequence of reducing livestock emissions to the global average level. About 10.5 TgN emitted from fertilizer application and 9.8 TgN from recycled manure would be reduced, and GHG emissions could be reduced by 709 Tg through improved feed management and by 936 Tg through livestock raising. This indicates that feed and manure management still have substantial potential for optimization globally, especially in countries with current levels of Nr and GHG emissions above global average levels. Oceania shows the largest Nr emission reduction (47%) because of feed production optimization. The largest decrease in GHG emissions (40%) is found in sub-Saharan Africa due to emission reduction of CH_4 stemming from enteric fermentation (Extended Data Fig. 9).

The ALL scenario was designed to combine elements of system optimization and feeding improvement, providing insight into the potential of response to emerging food security pressures, for example, as a result of the COVID-19 pandemic. This scenario could maximize the use of cellulose and save croplands for grain production for direct human consumption, while it could also reduce emissions of Nr and GHG through improving feeding strategies and manure management. Through the integration of SYS and FED scenarios, the benefits of both scenarios could be amplified and thus contribute to the increasingly efficient management of livestock production globally. The ALL scenario has a mitigation potential of 25 TgN, and results in an 87% Nr emission reduction in feed production, achieving benefits for food security and environmental protection at the same time. Furthermore, global GHG emissions would be reduced by 2.2 $PgCO_2e$ a year if the cropland saved was all reforested. Approximately 1.3 $PgCO_2e$ of GHG emissions would be reduced if the cropland was not returned to forest land use. However, several countries might experience increased GHG emissions without reforestation and a trade-off between emission reduction and feeding more people may occur (Supplementary Fig. 1). Alternatively, the cropland saved in these countries could be partly reforested and partly utilized to grow food to achieve a win–win situation for emission reduction and food security.

Cost–benefit analysis of optimizing livestock production

A cost–benefit analysis was undertaken to assess the feasibility of scenario implementation. Reduction of Nr and GHG emissions has the potential to benefit human health through less exposure to air pollution such as fine particulate matter ($PM_{2.5}$), as well as improve ecosystem health, while mitigating climate change. However, it is important to consider socioeconomic impacts, for example, exemplified through implementation costs.

Ruminants have high production costs due to the long feeding period and continuous feed inputs required, resulting in a low benefit-to-cost ratio under the SYS scenario (2.4) (Fig. 5). However, the cropland saved under this scenario could contribute to feeding 525 million more humans and thus help to achieve the global zero hunger goal. At the same time, GHG emissions of ruminants could be reduced through the feed production and manure management optimization as illustrated by the FED scenario. Overall lower costs could generate large huge environmental benefits (US$443 billion) from an optimized application of synthetic fertilizers and manures from croplands and grasslands (US$6 billion), and improvements in livestock farming and manure management (US$5 billion). The combination of the SYS and FED scenarios could achieve the largest environmental benefits (US$468 billion) and food security benefits as documented in the ALL scenario, with a benefit-to-cost ratio of 13.5, mainly through optimizing the relative shares of livestock types across the whole system and improving production efficiency.

Discussion

Taking a full life cycle perspective and feed production into consideration, we found that ruminants have comparatively lower Nr and GHG emissions than monogastric livestock. Emphasizing high Nr and GHG emissions from ruminants during the raising stage without a full life cycle analysis has misled policy recommendations on optimal livestock development. Land use change and synthetic nitrogen fertilizer use for grain feed production for monogastric livestock result in higher relative Nr and GHG emissions. Ruminants are able to convert human-inedible cellulose into high-quality protein, thus saving energy and nutrient otherwise required for feed production[4,10]—with benefits for human food security, environment and climate[8]. Therefore, shifting the balance in livestock production from ruminants to monogastric livestock requires more grain feed with substantial land use change implications and conversion from forest to croplands. This would lead to exacerbating biodiversity loss and threatening valuable carbon sinks, thus having clear negative impacts on a global strategy for achieving net zero carbon. Moreover, ruminants would deposit most manure on grasslands, which are directly used as nutrient for forage production[6]. Therefore, despite the low NUE of meat production, ruminants on aggregate only contribute to a small extent to Nr pollution to the environment, since the manure is recycled in grasslands. However, feedlots still have a substantial reduction potential with regard to Nr pollution from ruminants.

We determined the grassland carrying capacity using grassland cover share data to adjust the reasonable utilization of grassland due to the lack of country-specific data on grassland degradation (Methods). The calculation of implementation costs under the SYS scenario should utilize the production costs of all livestock in each country, but we used producer price data derived from FAOSTAT, which may be slightly higher than the actual implementation costs. Also, the 12% increase in ruminant production under the SYS scenario may potentially reduce and increase the production price of ruminants and monogastric livestock, respectively, but this is beyond the scope of this study and thus not considered here due to the complexity of the economic principles involved. The calculation of the potential for feeding more people would ideally have been based on the per-capita protein demand, but detailed data for all countries are lacking, so we utilized well-documented per-capita protein supply data in 2019 provided by FAOSTAT instead. Moreover, the cost of reducing Nr emissions was quantified in detail, while the implementation of Nr reduction (NH_3, NO_x, NO_3^- and N_2O) measures will have co-benefits due to associated carbon emissions reductions (CH_4 and CO_2). However, these co-benefits are complex to assess at a global scale and are outside the scope of this study.

The increase in ruminant livestock production could be accompanied by a change in primary crop types to increase the overall efficiency. Soybean production has a comparatively low yield and generates only a small amount of straw compared with maize production, although soybean has a higher NUE than maize[11]. Therefore, switching soybean for whole corn silage may benefit ruminant production while increasing the yield and reducing pollution. Nevertheless, more quantitative studies are still needed to assess the impacts of such a change at the farm-gate level. Moreover, to optimize the shares of ruminants and monogastric livestock at the local scale to maximize the use of grain and straw, it is important to spatially integrate croplands with animals for both feed use and manure recycling.

Without a fundamental change in existing production methods, about 24% more ruminants could be reared using current grass and straw production levels. However, improving production practices across cropland, grassland and livestock systems is an essential step, provided that production efficiency is improved during the raising stage. Compared to the SYS scenario, feed and manure optimization in the FED scenario have greater potential to reduce Nr and GHG emissions during animal food production. The specific emission reduction measures for cropland and grassland areas include enhancing nitrogen fertilizer application techniques[12,13] and fallow cultivation[14]. Emission reduction options for livestock raising focus on livestock dietary[15] and manure management[16]. Compared to system optimization, feeding practice improvement has lower costs and comparatively larger environmental benefits. It is an easy-to-implement approach to reduce emissions quickly to achieve mitigation targets.

The long breeding cycle induced a high production cost for ruminants, leading to a high price of red meat and a low consumption level on the household level. Hence, it is important to reduce the production cost to make it feasible to increase the proportion of ruminants globally. Governments should properly guide the breeding of cattle and sheep: (1) increase cattle and sheep breeding subsidies, such as risk subsidies, and subsidies for related breeding companies to reduce breeding costs[17]; (2) pay attention to the cultivation of new varieties of animals to improve feed use efficiency and reduce manure production; and (3) guide the coupling of crop planting and animal raising, especially in regions dominated by small-scale farming, to reduce transportation costs for feed and manure[18].

Human meat consumption is the fundamental driver of livestock production[19]. We have shown that reducing ruminant production while increasing monogastric livestock production at the current stage would lead to adverse effects on food security and environmental health, while human-inedible cellulose would go unused for food production through conversion via ruminants. However, overconsumption of red meat is associated with several chronic diseases, obesity and premature death[20]. Despite this association being short of strong evidence[21], we do not simply advocate eating more meat such as beef and mutton, but provide supporting evidence for achieving a balanced healthy diet, shifting towards ruminant protein in the current structure of meat protein demand and not exceeding the upper limit of recommendation for red meat consumption. Balancing dietary structure and relocating an increased production of ruminant products to countries where needed, especially in African countries, could help to achieve Sustainable Development Goals as a whole (such as zero hunger, good health and well-being). We advocate for an integrated assessment across the whole life cycle and all human and environmental determinants when developing recommendations for the whole production chain efficiency and the cellulose amount that we would use for ruminants. Related policy development should account for a more balanced dietary structure, including both ruminant and monogastric livestock products, based on a whole-system cost–benefit assessment.

Although replacing ruminants with monogastric livestock would release grasslands, natural and seminatural grassland (occupying most of the total grassland area) cannot be converted into croplands or forests everywhere due to climatic[22], soil fertility and topographical factors[23]. Grasslands are more stable carbon sinks than forests because of their inherent resilience to drought and wildfire[24]. Changes in albedo caused by afforestation may outweigh the benefits of carbon capture, resulting in a net warming effect[25]. Moreover, healthy grasslands can store an amount of organic carbon comparable to that of forests, mainly due to their rich underground carbon sinks[24]. Grasslands are also more conducive than forests to alleviating soil erosion and adding water conservation in semi-arid ecosystems[26], and forming habitats for a range of wildlife species[27]. Only a small portion of artificial grasslands may be suitable for conversion, but a lack of detailed information available about the area of convertible artificial grasslands, potential changes in productivity after reclamation into croplands and the degree of carbon sequestration after afforestation make it difficult to accurately project the potential benefits of grassland conversion. The conversion of artificial grassland to cropland would release a large amount of GHG emissions[28,29] and grassland afforestation is complex, and therefore it is unclear whether carbon sequestration would decrease[30,31] or increase[32]. Therefore, this study may only slightly underestimate the potential food security and climate benefits of monogastric livestock. Furthermore, the main purpose of this study is not to remove all ruminants, but to provide an extreme case to demonstrate the importance of ruminants in the context of maximum utilization of cellulose resources. Our aim is to provide guidance for policymakers—not to criticize or even eliminate ruminants—and highlight that ruminants can utilize human-inedible cellulose, freeing up large areas of cropland for conversion into forest or for human food production.

Methods

Data sources

FAOSTAT (Crop and Livestock Products, https://www.fao.org/faostat/en/#data/QCL) provides numbers (Producing Animals/Slaughtered), production (Production Quantity) and slaughtered weight yield (Yield) of each livestock[3]. We used the protein content of livestock products from Global Livestock Environment Assessment Model (GLEAM)[6].

Human protein demand for all products was from FAOSTAT (Food Balances)[3]. Proportion information for specific livestock systems, such as pig production systems containing backyard, intermediate and industrial systems, was obtained from GLW (Gridded Livestock of the World, https://dataverse.harvard.edu/dataverse/glw/).

The yield and production quantity of feed crops were derived from FAOSTAT data[3]. For grass yield, we acquired the data from the literature[33]. The nitrogen content of each crop and grass was from GLEAM[6]. We estimated synthetic fertilizer consumption of each crop and grass from FAO[3] (https://www.fao.org/faostat/en/#data/RFB), IFA[34] and the literature[35]. Nitrogen deposition rates on cropland and grassland were derived from the literature[36–38]. The irrigation nitrogen rates were obtained from Lesschen et al.[39] and the irrigation water use data was from AQUASTAT (https://www.fao.org/aquastat/en/). For the natural biological fixation from grass and crop biological nitrogen fixation, we used data from Lassaletta et al.[35] and Zhang et al.[37]. Global land cover data and land use data were from the GLC-SHARE database (https://data.apps.fao.org/catalog/dataset/global-land-cover-share-database) and FAOSTAT data[3].

Counterfactual analysis

We compare the environmental impacts between ruminants and monogastric livestock by estimating and comparing the Nr and GHG emissions from current ruminants and monogastric livestock replaced by the ruminants according to the standard of protein equality. Using this approach, we can analyse the huge land use change risks for growing feed crops and evaluate the contribution of ruminants and monogastric livestock to humans from a new perspective. The allocation of pigs and chickens among monogastric livestock is based on the human protein requirements of pigs, chicken and eggs (from FAOSTAT, Protein Supply Quantity)[3].

Nitrogen loss from livestock supply chains

Feed production emissions. To estimate Nr emissions from each livestock supply chain, we mainly used GLEAM. A detailed description of the GLEAM model can be found in the literature[6]. For feed production, we first estimated the dry matter feed by food conversion ratio (FCR)[4] and crop nitrogen content to calculate grass ($N_{\text{grass feed}}$), crop ($N_{\text{crop feed}}$) and crop residues ($N_{\text{crop residue feed}}$) feed nitrogen, respectively, following the feed ration percentage from the GLEAM model[6], and then Nr emissions from cropland and grassland were calculated.

We calculated cropland Nr emissions from synthetic fertilizer, recycled manure and decomposed crop residues. First, we used the CHANS model[40] to calculate all cropland NUE (NEU_{crop}, without differentiating between feed and ration cultivation) across global countries (equation (1)). Then, we used the NUE_{crop} to calculate the nitrogen input of crop feed, especially fertilizer and manure nitrogen input which were used to estimate nitrogen loss. We calculated the amount of nitrogen from decomposed crop residues returned to the field following equations in the GLEAM model, and used its removed fraction of above-ground residues of the cropland to estimate the crop residue feed quantity ($N_{\text{crop residue feed}}$). The available manure nitrogen recycled on cropland from each livestock system was estimated following Uwizeye et al.[1] Finally, the Nr emissions from synthetic fertilizer, manure and crop residues were calculated following equations in the GLEAM model.

$$NUE_{\text{crop}} = \frac{N_{\text{crop products}}}{N_{\text{CBNF}} + N_{\text{fertilizer}} + N_{\text{manure}} + N_{\text{irrigation}} + N_{\text{deposition}}} \tag{1}$$

where the nitrogen inputs of cropland consist of crop biological nitrogen fixation (N_{CBNF}), fertilizer nitrogen ($N_{\text{fertilizer}}$), manure nitrogen (N_{manure}), irrigation nitrogen ($N_{\text{irrigation}}$) and deposition nitrogen ($N_{\text{deposition}}$), and the nitrogen outputs of cropland are crop products ($N_{\text{crop products}}$).

We calculated grassland Nr emissions from synthetic fertilizer and manure deposited on pastures. The manure deposited on pastures from all livestock was calculated based on Uwizeye et al.[1] The nitrogen loss from grassland was calculated in the GLEAM model.

Livestock raising emissions. The Nr emissions from manure management systems were estimated as livestock raising emissions[6]. We calculated nitrogen excretion following IPCC methods[41,42] and the total ammoniacal nitrogen (TAN) from Uwizeye et al.[1], and used the fraction of manure management system (MS_{S}) and EF (emission factor) to calculate Nr emissions at the livestock raising stage.

Nitrogen balance

Feed production stage. The nitrogen inputs of cropland consist of crop biological nitrogen fixation (N_{CBNF}), fertilizer nitrogen ($N_{\text{fertilizer}}$), manure nitrogen (N_{manure}), irrigation nitrogen ($N_{\text{irrigation}}$) and deposition nitrogen ($N_{\text{deposition}}$), and nitrogen outputs of cropland are crop ($N_{\text{crop feed}}$) and crop residues ($N_{\text{crop residue feed}}$) as feed, other crop residues ($N_{\text{other crop residue}}$, not as feed for this livestock system, as feed for other livestock or for other uses) and Nr emissions (N_{emission}, including NH_3-N, NO_x-N, NO_3^--N, N_2O-N). NUE in a cropland system ($\text{NUE}_{\text{cropland}}$) is calculated as equation (2). The nitrogen inputs of grassland contain natural biological nitrogen fixation (N_{NBNF}), fertilizer nitrogen ($N_{\text{fertilizer}}$), deposited manure nitrogen (N_{manure}) and deposition nitrogen ($N_{\text{deposition}}$), and nitrogen outputs of grassland are grass feed ($N_{\text{grass feed}}$) and Nr emission (N_{emission}). NUE in a grassland system ($\text{NUE}_{\text{grassland}}$) is taken from equation (3).

$$NUE_{\text{cropland}} = \frac{N_{\text{crop feed}} + N_{\text{crop residue feed}}}{N_{\text{CBNF}} + N_{\text{fertilizer}} + N_{\text{manure}} + N_{\text{irrigation}} + N_{\text{deposition}}} \tag{2}$$

$$NUE_{\text{grassland}} = \frac{N_{\text{grass feed}}}{N_{\text{NBNF}} + N_{\text{fertilizer}} + N_{\text{deposited manure}} + N_{\text{deposition}}} \tag{3}$$

Livestock raising stage. Crop ($N_{\text{crop feed}}$), crop residues (including $N_{\text{crop residue feed}}$ and $N_{\text{other crop residue feed}}$ from the production of human rations or crop feed for other livestock), grass feed ($N_{\text{grass feed}}$), swill (N_{swill}) and other feed ($N_{\text{other feed}}$, including synthetic amino acids and fishmeal) are the nitrogen inputs, and the nitrogen output contained livestock products ($N_{\text{livestock products}}$, including meat, eggs and milk), Nr emission and manure nitrogen recycling to croplands and grassland. The NUE in the livestock system ($\text{NUE}_{\text{livestock}}$) is derived based on equation (4).

$$NUE_{\text{livestock}} = \frac{N_{\text{livestock products}}}{N_{\text{crop feed}} + N_{\text{crop residue feed}} + N_{\text{grass feed}} + N_{\text{other crop residue feed}} + N_{\text{swill}} + N_{\text{other feed}}} \tag{4}$$

Whole livestock production chain. We defined $\text{NUE}_{\text{whole chain}}$ based on the total livestock supply chain, including feed production and livestock raising stages (equation (5)). N_{BNF} contains N_{CBNF} from croplands and N_{NBNF} from grassland. $N_{\text{other manure}}$ is the manure nitrogen recycling to the cropland from other livestock, for instance, monogastric livestock that require more crop feed could not produce enough manure of their own and need manure nitrogen from other livestock.

$$NUE_{\text{whole chain}} = \frac{N_{\text{livestock products}}}{N_{\text{BNF}} + N_{\text{irrigation}} + N_{\text{fertilizer}} + N_{\text{deposition}} + N_{\text{other manure}} + N_{\text{other crop residue}} + N_{\text{swill}} + N_{\text{other feed}}} \tag{5}$$

GHG emissions from livestock supply chains

The major GHG emissions from livestock systems in the GLEAM model are: (1) CH_4 emissions from enteric fermentation in ruminants and pigs; (2) CH_4 emissions arising from manure management; (3) N_2O emissions released from manure management, done in the calculation of Nr emissions; (4) CH_4 emissions from rice production; (5) CO_2 emissions from fertilizer manufacture; (6) CO_2 emissions from field operations;

(7) CO_2 emissions from feed blending, processing and transport; (8) CO_2 emissions from land use change. Items (1)–(7) were calculated by the following methods described in Supplementary Table 1 and item (8) was calculated following equations (6) and (7).

We calculated the cropland area by monogastric livestock more than ruminants and take the cropland area as the relative land use change with monogastric livestock, as shown in equations (6) and (7).

$$\mathrm{Land}_c = \frac{\mathrm{DM}_c}{\mathrm{DMYG}_c \times \mathrm{FUE}_c} \times \frac{\mathrm{EFA}_c}{\mathrm{MFA}_c} \tag{6}$$

where Land_c is the land area of feed c, DMYG_c is the dry matter yield of feed c, in kg ha^{-1}, and is calculated based on crop yield according to the GLEAM method, FUE_c is feed use efficiency of feed c, and MFA_c and EFA_c are the mass fraction and economic fraction, respectively, and are derived from GLEAM.

$$\mathrm{LUC}_{\mathrm{monogastric}} = (\mathrm{Cropland}_{\mathrm{ruminant}} - \mathrm{Cropland}_{\mathrm{monogastric}} \times \mathrm{LUC}) \tag{7}$$

where $\mathrm{Cropland}_{\mathrm{ruminant}}$ and $\mathrm{Cropland}_{\mathrm{monogastric}}$ are the areas of cropland required for ruminant and monogastric feed, respectively, and LUC is the land use change value[43], representing annual GHG emissions released from forest to cropland, in tCO_2 ha^{-1} yr^{-1}. The LUC value takes into account the long-term effects and was discounted to an average value for each year[43]. There was a large uncertainty in the calculation of GHG emission changes from forest conversion to cropland and reforestation (Uncertainty analysis).

Scenario analysis

The baseline scenario has been established as BAU, assuming the total amount of ruminant and monogastric protein produced in 2019 is maintained at a constant level. Three optimized scenarios were designed to assess the impact on mitigating livestock nitrogen and GHG emissions, including SYS, FED and ALL scenarios.

BAU scenario. The BAU scenario assumes the amount of protein produced by ruminants and monogastric livestock to be 7.06 and 6.64 TgN-protein in 2019, respectively. Currently, there are partially underutilized grassland areas (Supplementary Fig. 2) and sustainable unused crop residue resources.

SYS scenario. In this scenario, we model the effect of maximizing ruminant production and reducing monogastric production accordingly while keeping total livestock protein production constant (13.7 TgN-protein, calculated from FAOSTAT) in 2019. The SYS scenario represents a switch of 12.3% of global livestock production from monogastric to ruminant livestock. The resource constraints for maximizing ruminant protein production are current maximum production of total cellulose while considering the carrying capacity of the grass and the total amount of crop residues. As for the maximum available value of grass nitrogen, we take into account the degradation conditions (grass degradation adjustment rate (DAR))[44] of grazing grassland to adjust the utilization efficiency (UE)[6] of grassland. For DAR, we set mild degradation to 80%, slightly mild degradation to 65%, moderate degradation to 50% and severe degradation to 30% (Extended Data Fig. 10). The country's average grassland cover share was calculated from the GLC-Share database[45] to reflect the extent of grassland degradation, and using 3/4 value, 1/2 value and 1/4 value quadrature into four intervals, the adjustment factors were set to 80%, 65%, 50% and 30%, respectively. In addition, grassland degradation is not considered for non-grazed grasslands. The maximum available value of grass nitrogen ($N\mathrm{max}_{\mathrm{grass}}$) is calculated as shown in equation (8).

$$\begin{aligned} N\mathrm{max}_{\mathrm{grass}} = {} & \mathrm{Production}_{\mathrm{grassN}} \times R_{\mathrm{grazing}} \times \mathrm{UE} \times \mathrm{DAR} \\ & + \mathrm{Production}_{\mathrm{grassN}} \times (1 - R_{\mathrm{grazing}}) \times \mathrm{UE} \end{aligned} \tag{8}$$

where $\mathrm{Production}_{\mathrm{grassN}}$ is the total grass nitrogen production and R_{grazing} is the grazing ratio of ruminants.

The maximum crop residue nitrogen removed from croplands was calculated from crop nitrogen ($\mathrm{Production}_{\mathrm{cropN}}$), crop residues to crop ratio ($R_{\mathrm{residue-crop}}$)[6] and the proportion of crop residues removed (R_{removed})[6], as shown in equation (9).

$$N\mathrm{max}_{\mathrm{crop\ residues}} = \mathrm{Production}_{\mathrm{cropN}} \times R_{\mathrm{residue-crop}} \times R_{\mathrm{removed}} \tag{9}$$

The maximum cellulose nitrogen production was obtained from the sum of $N\mathrm{max}_{\mathrm{grass}}$ and $N\mathrm{max}_{\mathrm{crop\ residues}}$, dividing by the current amount of cellulose utilized by the ruminants and getting the maximum available ruminant production multiplier. Meanwhile, in the context of the Nr emission intensity of ruminants being lower than that of monogastric livestock, we can obtain the proportion of ruminants that maximizes cellulose utilization.

SYS2 scenario. This scenario is an extreme variant of the SYS scenario; it assumes the crop residues are not returned to the cropland and all removed crop residues are used to produce feed for ruminants, that is, $R_{\mathrm{removed}} = 1$. In SYS2, it is also a prerequisite that the Nr emission intensity of ruminants is lower than that of monogastric livestock. The SYS2 scenario reflects a switch of 20.7% of global livestock production from monogastric to ruminant livestock. To fully realize the benefits of this scenario it would be necessary to account for the fact that cropland may be deprived of nutrients from recycled crop residues; however, the deficit could be supplemented by the ruminant manure. This scenario would release more croplands and feed more people than the SYS scenario.

FED scenario. In this scenario, the production of ruminants and monogastric livestock remained was kept consistent with the BAU scenario. All Nr emissions (nitrogen from NH_3, NO_x and NO_3^-) from feed production and livestock raising are reduced to the global average, and those countries that are already below the global average remain unchanged. The FED scenario was designed to produce substantial emission reductions and could be achieved through targeted abatement measures on cropland, grassland and livestock system (Supplementary Table 2), but no additional croplands would be released.

ALL scenario. The ALL scenario is a combination of the SYS scenario and the FED scenario to achieve both an optimal livestock production ratio and emission levels. In this scenario, maximizing ruminant production (ruminant protein production is consistent with the SYS scenario) and targeted abatement measures at all stages are needed. The ALL scenario could maximize the benefits of food security, environmental protection and climate mitigation. This is the scenario advocated in this study.

Cost–benefit analysis

Implementation cost. The implementation cost under the SYS scenario is considered to be equal to the change in protein quality of all livestock P_j (where j represents different livestock systems) multiplied by their unit product cost (PPrice_j, in US$ per kg protein), as shown in equation (10). Here PPrice_j is the regional animal producer price and is derived from the FAOSTAT database with regional producer prices.

$$\mathrm{Cost}_{\mathrm{SYS}} = \sum P_j \times \mathrm{PPrice}_j \tag{10}$$

For the FED scenario, we used the Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model (https://gains.iiasa.ac.at/models/index.html) to calculate the abatement costs from cropland ($\mathrm{Cost}_{\mathrm{FED-cropland},k}$), grassland ($\mathrm{Cost}_{\mathrm{FED-grassland},k}$) and livestock ($\mathrm{Cost}_{\mathrm{FED-livestock},k}$) for each country. A detailed description of the GAINS model can be found in Klimont et al.[46] The implementation cost under the FED scenario is calculated in equations (11)–(13).

$$\text{Cost}_{\text{FED}-\text{cropland},k} = \nabla E_{\text{N}-\text{cropland},k} \times C_{\text{cropland},k} \tag{11}$$

$$\text{Cost}_{\text{FED}-\text{grassland},k} = \nabla E_{\text{N}-\text{grassland},k} \times C_{\text{grassland},k} \tag{12}$$

$$\text{Cost}_{\text{FED}-\text{livestock},j} = N_{i,j} \times C_{\text{livestock},j} \times \text{AR}_k \tag{13}$$

Where $\nabla E_{\text{N-cropland},k}$ and $\nabla E_{\text{N-grassland},k}$ are the Nr emission reduction from cropland and grassland in country k, respectively, $C_{\text{cropland},k}$, $C_{\text{grassland},k}$ and $C_{\text{livestock},k}$ are the unit abatement cost of the most appropriate mitigations (shown in Supplementary Tables 2 and 3) to reduce cropland nitrogen, grassland nitrogen and livestock nitrogen loss modified for the specific farming practices of country k, respectively; $C_{\text{grassland},k}$ is set at one-fifth of $C_{\text{cropland},k}$. AR_k is the calculated abatement rate for country k.

For the ALL scenario, the abatement costs from cropland and grassland are assumed to be equal to those in the FED scenario, and the abatement costs from livestock are the sum of the FED and SYS scenarios.

Societal benefits assessment. The societal benefits of optimizing global ruminant production in this study are defined as the sum of avoided damage costs for ecosystem health (E_{benefit}), human health (H_{benefit}) and climate change mitigation (C_{benefit}), as shown in equation (14).

$$SO_{\text{benefit}} = E_{\text{benefit}} + H_{\text{benefit}} + C_{\text{benefit}} \tag{14}$$

The E_{benefit} is assumed to be the benefit of Nr mitigation on the ecosystem, which is also equal to reducing the avoided damage costs. We assume unit Nr damage cost in Europe and the United States is also applicable to other countries after adjusting for differences in the regional willingness to pay (WTP) and purchasing power parity (PPP) for the ecosystem services, as shown in equation (15).

$$\text{UE}_{\text{benefit,Nr},k} = \partial_{\text{EU}} \times \frac{\text{WTP}_k}{\text{WTP}_{\text{EU}}} \times \frac{\text{PPP}_k}{\text{PPP}_{\text{EU}}} \tag{15}$$

where ∂_{EU} is the estimated unit ecosystem damage cost of Nr emissions based on the literature[45,47]; the value of $\text{UE}_{\text{benefit,Nr},k}$ can be found in Supplementary Table 4.

Then, the E_{benefit} is summed according to equation (16).

$$E_{\text{benefit}} = \nabla E_{\text{N}_2\text{O}} \times \text{UE}_{\text{benefit,N}_2\text{O}} + \nabla E_{\text{NH}_3} \times \text{UE}_{\text{benefit,NH}_3} + \nabla E_{\text{NO}_x} \times \text{UE}_{\text{benefit,NO}_x} \tag{16}$$

where $\nabla E_{\text{N}_2\text{O}}$, ∇E_{NH_3} and ∇E_{NO_x} are the calculated reduction in N_2O, NH_3 and NO_x, and $\text{UE}_{\text{benefit,N}_2\text{O}}$, $\text{UE}_{\text{benefit,NH}_3}$ and $\text{UE}_{\text{benefit,NO}_x}$ represent the unit ecosystem benefit of N_2O, NH_3 and NO_x emission reduction, respectively, in US\$ kgN^{-1} (values are listed in Supplementary Table 4).

The human health benefit (H_{benefit}) refers to the benefit of prevented mortality derived from $PM_{2.5}$ mitigation caused by animal Nr abatement. We derived the national-specific unit health damage costs of Nr emission from Gu et al.[48], which connected the economic costs of mortality per unit of Nr emission with the population density, GDP per capita, urbanization and nitrogen share. The calculation of health benefits in this study is shown in equation (17).

$$H_{\text{benefit}} = \nabla E_{\text{Nr}} \times H_{\text{benefit,Nr}} \tag{17}$$

where ∇E_{Nr} is the Nr emission reduction in specific scenarios and $H_{\text{cost,Nr}}$ represents the unit health benefit of Nr reduction in US\$ kgN^{-1}.

The climate-related benefits of optimizing ruminant production (C_{benefit}) are considered to be the sum of the GHG mitigation benefits and the Nr (NH_3 and NO_x) mitigation impact on climate, as shown in equation (18).

$$\begin{aligned} C_{\text{benefit}} &= \nabla E_{\text{GHG}} \times \text{UC}_{\text{benefit,GHG}} \\ &\quad -(\nabla E_{\text{NH}_3} \times C_{\text{benefit,NH}_3} + \nabla E_{\text{NO}_x} \times C_{\text{benefit,NO}_x}) \end{aligned} \tag{18}$$

where ∇E_{GHG} is the GHG emission reduction in a specific scenario, in kgCO_2e, and the GWP_{100} for CH_4 and N_2O are 27.9 and 273 kgCO_2e, respectively. $\text{UC}_{\text{benefit,GHG}}$ represents the monetary climate benefit due GHG mitigation, which is assumed to be the carbon price, of US\$40–80 tCO_2^{-1} (ref. [49]). $C_{\text{benefit,NH}_3}$ and $C_{\text{benefit,NO}_x}$ represent the monetary climate impact due to changed NH_3 and NO_x emissions, which is associated with the cooling effect of NH_3 and NO_x on the global climate based on previous studies.

Cropland recovered for human food production

We first calculated the recovered or 'saved' cropland area ($\text{Land}_{\text{sys and all}}$) under the SYS and ALL scenarios (no cropland is released in the FED scenario). Next, we calculated crop nitrogen yield per unit of cropland ($\text{Yield}_{\text{cropN}}$) by dividing all crop nitrogen production ($\text{Production}_{\text{cropN}}$) using the total cropland area ($\text{Cropland}_{\text{total}}$, from FAOSTAT), which is multiplied by $\text{Land}_{\text{sys and all}}$ to obtain the total value of saved crop nitrogen production. We estimate the additional number of people that could be sustained under the assumption of a purely vegetarian diet by extra food production from saved croplands ($\text{Population}_{\text{saved}}$) by dividing the total saved crop nitrogen production by unit nitrogen nutrition requirements ($\text{Protein}_{\text{unit}}/6.25$, where 6.25 is the protein to nitrogen conversion ratio and $\text{Protein}_{\text{unit}}$ is the per-capita protein requirement, in kg protein per capita per year, calculated from FAOSTAT). The calculation is depicted in equations (19) and (20).

$$\text{Yield}_{\text{cropN}} = \frac{\text{Production}_{\text{cropN}}}{\text{Cropland}_{\text{total}}} \tag{19}$$

$$\text{Population}_{\text{saved}} = \frac{\text{Yield}_{\text{cropN}} \times \text{Land}_{\text{sys and all}}}{\text{Protein}_{\text{unit}}} \tag{20}$$

Uncertainty analysis

In this study, we estimated the uncertainties of nitrogen losses, GHG emissions, costs and benefits for each scenario in 166 countries using 10,000 Monte Carlo simulations. The 95% confidence intervals for all results were calculated. The coefficients of variation (CVs, %) of activity data and parameters are shown in Supplementary Tables 5 and 6, and the uncertainties of the final simulation results are shown in Supplementary Data.

Reporting summary

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

Data availability

Data supporting the findings of this study are available within the Article, a separate source data file and its Supplementary Information files. Source data are provided with this paper.

Code availability

No code is used in this research. The spatial analysis is run in ArcGIS v.10.2.

References

1. Uwizeye, A. et al. Nitrogen emissions along global livestock supply chains. *Nat. Food* **1**, 437–446 (2020).
2. Gerber, P.J.S.H. *Tackling Climate Change through livestock—A Global Assessment of Emissions and Mitigation Opportunities* (FAO, 2013).

3. *FAOSTAT: FAO Statistical Databases* (FAO, 2021).
4. Mottet, A. et al. Livestock: on our plates or eating at our table? A new analysis of the feed/food debate. *Food Secur. Gov. Lat Am.* **14**, 1–8 (2017).
5. Ripple, W. J. et al. Ruminants, climate change and climate policy. *Nat. Clim. Chang.* **4**, 2–5 (2013).
6. *Global Livestock Environmental Assessment Model. Version 2. Data Reference Year: 2010* (FAO, 2018); https://www.fao.org/fileadmin/user_upload/gleam/docs/GLEAM_2.0_Model_description.pdf
7. Eisler, M. C. et al. Agriculture: steps to sustainable livestock. *Nature* **507**, 32–34 (2014).
8. Tilman, D. & Clark, M. Global diets link environmental sustainability and human health. *Nature* **515**, 518–522 (2014).
9. Ioat, L. L. et al. Increasing importance of precipitation variability on global livestock grazing lands. *Nat. Clim. Chang.* **8**, 214–218 (2018).
10. Van Zanten, H. H. E. et al. Defining a land boundary for sustainable livestock consumption. *Glob. Change Biol.* **24**, 4185–4194 (2018).
11. Wortmann, C. S. et al. Nitrogen use efficiency of irrigated corn for three cropping systems in Nebraska. *Agron. J.* **103**, 76–84 (2011).
12. Zhang, X. et al. Optimized fertigation maintains high yield and mitigates N_2O and NO emissions in an intensified wheat–maize cropping system. *Agr. Water. Manag.* **211**, 26–36 (2019).
13. Zhao, Z. et al. Nitrification inhibitor's effect on mitigating N_2O emissions was weakened by urease inhibitor in calcareous soils. *Atmos. Environ.* **166**, 142–150 (2017).
14. Liang, X. et al. No-tillage effects on N and P exports across a rice-planted watershed. *Environ. Sci. Pollut. Res.* **23**, 8598–8609 (2016).
15. Ferrer, P. et al. Nutritional value of crude and partially defatted olive cake in finishing pigs and effects on nitrogen balance and gaseous emissions. *Anim. Feed Sci. Technol.* **236**, 131–140 (2018).
16. Zhang, Z. et al. Mitigation of carbon and nitrogen losses during pig manure composting: a meta-analysis. *Sci. Total Environ.* **783**, 147103 (2021).
17. Li, Q., Wang, Y. & Shi, Z. Evaluation and reflection of the beef cattle improved variety subsidy in China. *J. China Agric. Univ.* **24**, 234–240 (2019).
18. Jin, S. et al. Decoupling livestock and crop production at the household level in China. *Nat. Sustain.* **4**, 48–55 (2021).
19. Gu, B., Zhang, X., Bai, X., Fu, B. & Chen, D. Four steps to food security for swelling cities. *Nature* **566**, 31–33 (2019).
20. Wolk, A. Potential health hazards of eating red meat. *J. Intern. Med.* **281**, 106–122 (2017).
21. Zeraatkar, D. et al. Red and processed meat consumption and risk for all-cause mortality and cardiometabolic outcomes. *Ann. Intern. Med.* **171**, 703–710 (2019).
22. Bardgett, R. D. et al. Combatting global grassland degradation. *Nat. Rev. Earth Environ.* **2**, 720–735 (2021).
23. Aune, S., Bryn, A. & Hovstad, K. A. Loss of semi-natural grassland in a boreal landscape: impacts of agricultural intensification and abandonment. *J. Land Use Sci.* **13**, 375–390 (2018).
24. Dass, P., Houlton, B. Z., Wang, Y. & Warlind, D. Grasslands may be more reliable carbon sinks than forests in California. *Environ. Res. Lett.* **13**, 74027 (2018).
25. Kirschbaum, M. U. F. et al. Implications of albedo changes following afforestation on the benefits of forests as carbon sinks. *Biogeosciences* **8**, 3687–3696 (2011).
26. Wu, G. L. et al. Trade-off between vegetation type, soil erosion control and surface water in global semi-arid regions: a meta-analysis. *J. Appl. Ecol.* **57**, 875–885 (2020).
27. Steidl, R. J., Litt, A. R. & Matter, W. J. Effects of plant invasions on wildlife in desert grasslands. *Wildl. Soc. Bull.* **37**, 527–536 (2013).
28. Kätterer, T., Andersson, L., Andrén, O. & Persson, J. Long-term impact of chronosequential land use change on soil carbon stocks on a Swedish farm. *Nutr. Cycl. Agroecosyst* **81**, 145–155 (2008).
29. Davidson, E. A. & Ackerman, I. L. Changes in soil carbon inventories following cultivation of previously untilled soils. *Biogeochemistry* **20**, 161–193 (1993).
30. Dowell, R. C., Gibbins, D., Rhoads, J. L. & Pallardy, S. G. Biomass production physiology and soil carbon dynamics in short-rotation-grown *Populus deltoides* and *P. deltoides* × *P. nigra* hybrids. *For. Ecol. Manage.* **257**, 134–142 (2009).
31. Paul, K. I., Polglase, P. J., Nyakuengama, J. G. & Khanna, P. K. Change in soil carbon following afforestation. *For. Ecol. Manage.* **168**, 241–257 (2002).
32. Lima, A. M. N. et al. Soil organic carbon dynamics following afforestation of degraded pastures with eucalyptus in southeastern Brazil. *For. Ecol. Manage.* **235**, 219–231 (2006).
33. Craven, D. et al. Plant diversity effects on grassland productivity are robust to both nutrient enrichment and drought. *Phil. Trans. R. Soc. B* **371**, 20150277 (2016).
34. Heffer, P., Gruère, A. & And Terry, R. *Assessment of Fertilizer Use by Crop at the Global Level* (IFA and IPNI, 2017).
35. Lassaletta, L., Billen, G., Grizzetti, B., Anglade, J. & Garnier, J. 50 year trends in nitrogen use efficiency of world cropping systems: the relationship between yield and nitrogen input to cropland. *Environ. Res. Lett.* **9**, 105011 (2014).
36. Dentener, F.J. *Global Maps of Atmospheric Nitrogen Deposition, 1860, 1993, and 2050* (DAAC, 2006).
37. Zhang, X. et al. Managing nitrogen for sustainable development. *Nature* **528**, 51–59 (2015).
38. Yang, Y. et al. Soil nitrous oxide emissions by atmospheric nitrogen deposition over global agricultural systems. *Environ. Sci. Technol.* **55**, 4420–4429 (2021).
39. Lesschen, J. P., Stoorvogel, J. J., Smaling, E. M. A., Heuvelink, G. B. M. & Veldkamp, A. A spatially explicit methodology to quantify soil nutrient balances and their uncertainties at the national level. *Nutr. Cycl. Agroecosyst.* **78**, 111–131 (2007).
40. Gu, B., Ju, X., Chang, J., Ge, Y. & Vitousek, P. M. Integrated reactive nitrogen budgets and future trends in China. *Proc. Natl Acad. Sci. USA* **112**, 8792–8797 (2015).
41. *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC, 2006); https://www.ipcc-nggip.iges.or.jp/public/2006gl
42. *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC, 2019); https://www.ipcc-nggip.iges.or.jp/public/2019rf
43. *PAS 2050: 2011. Specification for the Assessment of the Life Cycle Greenhouse Gas Emissions of Goods and Services* (BSI, 2011).
44. Ministry of Agriculture of the People's Republic China. *Calculation of Proper Carrying of Rangelands* (in Chinese). PR China—Agriculture Vocation Standard NY/T 635-2015 (China Standard Press, 2015).
45. Jones, L. et al. A review and application of the evidence for nitrogen impacts on ecosystem services. *Ecosyst. Serv.* **7**, 76–88 (2014).
46. Klimont, Z. & Winiwarter, W. in *Costs of Ammonia Abatement and the Climate Co-Benefits* (eds Reis, S. et al.) 233–261 (Springer, 2015).
47. Sutton, M. A. et al. Too much of a good thing. *Nature* **472**, 159–161 (2011).
48. Gu, B. et al. Abating ammonia is more cost-effective than nitrogen oxides for mitigating $PM_{2.5}$ air pollution. *Science* **374**, 758–762 (2021).
49. *State and Trends of Carbon Pricing 2021* (World Bank, 2021).

Acknowledgements

This study was supported by the National Natural Science Foundation of China (42261144001 and 42061124001), the National Key Research and Development Project of China (2022YFD1700700) and the Pioneer and Leading Goose R&D Programme of Zhejiang (2022C02008). This work is a contribution from Activity 1.4 to the 'Towards the International Nitrogen Management System' project (INMS, http://www.inms.international/) funded by the Global Environment Facility (GEF) through the United Nations Environment Programme (UNEP).

Author contributions

B.G. designed the study. L.C. performed the research. X.Z. analysed economic-related data. L.C. prepared the distribution maps. L.C. and B.G. wrote the paper, S.R., X.Z. and C.R. revised the paper and all other authors contributed to the discussion of the paper.

Competing interests

The authors declare no competing interests.

Additional information

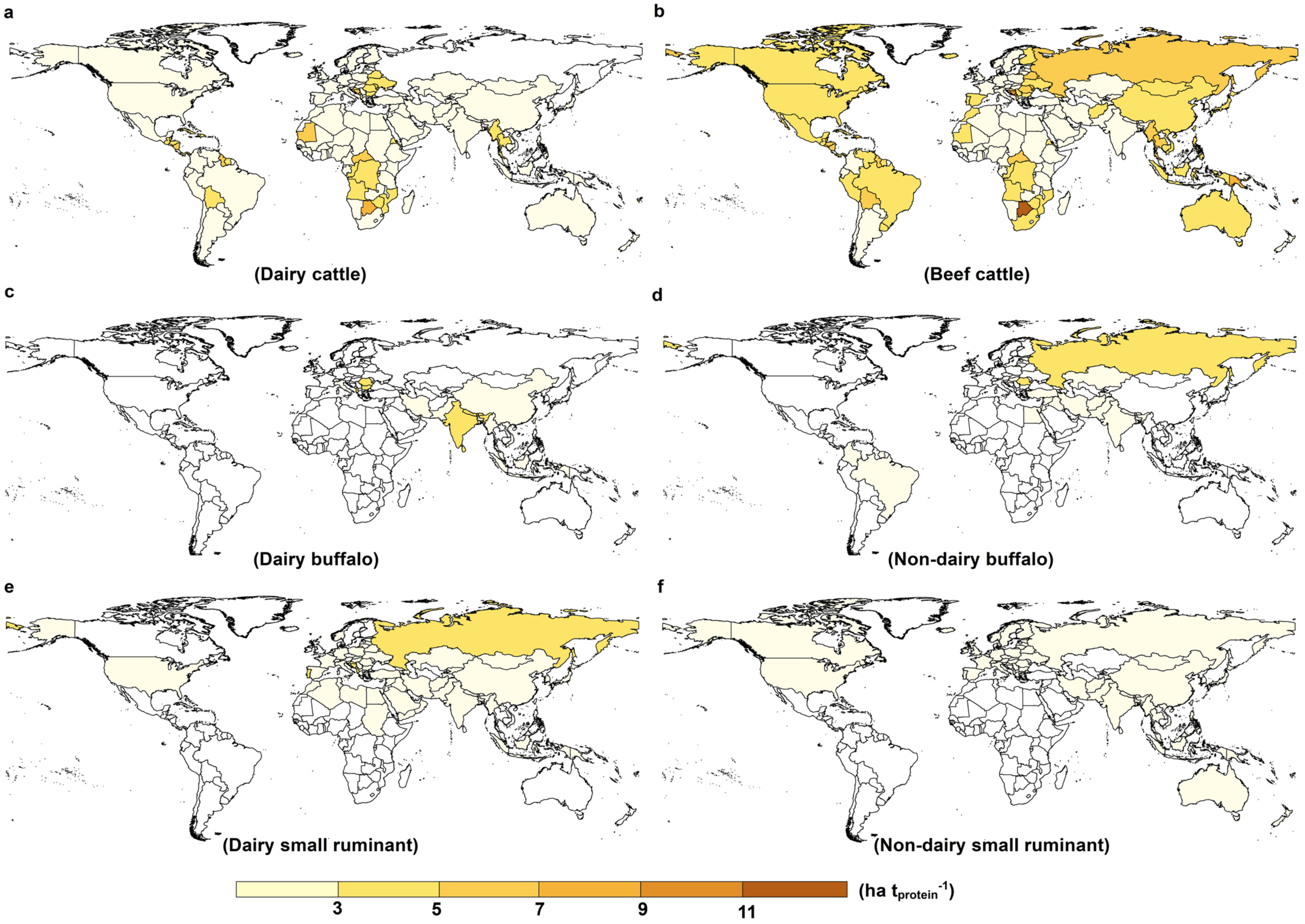
Extended data is available for this paper at https://doi.org/10.1038/s43016-022-00661-1.

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s43016-022-00661-1.

Correspondence and requests for materials should be addressed to Baojing Gu.

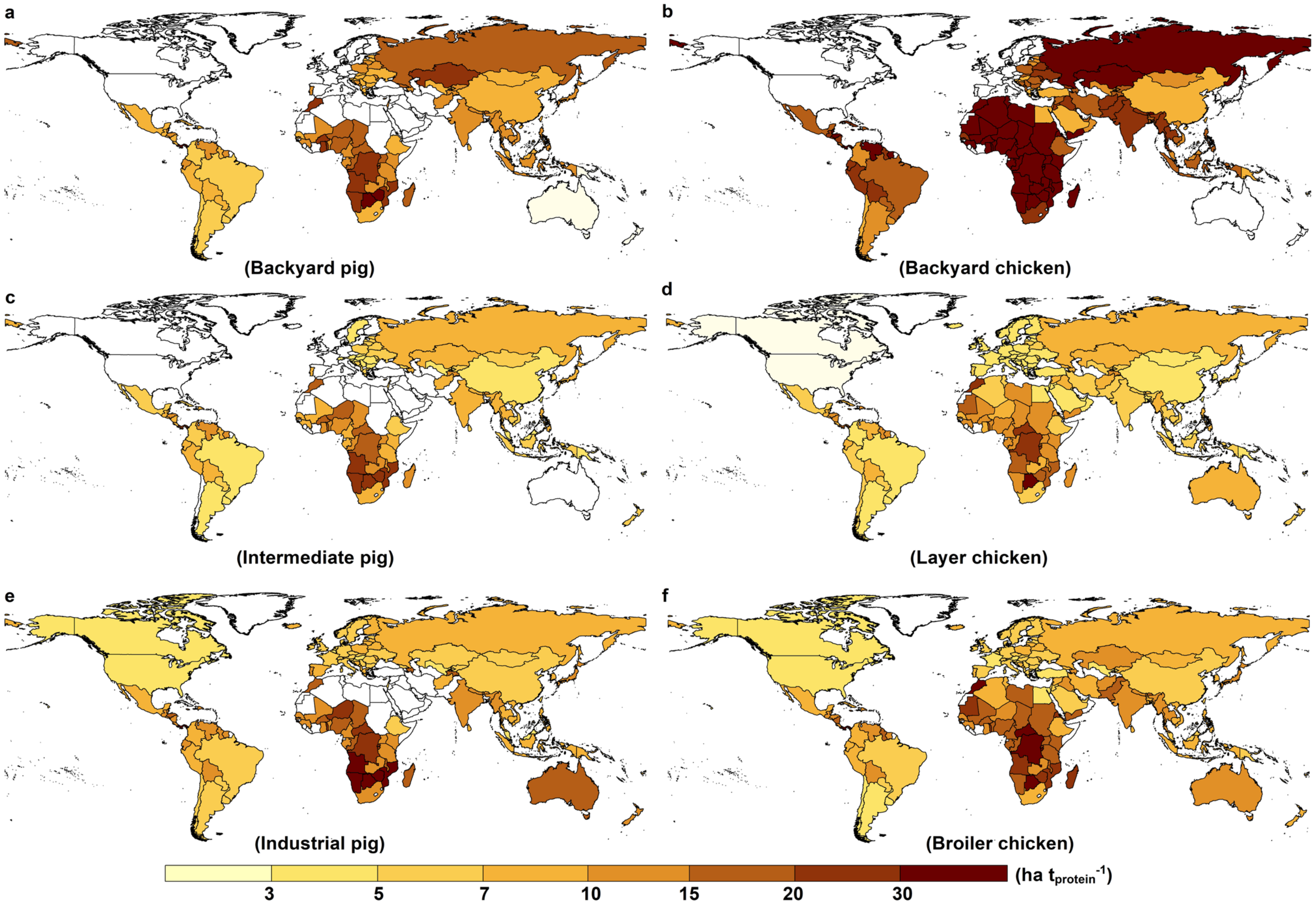
Peer review information *Nature Food* thanks Xuejun Liu and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.

Extended Data Fig. 1 | The N proportion of dry matter components in different livestock feed.

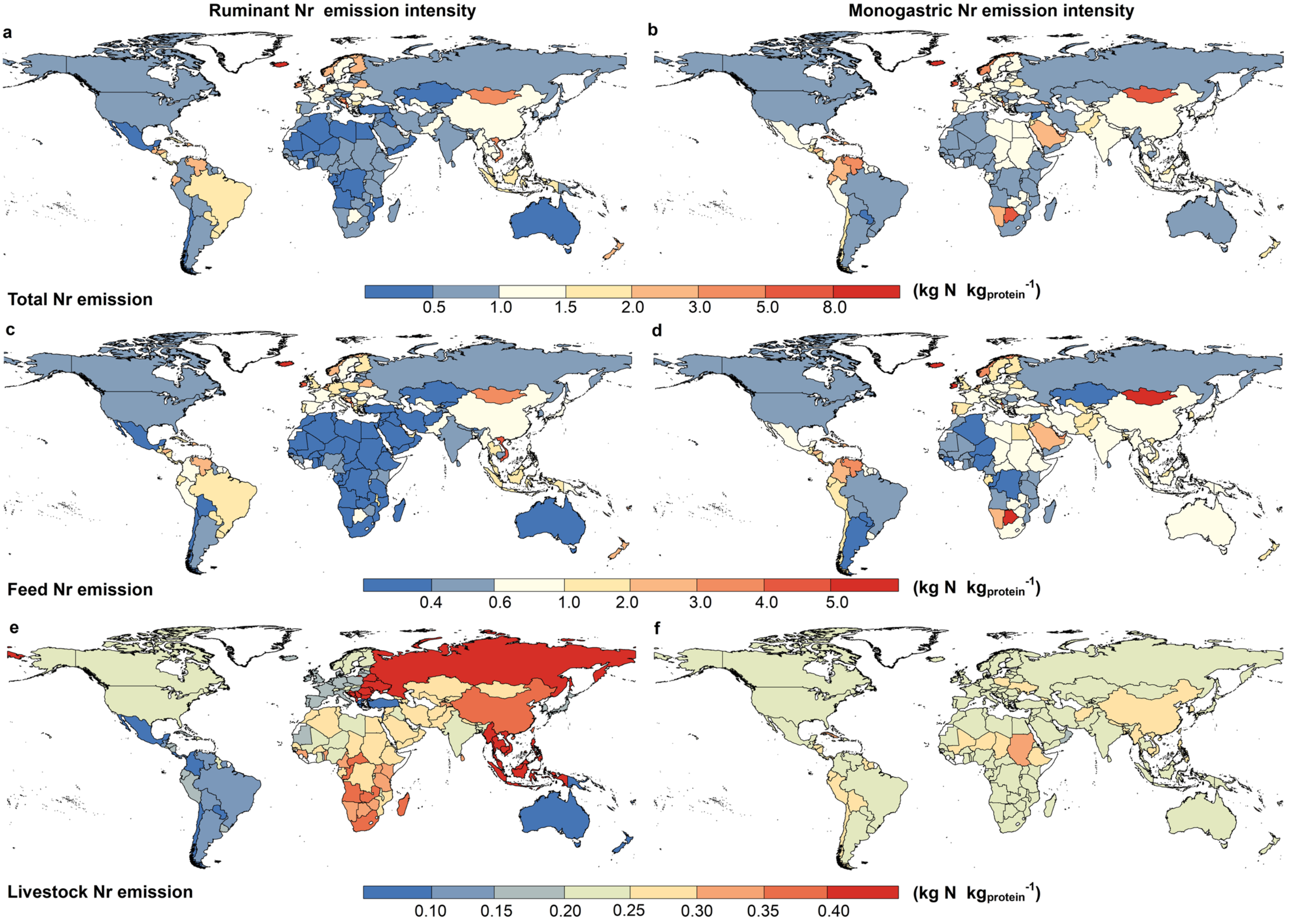


Extended Data Fig. 2 | Area of cropland required to produce the feed per unit of ruminant protein. The base map was applied without endorsement using data from the Database of Global Administrative Areas (GADM; https://gadm.org/).

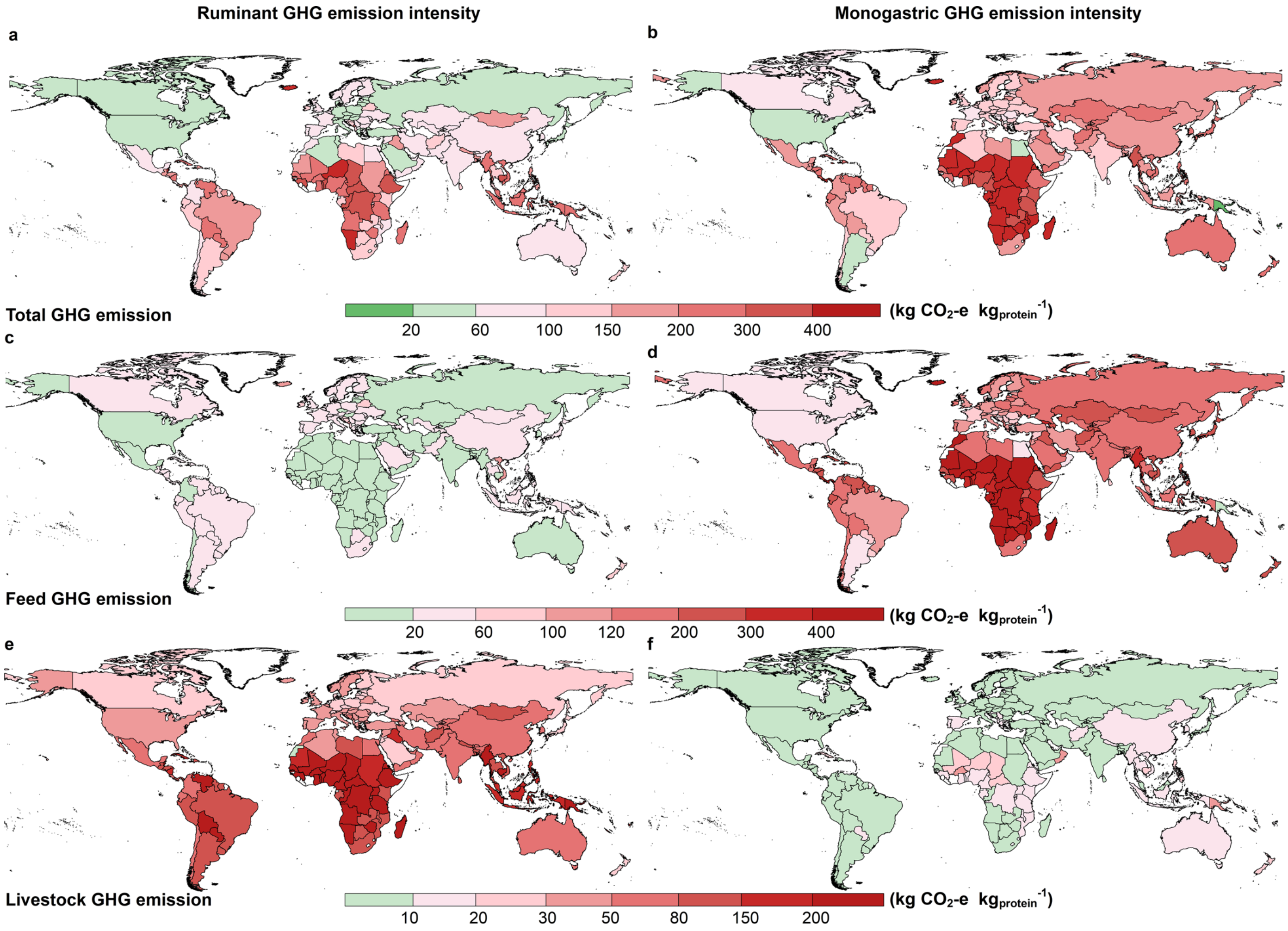
https://doi.org/10.1038/s43016-022-00661-1



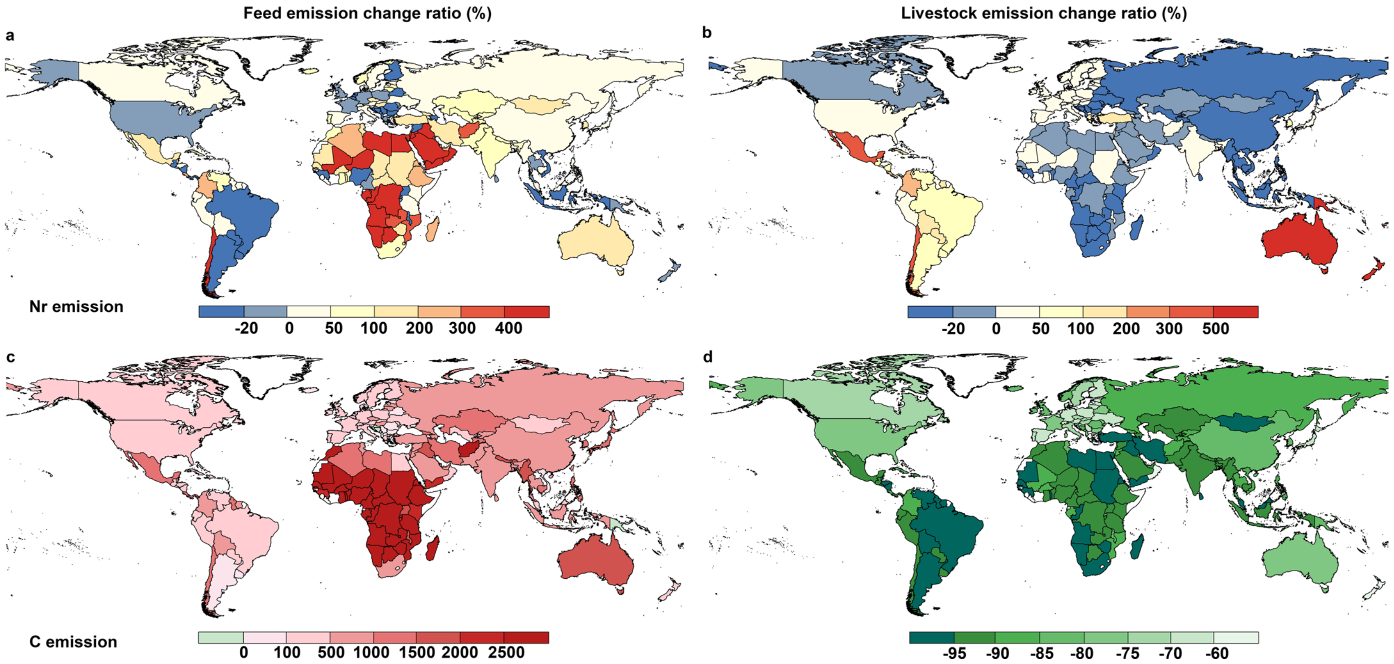
Extended Data Fig. 3 | Area of cropland required to produce the feed per unit of monogastric protein. The base map was applied without endorsement using data from the Database of Global Administrative Areas (GADM; https://gadm.org/).



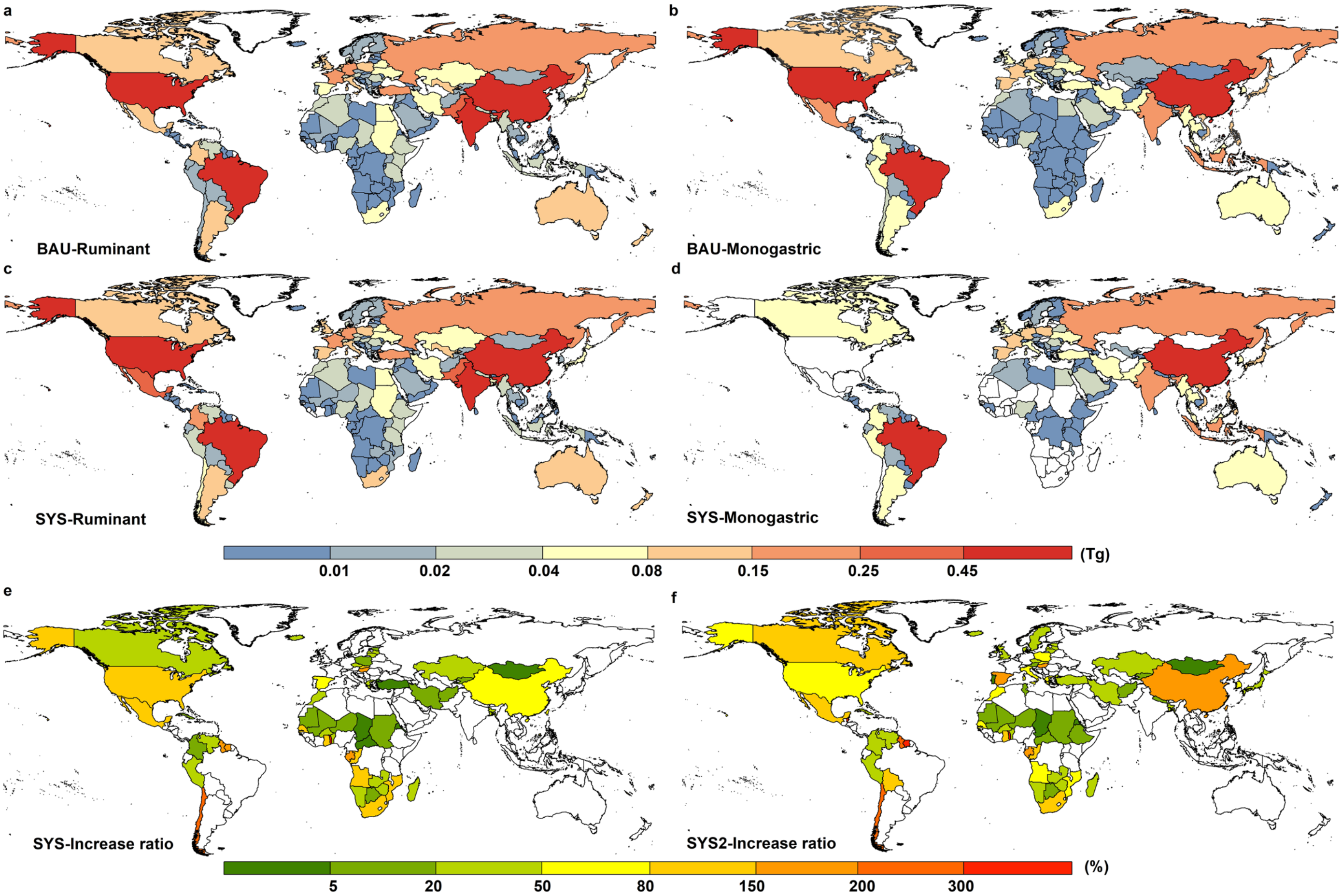
Extended Data Fig. 4 | Nr emission intensity of ruminants and monogastric livestock at each stage. The base map was applied without endorsement using data from the Database of Global Administrative Areas (GADM; https://gadm.org/).



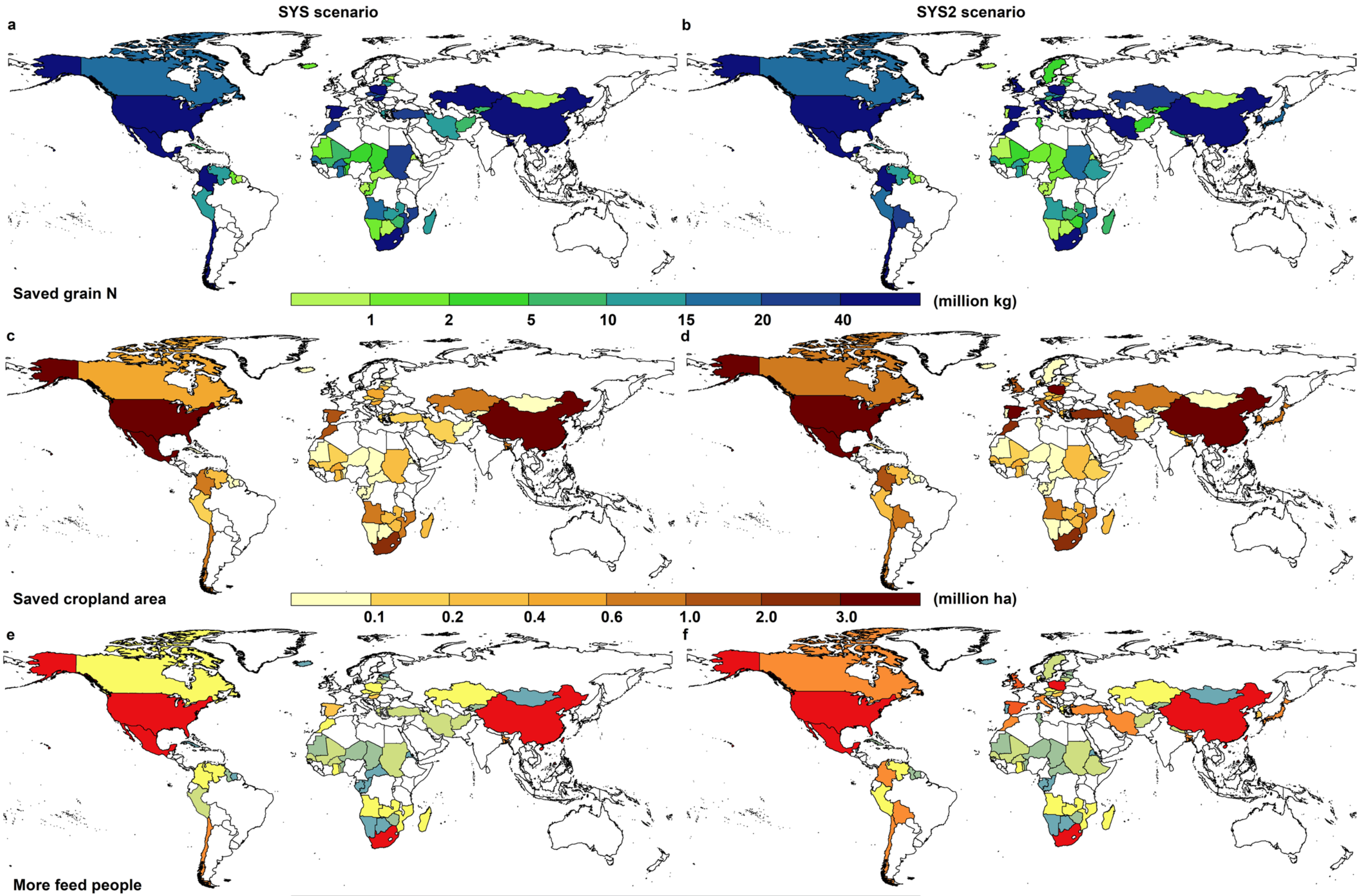
Extended Data Fig. 5 | GHG emission intensity of ruminants and monogastric livestock at each stage. The base map was applied without endorsement using data from the Database of Global Administrative Areas (GADM; https://gadm.org/).



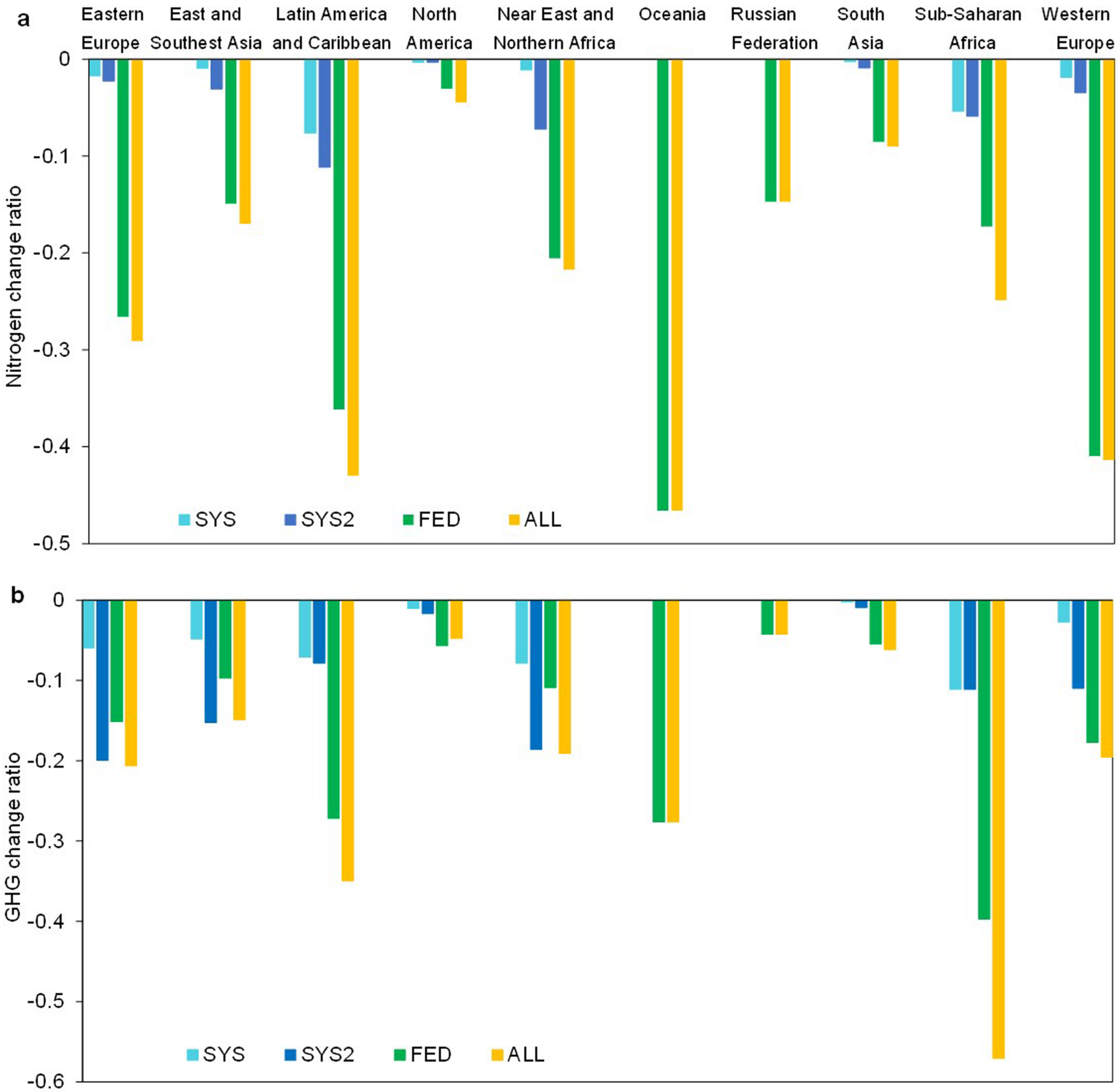
Extended Data Fig. 6 | Change ratio in Nr and GHG emissions at all stages after monogastric livestock replacing ruminants. a, the change ratio of Nr emissions at feed production stage. b, the change ratio of Nr emissions at livestock raising stage. c, the change ratio of GHG emissions at feed production stage. d, the change ratio of GHG emissions at livestock raising stage. The base map was applied without endorsement using data from the Database of Global Administrative Areas (GADM; https://gadm.org/).



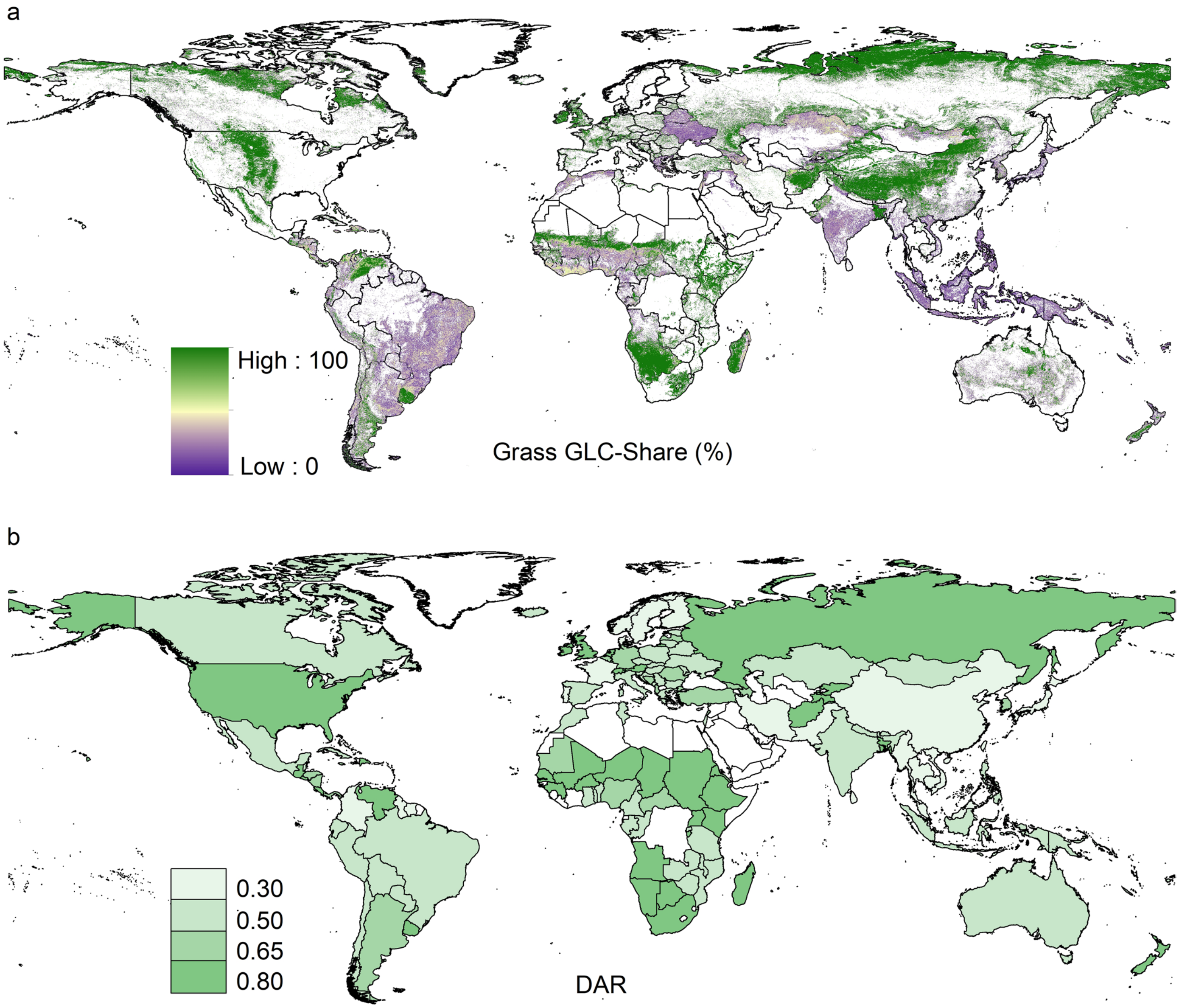
Extended Data Fig. 7 | N-Protein amounts of ruminants and monogastric livestock for BAU and SYS scenario and the increase ratio of ruminant production for the SYS and SYS2 scenarios. a and b are ruminant and monogastric N-protein in the BAU scenario, respectively. c and d are ruminant and monogastric N-protein in the SYS scenario, respectively. e and f are the increase ratio of ruminant protein in the SYS and SYS2 scenario, respectively. The base map was applied without endorsement using data from the Database of Global Administrative Areas (GADM; https://gadm.org/).



Extended Data Fig. 8 | The saved grain N, cropland area and more population from saved land under the SYS and SYS2 scenarios. The SYS and ALL scenarios have the same area of saved land because there were not potentials for saved cropland under the FED scenario. The base map was applied without endorsement using data from the Database of Global Administrative Areas (GADM; https://gadm.org/).



Extended Data Fig. 9 | Regional gas emission reduction ratio under each scenario. a, Regional nitrogen emission reduction rates under assumed different scenarios. b, Regional GHG emission reduction rates under assumed scenario. The division of regions is based on the GLEAM model.



Extended Data Fig. 10 | Global grassland cover share and grass degradation adjustment rate (DAR). a is derived from GLC-SHARE Beta-Release 1.0 database-2014(https://data.apps.fao.org/map/catalog/srv/eng/catalog.search#/metadata/ba4526fd-cdbf-4028-a1bd-5a559c4bff38). It shows the grassland share of each country and is used as the basis for setting the DAR (b). The base map was applied without endorsement using data from the Database of Global Administrative Areas (GADM; https://gadm.org/).

nature portfolio

Corresponding author(s): Baojing Gu

Last updated by author(s): Nov 3, 2022

Reporting Summary

Nature Portfolio wishes to improve the reproducibility of the work that we publish. This form provides structure for consistency and transparency in reporting. For further information on Nature Portfolio policies, see our Editorial Policies and the Editorial Policy Checklist.

Statistics

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
☒	☐	A full description of the statistical parameters including central tendency (e.g. means) or other basic estimates (e.g. regression coefficient) AND variation (e.g. standard deviation) or associated estimates of uncertainty (e.g. confidence intervals)
☒	☐	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	No software was used for data collection.
Data analysis	The spatial analysis is run in ArcGIS version 10.2.

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

Our analysis mainly used livestock, crop products and human protein demand from FAOSTAT (https://www.fao.org/faostat/en/#data/), livestock system data from GLEAM 2.0 (https://www.fao.org/gleam/en/) and GLW3 (https://dataverse.harvard.edu/dataverse/glw/) and , global land cover and land use data from GLC-SHARE 2013 (https://data.apps.fao.org/map/catalog/srv/eng/catalog.search#/metadata/ba4526fd-cdbf-4028-a1bd-5a559c4bff38). Fertilizer data was from FAOSTAT (https://www.fao.org/faostat/en/#data/RFB), IFA data (2017, https://www.fertilizer.org/images/Library_Downloads/2017_IFA_AgCom_17_134%20rev_FUBC%

20assessment%202014.pdf) and Lassaletta (2014). N deposition data was from Dentener (2006), Zhang et al (2015) and Yang et al (2021). The irrigation N rates (3.3 × 10−3 kg N m−3) were obtained from Lesschen (2007) and the irrigation water use data was from AQUASTAT (https://www.fao.org/aquastat/en/). Biological N fixation data was from Lassaletta (2014) and Zhang et al (2015).

Human research participants

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

Reporting on sex and gender	Sex and gender is no relevant to this study.
Population characteristics	Population characteristics is no relevant to this study.
Recruitment	Recruitment is no relevant to this study.
Ethics oversight	Ethics oversight is no relevant to this study.

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.

☐ Life sciences ☐ Behavioural & social sciences ☒ Ecological, evolutionary & environmental sciences

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	Emphasizing high Nr and GHG emissions from ruminants during the raising stage without a full life cycle analysis misled policy recommendations on optimal livestock development. Taking a full life cycle perspective, we found that ruminants have comparatively lower Nr and GHG emissions than monogastric livestock, when taking feed production into consideration. The land use change and synthetic N fertilizer use for grain feed production for monogastric livestock result in higher relative Nr and GHG emissions. The key reason for this difference is that ruminants are able to convert human-inedible cellulose into high-quality protein, thus saving energy and nutrient otherwise required for feed production.
Research sample	Data was collected from 166 countries in the world in 2019 with considering feed production and livestock raising stages.
Sampling strategy	Sampling strategy is no relevant to our study.
Data collection	The spatial data was from published land cover map and all systems of livestock numbers distribution. Other data was from published papers and database.
Timing and spatial scale	Timing scale: crop and livestock production data is for 2019. Spatial scale: country scale (166 countries).
Data exclusions	No data were excluded.
Reproducibility	The results can be reproduced.
Randomization	Randomization is no relevant to our study.
Blinding	Blinding is not relevant to this study, as no treatment is applied.

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