Assessing the net climate benefits of improved grazing intensity in global rangelands

by Powell, R.S., Davis, S.J., Encarnation, D.G., Piipponen, J., Chang, J., Currier, C.M., Erb, K., Eze, S., Hong, C., Ploton, P., Ren, S., Smith, P., Su, J., Tempio, G., Terrer, C., Wisser, D., Xu, F. and Pellegrini, A.F.A.

Powell, R.S., Davis, S.J., Encarnation, D.G., Piipponen, J., Chang, J., Currier, C.M., Erb, K., Eze, S., Hong, C., Ploton, P., Ren, S., Smith, P., Su, J., Tempio, G., Terrer, C., Wisser, D., Xu, F. and Pellegrini, A.F.A. (2026) 'Assessing the net climate benefits of improved grazing intensity in global rangelands', *Science,* 392(6803), pp. 1161–1166

Assessing the net-climate benefits of improved grazing intensity in global rangelands

Robert S. Powell[1,2*], Steven J. Davis[3,4], David G. Encarnation[1,2], Johannes Piipponen[5], Jinfeng Chang[6], Courtney M. Currier[1,2], Karl-Heinz Erb[7], Samuel Eze[8], Chaopeng Hong[9], Pierre Ploton[10,11,12], Shuai Ren[13], Pete Smith[14], Jishuai Su[15], Giuseppe Tempio[16], Cesar Terrer[17], Dominik Wisser[16], Fengwei Xu[17,18], and Adam F. A. Pellegrini[1,2,3*]

[1]Department of Plant Sciences, University of Cambridge, Cambridge, UK
[2]Conservation Research Institute, University of Cambridge, Cambridge, UK
[3] Department of Earth System Science, Stanford University, Stanford, CA, USA
[4] Department of Energy Science and Engineering, Stanford University, Stanford, CA, USA,
[5] Water & Development Research Group, Aalto University, Espoo, Finland,
[6] State Key Laboratory of Soil Pollution Control and Safety, College of Environmental and Resource Sciences, Zhejiang University, Hangzhou, 310058, China
[7]Institute of Social Ecology Vienna, University of Natural Resources and Life Sciences, Vienna, Austria,
[8]Deptartment of Agriculture and Environment, Harper Adams University, Newport, UK,
[9]Tsinghua Shenzhen International Graduate School, Shenzhen, China,
[10]AMAP Univ Montpellier, IRD, CNRS, INRAE, CIRAD, Montpellier, France,
[11]Plant Systematics and Ecology Laboratory, Higher Teachers' Training College, University of Yaoundé I, P.O. Box 047, Yaoundé, Cameroon,
[12]International Joint Laboratory DYCOFAC, IRD-UYI-IRGM, P.O Box 1857, Yaoundé, Cameroon,
[13]Department of Civil and Environmental Engineering, Massachusetts Institute of Technology, Cambridge, MA, USA,
[14]Institute of Biological and Environmental Sciences, University of Aberdeen, Cruickshank Building, Aberdeen AB24 3UU, United Kingdom,
[15]College of Life Sciences, Hebei University, Baoding, Hebei, China,
[16]Animal Production and Health Division (NSA), Food and Agriculture Organization of the United Nations (FAO), 00153 Rome, Italy,
[17] Institute of Ecological Conservation and Restoration, Chinese Academy of Forestry, Beijing 100091, China
[18] Grassland Research Center, National Forestry and Grassland Administration, Beijing 100091, China
***Corresponding Authors: Emails:** rsp46@cam.ac.uk, afapelle@stanford.edu

.

Abstract

Improved rangeland grazing could mitigate climate change via CO_2 sequestration in soils and vegetation. However, altering grazing practices to increase ecosystem carbon storage may also decrease livestock production and/or increase greenhouse gas emissions through the supply chain, such that the net-emissions impacts remain unclear. Here we assess the global net-mitigation potential of improving grazing intensity by quantifying potential CO_2 sequestration alongside system-level impacts of plant-productivity changes, livestock emissions, feed requirements, and production constraints. Improving grazing intensity in global rangelands could sequester 2.2 ± 0.43 $GtCO_2eqyr^{-1}$ in the near term, but maintaining livestock production via supplemental feeding would reduce net mitigation by 2%-31% (to 1.8 ± 0.45 $GtCO_2eqyr^{-1}$). Our results suggest that neglecting systems-level emissions impacts may substantially overestimate the global climate benefits of improved grazing.

Main text

Improving management of grazing lands could remove substantial quantities of CO_2 from the atmosphere (*1-6*) by increasing plant biomass production and stocks and in turn driving soil organic carbon (SOC) sequestration (*7, 8*). Although grazing does not always decrease SOC or plant productivity (*7, 9*), up to 50% of global rangelands are degraded relative to their natural potential, largely attributed to overgrazing (*10*). Grazing intensity can be improved, whereby grazing pressure is reduced or, sometimes, increased to low-to-moderate levels to enhance plant productivity (*14–16*) and increase carbon sequestration and storage (*7*, 8, *11–13*). However, the magnitude of any SOC increase depends on both how low initial levels of plant biomass and SOC stocks are relative to their maxima and the effectiveness of altered grazing practices to close such gaps (*7*, *17–19*).

A series of recent studies have sought to estimate the global magnitude, spatial distribution and variability of this potential natural climate solution (NCS) (*7*, 8 *20–21*). These works have concluded there is substantial global potential for increased carbon storage through improved grazing practices, leading to countries and project developers increasingly prioritizing interventions in livestock production systems (e.g. (*22*, *23*)). For example, roughly a third of parties to the Paris Climate Agreement named grazing lands and livestock as priorities for meeting their emission mitigation goals (*24*). Yet estimates of the global carbon sequestration potential of improved grazing differ markedly between studies (e.g., 0.1-2.6 $GtCO_2\ yr^{-1}$) (*1–4*) and comparisons between various empirical approaches and process-based models remain rare. Moreover, these studies neglect two critical complexities. First, recent estimates of global potential for this NCS are narrowly focused on increases in plant biomass and SOC (*7*, *17*) and neglect the effect of concomitant changes in livestock production and/or associated greenhouse gas (GHG) emissions to the atmosphere (*7*, *20*). Yet livestock and agricultural supply chains are major sources of emissions (*25–27*), and livestock production-related trade-offs could affect food security and increase emissions via spillover effects (*20*, *25*). Secondly, recent global grazing studies (*7*, *28*) assume plant biomass stocks increase proportionally with decreases in grazer forage consumption and vice versa. But ecological theory predicts that aboveground net-primary productivity (ANPP) changes dynamically with grazing intensity (*13*, *20*), such that moderate grazing can, via improved light availability (*29*) and nutrient cycling (*30*), stimulate plant growth, forage production and SOC sequestration. This could greatly alter estimates of SOC sequestration and livestock production trade-offs, thereby changing the net-climate benefit of improved grazing and pointing to an urgent need for fuller assessments of rangeland-based NCS.

Here, we build on previous work by systematically analyzing the potential net climate benefits (sequestration minus emissions) of improved grazing intensity as a result of simultaneous changes in: (i) ecological processes that regulate how plant biomass productivities and livestock emissions respond to changes in grazing intensity; (ii) emissions from feed required to replace forgone forage consumption; (iii) spatial and geopolitical constraints on the scales of livestock and food production. We focus on altering grazing intensity, the pathway underlying most estimates of global grazing climate mitigation potential (*7*, 17, 20), and not other potentially beneficial grazing practices, such as rotational grazing, for which global experimental data are limited (*31*).

We first compiled a geographically-diverse dataset of paired observations of grazing intensity, plant biomass and SOC: 4,257 measurements of plant biomass and SOC from 210 studies across 333 sites manipulated for 1-91 years (average 11 years; Figure S1). We then applied a random forest approach to this dataset to estimate potential carbon sequestration of improving grazing intensity with and without including dynamic effects on plant productivity over >22 million km^2 of global rangelands (*32*). We accounted for spatial autocorrelation (i.e., nearby observations behaving similarly irrespective of underlying predictors) (*33*, *34*) and quantified starting grazing intensities using IPCC Tier 2 livestock feed demand modelling (*35*), livestock distributions from the Gridded Livestock of the World dataset (*36*) and satellite-derived ANPP measurements (Methods (*37*) , Figures S2-S3). These empirically estimated biophysical responses were compared with simulations from four different process-based and empirical approaches, before being combined with estimated N_2O and CH_4 emissions from livestock excrement deposition on soils, CH_4 emissions from enteric fermentation, and emissions related to the production of supplementary feed and displacement of livestock production (Methods (*37*)). Throughout, we assessed the impact of maintaining livestock production, a critical requirement for NCS (*38*), at either local, country, or global scales. Thus, our assessment's system boundary is greatly expanded compared to previous studies of rangeland interventions.

Biophysical potential for carbon sequestration

Within studies, large increases in plant biomass were observed where grazing pressure decreased from high to low levels, whereas shifts from high to moderate or moderate to low grazing intensities led to variable plant biomass responses (Figure 1A). Across studies, greater increases in plant biomass led to larger SOC gains (Figure 1B). Given the lack of standardisation across field-study-defined grazing intensity categories, we incorporated the response of plant biomass to changes in grazing intensity as a predictor of SOC change into a random forest model.

SOC gains depended on soil characteristics, climate, and plant biomass change (Figure 1C). Control-plot SOC concentration and precipitation seasonality were the two most important predictors, with greater SOC increases in areas with greater climatic variability and lower SOC concentrations (a potential statistical artifact (*39*), Methods *(37*)). Plant biomass change was the third most important predictor, with SOC gains increasing with the response ratio of plant biomass and plateauing at high plant biomass responses (Figure S4). Thus, linking responses of SOC with plant biomass is an important advance on previous empirical studies (e.g. (*40*, *41*)), which facilitates our upscaling below. Furthermore, we found spatial interdependence between clustered observations was important, with model performance dropping from 43% to 24% when accounting for spatial autocorrelation (Figure 1D, Methods (*37*)). Accounting for spatial interdependence is lacking from many global studies (*8*, *42–44*), potentially leading to overestimates of model performance.

We next compared our findings with two process-based models and two alternative empirical approaches: (i) a global vegetation model adapted for managed grasslands, ORCHIDEE-GM v.3.2 (*45*) forced with grazing intensity changes simulated in our empirical approach and (ii) GSOCseq v.1.1 (*46*) forced by changes in C inputs, (iii) a recent statistical model (*7*) and (iv) the standard IPCC Tier 1 method (Methods (*37*)). Our model's prediction of SOC sequestration potential landed at the upper end of estimates (Figures 1E, S5). Both the empirical and process-based SOC models do not assess the implications of production constraints or supply chains (nor does any ecosystem model, to our knowledge); subsequently, we integrated the other modelled predictions into our systems analysis to estimate net-emission impacts.

Net-emissions reduction potential

Total carbon sequestration in plants and soils amounted to 2,203 ± 432 $MtCO_2eq\ yr^{-1}$ (1,747 ± 392 from soils and 456 ± 112 from vegetation; Figure 2A). However, this potential was partly offset by emissions from increased feed supplementation (+411 ± 418 $MtCO_2eq\ yr^{-1}$), while direct CH_4 and N_2O emissions varied widely (+255 ± 325 $MtCO_2eq\ yr^{-1}$) and livestock production increases in some areas displaced emissions required to produce livestock elsewhere (-293 ± 256 $MtCO_2eq\ yr^{-1}$) (Figure 2B). Net mitigation therefore totalled 1,829 ± 454 $MtCO_2$ eq yr^{-1}, which is 16 ± 14% (373 ± 343 $MtCO_2eq\ yr^{-1}$) lower compared to biophysical potential alone (Figure 2C).

Changes in net-mitigation potential were spatially heterogenous. For example, large decreases in mitigation potential were observed in Brazil (-48 ± 44%), Tanzania (-146 ± 138%) and Mongolia (-18 ± 11%), while there were relatively small or uncertain changes in the U.S. (+3 ± 12%) and Australia (-21 ± 38%) (Figure 2C). This assumed that ecosystem C stock changes were annualized over an 11-year intervention period (mean duration of grazing-manipulation experiments in our dataset) under an empirically supported "core" scenario: where plant productivity responds dynamically to grazing (ref. (*47*), Figure 1A) and where livestock production is maintained at the country level considering increasing global trade barriers (*48*, *49*) and national food security considerations.

While modelled predictions of SOC change varied (Figure 1E), integrating feed and livestock emission changes and production constraints all led to mean reductions in net-emissions mitigation potential: with 40 ± 41%, 32 ± 29%, 24 ± 20% and 12 ± 16% reductions for the ORCHIDEE-GM, GSOCseq, Ren et al. (*7*) and IPCC approaches, respectively (Figure S6). Thus, the magnitude of reduction in net-mitigation potential was robust across SOC modelling approaches. We next assessed the drivers underlying these declines in net mitigation.

Role of plant production in net-emissions reduction potential

To assess sensitivities to grazing-plant productivity relationships, we considered two scenarios. The first approach (assumed in our "core" scenario) accounts for dynamic grazing-plant productivity responses (Plant-Dynamic), where ANPP is maximized at low-to-moderate grazing intensities ("optimal grazing hypothesis" (*14-16*)) (Figures S7-8). The second assumes no effects of altered grazing intensity on ANPP, meaning plant biomass changes linearly with livestock forage consumption (*7*, *28*) (Plant-Proportional).

With improved grazing intensity, we observed neutral-to-positive livestock forage consumption changes (296 ± 649 Mt forage yr^{-1}) assuming Plant-Dynamic responses, but large decreases in forage consumption (-532 ± 169 Mt forage yr^{-1}) when assuming Plant-Proportional responses (Figure 3A). This was primarily because ANPP increased non-linearly in areas where grazing intensity declined, resulting in greater biomass production under the Plant-Dynamic scenario. Consequently, ecosystem carbon gains were 60% higher under the Plant-Dynamic scenario (Fig. 3B), contributing to its greater net-emission mitigation potential compared to the Plant-Proportional scenario (1,830 ± 454 vs. 373 ± 223 $MtCO_2eq\ yr^{-1}$; Fig. 3C). Thus, allowing ANPP to change dynamically with grazing leads to greater estimated increases in storage and net-emissions mitigation potential.

Role of direct livestock emissions in net-emission mitigation potential

Improving grazing intensity changed the quantity and composition of feed consumed and digested by livestock, thereby shifting direct livestock emissions via enteric fermentation (CH_4) and manure deposition (CH_4, N_2O). Globally, livestock emissions slightly increased under our "core" scenario (+255 ± 325 $MtCO_2eq\ yr^{-1}$) but exhibited high variability across space (Figures 3D, S8). In some areas, improved grazing increased plant ANPP nonlinearly, and thus increased forage consumption and livestock production, thereby raising livestock emissions (Figure 3C). When decreases in forage consumption were required (all areas assuming Plant-Proportional responses) and livestock were supplemented with more digestible feed, enteric methane and manure emissions decreased by 188 ± 62 $MtCO_2eq\ yr^{-1}$ (Figure 3D). Thus, the greatest declines in direct livestock emissions were in areas where livestock production and forage consumption decreased or feed supplementation replaced low digestibility forage (e.g. mid-western U.S, southern Brazil), while the greatest increases occurred where forage consumption rose due to gains in ANPP (e.g. southern Africa, northern Australia) (Figure S8-S10).

Feed emissions regulated by plant productivity and embodied in global trade

Emissions from producing supplemental feed required to maintain livestock production where forage consumption decreased were large (411 ± 418 $MtCO_2eq\ yr^{-1}$), and comprised the greatest single contributor to reducing net-emission mitigation potential. However, differences in emissions associated with feed production across space meant that emissions from feed supplementation in one area depended on where that feed was produced, requiring an understanding of trade (Figure S11A). Accounting for trade between high and low emissions intensity countries shaped feed emissions, with trade leading to 14–40% reductions in Asia, Oceania, and Africa, and 10% increases in Europe (Figures 3E, S11A-B) compared to if all feed was domestically sourced. If countries relied solely on domestic production, global feed emissions would be 50 $MtCO_2eq\ yr^{-1}$ (12%) greater than if countries traded feed. Thus, feed emissions were an important driver of total mitigation potential, but were mediated by global trade.

Conservation of food production changes net-emission mitigation potential

We evaluated how constraints on shifting livestock production limited net-mitigation potential by assessing scenarios where production shifts freely with changes in livestock forage consumption "globally," production is conserved "nationally" at the country level, or "locally" at the pixel level while incorporating the aforementioned emissions pathways. Conserving production nationally yielded a net-mitigation potential of -1,829 ± 454 MtCO2eq yr^{-1}, 21% greater than at the 'local' level (-1,514 ± 396 $MtCO_2eq\ yr^{-1}$) but 10% less than the scenario allowing for freely shifting global production (-2,017 ± 615

$MtCO_2eq\ yr^{-1}$) (Figure 3F, Figure S12). Discrepancies were largely due to: (i) whether feed supplementation was required where forage consumption decreased, and (ii) how increased livestock production in some areas displaced production emissions elsewhere. Although the greatest net-emission mitigation potential resulted from freely shifting global production, smaller scales of production conservation are thought to be more realistic (e.g., within countries (*25*)).

Mitigation potential and grazing carbon projects

To assess the relevance of our findings for grazing NCS implementation, we compared our maps of net-emissions mitigation with the locations of 56 grazing-based carbon credit projects from the Verified Carbon Standard Registry (*50*) (Methods *(37)),* comprising 955 $MtCO_2eq$ of listed credit generation potential. Of these, 60% saw a reduction in net-emissions mitigation potential (mean decrease of 36%) compared to biophysical potential alone (Figure 4). Yet this discrepancy varied spatially, ranging from little change for projects in the U.S. and China (where feed emissions were low) to a predicted increase in net-emissions (+26%) for projects in Tanzania (where production trade-offs and feed emissions intensities are high) (Figures 4, S13). While project design varied widely, often including multiple interventions for grazing (intensity/stocking density n=32, rotational grazing n=52) and grassland management (fire management, seeding, pest control etc.), two points are cause for concern: most projects are in regions with predicted reductions in net-mitigation potential, and future projects are skewed towards regions where emissions mitigation potential is lower than biophysical potential alone (Figure 4).

Discussion

Considering emissions directly from livestock (CH_4 & N_2O) and feed supplementation (which varied widely but reduced mitigation potential by, on average, 13% and 20%, respectively, (Figures 2B, S8-S9)), is key to not overestimating the net-mitigation potential of improved grazing intensity. We go beyond prior empirical estimates of biophysical NCS potential (e.g. (*7*, 9, 17, *41*)) by explicitly coupling estimates of CO_2 removal with livestock productivity and supply-chain emissions. Regions experienced increased mitigation potential where feed emissions intensities were low (e.g. midwestern U.S.) or improved local production displaced emissions elsewhere (e.g. northern Australia) (Figure 2B). However, there was a reduction in global mitigation potential, which was observed across multiple approaches for modelling SOC change (Figure S6). Thus, quantifying the biophysical potential of NCS alone is insufficient to inform the true net-emissions outcomes of climate mitigation strategies.

Allowing ANPP to respond dynamically to grazing intensity is a key compensatory mechanism globally. While our analysis accounts for uncertainties associated with different fire histories and plant-grazer coevolutionary contexts (*47*), further work is needed to better parameterize localized plant productivity responses to grazing changes (Figure 1A), the mechanisms leading to ANPP compensation (increased light and/or nutrient availability) ((*29*, *30*) and their interactions with environmental conditions (Figure 1C). Prior mechanistic modelling captured dynamic ANPP and livestock emissions (*20*) but omitted feed-related emissions and spatial production constraints. However, these considerations were key, shifting mitigation potential across extremes by 781 and 503 Mt CO_2eq yr^{-1}, respectively (Fig. 3F; Fig. S12).

While it is known that feed and supply chains are important sources of emissions from livestock production (e.g. (*26*)), how they interact with potential mitigation from grazing NCS has never been shown. For example, a systems-level spatial optimization of cattle production (*25*) did not account for the emissions impacts of grazing management, which we show could mitigate 2,203 Mt CO_2eq yr^{-1}. Furthermore, we found that trade was important: many countries relied on feed imports to sustain livestock production, but increases in feed emissions depended on where feed was sourced and widely varying intensities across countries (Figure 3E, Figure S11). Thus, our findings add to the literature on the complex interplay between climate mitigation policies, trade and leakage (i.e., displacement of emissions-generating activities (*51*)), by being the first to quantify these impacts for any improved grazing intervention.

Several limitations apply to our analysis. Performance of our empirical SOC model was lower than previous studies (e.g. (*7*)) and process-based SOC simulations (*46*) predicted more conservative estimates of global SOC potential (potentially driven by lower plant C inputs, see Methods *(37*), Figure 1E). Our empirical modelling illustrates the limitations arising from spatial autocorrelation, which can be important (*52*), but have not been incorporated in prior estimates of grazing or other NCS (e.g. (*7*, *43*, *53*)). Furthermore, SOC gains are expected to saturate over longer timescales based on biogeochemical theory and observations (*54*, *55*), leading to lower sequestration rates beyond our 11-year simulation. However, we and others (*7*) did not observe a clear saturating relationship between SOC gains and duration of study (Figure S14). The potential saturation of biophysical storage contrasts with the immediate and persistent changes in emissions from feed and livestock. Yet, our feed emission intensities are conservative, accounting only for land use and land cover change while excluding other lifecycle emissions (e.g. transport, Methods (*37*)) (*27*). Although improved grazing yielded near-term benefits, longer term mitigation remains uncertain as climate change impacts soil carbon storage and plant productivity (*56*), as well as feed (*57*) and livestock (*58*) production efficiencies. Furthermore, future patterns of trade are uncertain (e.g. tariffs (*49*)), meaning regional feed intensities could vary.

While socio-cultural (*59*), financial (*60*) and informational barriers (*61*) can impede implementation of improved grazing practices, feed costs in areas where supplementation was required averaged \$33 per-tonne CO_2eq ecosystem carbon sequestered (using FAOSTAT prices (*62*)), which is higher than current agricultural carbon credit prices (*63*), but well below thresholds for NCS cost-effectiveness (\$100) (*6*, *64*). Furthermore, this NCS could only mitigate approximately 4% of global anthropogenic emissions (*65*), underscoring its limited, but potentially meaningful, contribution to climate mitigation. Finally, we recognize the mitigation potential of improved grazing could be increased by reducing demand for livestock products (i.e., lower meat consumption (*66*))

We demonstrate the importance of systems-level assessments of NCS by accounting for emissions and food production ramifications. Although targeted interventions could reduce near-term net emissions in many regions and efforts to reduce the impacts of food production should be explored (*25*), win-win scenarios for improved grazing intensity at the global scale appear more elusive and uncertain than previously thought.

References

1. S. Roe, C. Streck, M. Obersteiner, S. Frank, B. Griscom, L. Drouet, O. Fricko, M. Gusti, N. Harris, T. Hasegawa, Z. Hausfather, P. Havlík, J. House, G. J. Nabuurs, A. Popp, M. J. S. Sánchez, J. Sanderman, P. Smith, E. Stehfest, D. Lawrence, Contribution of the land sector to a 1.5 °C world. *Nat. Clim. Chang.* **9**, 817–828 (2019).
2. IPCC, "Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change" (IPCC, Geneva, Switzerland, 2023); https://doi.org/10.59327/IPCC/AR6-9789291691647.
3. K. Paustian, J. Lehmann, S. Ogle, D. Reay, G. P. Robertson, P. Smith, Climate-smart soils. *Nature* **532**, 49–57 (2016).
4. P. Smith, D. Martino, Z. Cai, D. Gwary, H. Janzen, P. Kumar, B. McCarl, S. Ogle, F. O'Mara, C. Rice, B. Scholes, O. Sirotenko, M. Howden, T. McAllister, G. Pan, V. Romanenkov, U. Schneider, S. Towprayoon, M. Wattenbach, J. Smith, Greenhouse gas mitigation in agriculture. Philosophical Transactions of the *Roy. Soc. B: Bio. Sci.* 363, 789–813 (2008).
5. B. W. Griscom, J. Adams, P. W. Ellis, R. A. Houghton, G. Lomax, D. A. Miteva, W. H. Schlesinger, D. Shoch, J. V. Siikamäki, P. Smith, P. Woodbury, C. Zganjar, A. Blackman, J. Campari, R. T. Conant, C. Delgado, P. Elias, T. Gopalakrishna, M. R. Hamsik, M. Herrero, J. Kiesecker, E. Landis, L. Laestadius, S. M. Leavitt, S. Minnemeyer, S. Polasky, P. Potapov, F. E. Putz, J. Sanderman, M. Silvius, E. Wollenberg, J. Fargione, Natural climate solutions. *Proc. Natl. Acad. Sci. U. S. A.* **114**, 11645–11650 (2017).
6. D. A. Bossio, S. C. Cook-Patton, P. W. Ellis, J. Fargione, J. Sanderman, P. Smith, S. Wood, R. J. Zomer, M. von Unger, I. M. Emmer, B. W. Griscom, The role of soil carbon in natural climate solutions. *Nat. Sustain.* **3**, 391–398 (2020).
7. S. Ren, C. Terrer, J. Li, Y. Cao, S. Yang, D. Liu, Historical impacts of grazing on carbon stocks and climate mitigation opportunities. *Nat. Clim. Chang.* **14**, 380–386 (2024).
8. Y. Bai, M. F. Cotrufo, Grassland soil carbon sequestration: Current understanding, challenges, and solutions. *Science.* **377**, 603–608 (2022).
9. M. Abdalla, A. Hastings, D. R. Chadwick, D. L. Jones, C. D. Evans, M. B. Jones, R. M. Rees, P. Smith, Critical review of the impacts of grazing intensity on soil organic carbon storage and other soil quality indicators in extensively managed grasslands. *Agric. Ecosyst. Environ.* **253**, 62–81 (2018).
10. UNCCD, "Global Land Outlook: Thematic Report on Rangelands and Pastoralists" (Bonn, 2024); www.unccd.int.
11. J. A. Kristensen, J. C. Svenning, K. Georgiou, Y. Malhi, Can large herbivores enhance ecosystem carbon persistence? *Trends Ecol. Evol.* **37**, 117–128 (2022).
12. Z. Y. Jiang, Z. M. Hu, D. Y. F. Lai, D. R. Han, M. Wang, M. Liu, M. Zhang, M. Y. Guo, Light grazing facilitates carbon accumulation in subsoil in Chinese grasslands: A meta-analysis. *Glob. Chang. Biol.* **26**, 7186–7197 (2020).
13. E. W. Bork, D. B. Hewins, E. G. Lamb, C. N. Carlyle, M. P. Lyseng, S. X. Chang, M. J. Alexander, W. D. Willms, M. Iravani, Light to moderate long-term grazing enhances ecosystem carbon across a broad climatic gradient in northern temperate grasslands. *Sci. Total Environ.* **894**, 164978 (2023).
14. L. Ellison, Influence of grazing on plant succession of rangelands. *Bot. Rev.* **26**, 1–78 (1960).
15. D. W. Hilbert, D. M. Swift, J. K. Detling, M. I. Dyer, Relative growth rates and the grazing optimization hypothesis. *Oecologia* **51**, 14–18 (1981).
16. S. J. McNaughton, Grazing as an optimization process : Grass-ungulate relationships in the Serengeti. *Am.Nat.* **113**, 691–703 (1979).
17. R. T. Conant, K. Paustian, Potential soil carbon sequestration in overgrazed grassland ecosystems. *Global Biogeochem. Cycles* **16**, 90-1-90–9 (2002).

18. D. J. Augustine, J. D. Derner, M. E. Fernández-Giménez, L. M. Porensky, H. Wilmer, D. D. Briske, Adaptive, Multipaddock rotational grazing management: A ranch-scale assessment of effects on vegetation and livestock performance in semiarid rangeland. *Rangel. Ecol. Manag.* **73**, 796–810 (2020).
19. T. Garnett, C. Godde, A. Muller, E. Röös, P. Smith, I. De Boer, E. Zu Ermgassen, M. Herrero, C. Van Middelaar, C. Schader, H. Van Zanten, R. Conant, N. Ericsson, A. Falcucci, B. Henderson, D. Johansson, A. Mottet, C. Opio, M. Persson, E. Stehfest, H. Bartlett, C. Godfray, Grazed and confused? Ruminating on cattle, grazing systems, methane, nitrous oxide, the soil carbon sequestration question-and what it all means for greenhouse gas emissions. *Food Climate Research Network*, 1–127 (2017).
20. B. B. Henderson, P. J. Gerber, T. E. Hilinski, A. Falcucci, D. S. Ojima, M. Salvatore, R. T. Conant, Greenhouse gas mitigation potential of the world's grazing lands: Modeling soil carbon and nitrogen fluxes of mitigation practices. *Agric. Ecosyst. Environ.* **207**, 91–100 (2015).
21. R. Lal, Soil carbon sequestration impacts on global climate change and food security. *Science.* **304**, 1623–1627 (2004).
22. Climate Action Reserve, "U.S. Grassland Protocol Version 2.1" (2020).
23. Soils for the future, VM0032 methodology for the adoption of sustainable grasslands through adjustment of fire and grazing. *Verra*, 1–84 (2015).
24. UNFCCC, Nationally determined contributions under the Paris Agreement: Synthesis report by the secretariat. *English*, 1–42 (2021).
25. A. C. Castonguay, S. Polasky, M. H. Holden, M. Herrero, D. Mason-D'Croz, C. Godde, J. Chang, J. Gerber, G. B. Witt, E. T. Game, B. A. Bryan, B. Wintle, K. Lee, P. Bal, E. McDonald-Madden, Navigating sustainability trade-offs in global beef production. *Nat. Sustain.* **6**, 284–294 (2023).
26. Opio, C., P. Gerber, A. Mottet, A. Falcucci, G. Tempio, M. MacLeod, T. Vellinga, B. Henderson, H. Steinfeld, *Greenhouse Gas Emissions from Ruminant Supply Chains* (2013; https://www.fao.org/3/i3461e/i3461e00.htm).
27. C. Hong, J. A. Burney, J. Pongratz, J. E. M. S. Nabel, N. D. Mueller, R. B. Jackson, S. J. Davis, Global and regional drivers of land-use emissions in 1961–2017. *Nature* **589**, 554–561 (2021).
28. K. R. Sahlin, L. J. Gordon, R. Lindborg, J. Piipponen, P. Van Rysselberge, J. Rouet-Leduc, E. Röös, An exploration of biodiversity limits to grazing ruminant milk and meat production. *Nat. Sustain.* **7**, 1160–1170 (2024).
29. A. K. Knapp, T. R. Seastedt, Detritus Accumulation Limits Productivity of Tallgrass Prairie: The effects of its plant litter on ecosystem function make the tallgrass prairie unique among North American biomes. *Bioscience* **36**, 662–668 (1986).
30. C. De Mazancourt, M. Loreau, L. Abbadie, Grazing optimization and nutrient cycling: When do herbivores enhance plant production? *Ecology* **79**, 2242–2252 (1998).
31. K. Phukubye, M. Mutema, N. Buthelezi, P. Muchaonyerwa, C. Cerri, V. Chaplot, On the impact of grassland management on soil carbon stocks: a worldwide meta-analysis. *Geoderma Reg.* **28**, e00479 (2022).
32. U. and I. ILRI, IUCN, FAO, WWF, "Rangelands Atlas" (Nairobi Kenya, 2021).
33. H. Meyer, E. Pebesma, Machine learning-based global maps of ecological variables and the challenge of assessing them. *Nat. Commun.* **13**, 1–4 (2022).
34. P. Ploton, F. Mortier, M. Réjou-Méchain, N. Barbier, N. Picard, V. Rossi, C. Dormann, G. Cornu, G. Viennois, N. Bayol, A. Lyapustin, S. Gourlet-Fleury, R. Pélissier, Spatial validation reveals poor predictive performance of large-scale ecological mapping models. *Nat. Commun.* **11**, 4540 (2020).
35. IPCC, "Intergovernmental panel on climate change (IPCC) guidelines for national greenhouse gas inventories. Vol. 4 Agriculture, forestry and other land uses" (2019).
36. M. Gilbert, G. Cinardi, D. Da Re, W. G. R. Wint, D. Wisser, T. P. Robinson, Gridded Livestock of the World - 2015 (GLW 4). Harvard Dataverse [Preprint] (2022). https://doi.org/doi/10.7910/DVN/LHBICE.

37. Supplementary Materials and Methods

38. P. W. Ellis, A. M. Page, S. Wood, J. Fargione, Y. J. Masuda, V. Carrasco Denney, C. Moore, T. Kroeger, B. Griscom, J. Sanderman, T. Atleo, R. Cortez, S. Leavitt, S. C. Cook-Patton, The principles of natural climate solutions. *Nat. Commun.* **15**, 547 (2024).

39. E. W. Slessarev, A. Mayer, C. Kelly, K. Georgiou, J. Pett-Ridge, E. E. Nuccio, Initial soil organic carbon stocks govern changes in soil carbon: Reality or artifact? *Glob. Chang. Biol.* **29**, 1239–1247 (2023).

40. S. Eze, S. M. Palmer, P. J. Chapman, Soil organic carbon stock in grasslands: Effects of inorganic fertilizers, liming and grazing in different climate settings. *J. Environ. Manage.* **223**, 74–84 (2018).

41. M. E. Mcsherry, M. E. Ritchie, Effects of grazing on grassland soil carbon: a global review. *Glob. Chang. Biol.* **19**, 1347–1357 (2013).

42. J.-F. Bastin, Y. Finegold, C. Garcia, D. Mollicone, M. Rezende, D. Routh, C. M. Zohner, T. W. Crowther, The global tree restoration potential. *Science.* **366**, 76–79 (2019).

43. Y. Ma, D. Woolf, M. Fan, L. Qiao, R. Li, J. Lehmann, Global crop production increase by soil organic carbon. *Nat. Geosci.* **16**, 1159–1165 (2023).

44. J. van den Hoogen, S. Geisen, D. Routh, H. Ferris, W. Traunspurger, D. A. Wardle, R. G. M. de Goede, B. J. Adams, W. Ahmad, W. S. Andriuzzi, R. D. Bardgett, M. Bonkowski, R. Campos-Herrera, J. E. Cares, T. Caruso, L. de Brito Caixeta, X. Chen, S. R. Costa, R. Creamer, J. Mauro da Cunha Castro, M. Dam, D. Djigal, M. Escuer, B. S. Griffiths, C. Gutiérrez, K. Hohberg, D. Kalinkina, P. Kardol, A. Kergunteuil, G. Korthals, V. Krashevska, A. A. Kudrin, Q. Li, W. Liang, M. Magilton, M. Marais, J. A. R. Martín, E. Matveeva, E. H. Mayad, C. Mulder, P. Mullin, R. Neilson, T. A. D. Nguyen, U. N. Nielsen, H. Okada, J. E. P. Rius, K. Pan, V. Peneva, L. Pellissier, J. Carlos Pereira da Silva, C. Pitteloud, T. O. Powers, K. Powers, C. W. Quist, S. Rasmann, S. S. Moreno, S. Scheu, H. Setälä, A. Sushchuk, A. V. Tiunov, J. Trap, W. van der Putten, M. Vestergård, C. Villenave, L. Waeyenberge, D. H. Wall, R. Wilschut, D. G. Wright, J. in Yang, T. W. Crowther, Soil nematode abundance and functional group composition at a global scale. *Nature* **572**, 194–198 (2019).

45. J. Chang, P. Ciais, T. Gasser, P. Smith, M. Herrero, P. Havlík, M. Obersteiner, B. Guenet, D. S. Goll, W. Li, V. Naipal, S. Peng, C. Qiu, H. Tian, N. Viovy, C. Yue, D. Zhu, Climate warming from managed grasslands cancels the cooling effect of carbon sinks in sparsely grazed and natural grasslands. *Nat. Commun.* **12**, 118 (2021).

46. FAO, "Global Soil Organic Carbon Sequestration Potential Map– GSOCseq v1.1" (2022); https://doi.org/10.4060/cb9002en.

47. D. G. Milchunas, W. K. Lauenroth, Quantitative effects of grazing on vegetation and soils over a global range of environments. *Ecol. Monogr.* **63**, 327–366 (1993).

48. M. M. Chu, E. Wang, S. Bu, X. Chen, China strikes back at Trump with own tariffs, export curbs | Reuters, *Reuters* (2025). https://www.reuters.com/world/china-impose-tariffs-34-all-us-goods-april-10-2025-04-04/.

49. D. Laborde, A. Mamun, M. Parent, COVID-19 Food Trade Policy Tracker [dataset]., *International Food Policy Research Institute (IFPRI)* (2020). https://www.foodsecurityportal.org/tools/COVID-19-food-trade-policy-tracker#the-tool.

50. Verified Carbon Standard Registry. https://registry.verra.org/app/search/VCS/All%20Projects.

51. A. A. Golub, B. B. Henderson, T. W. Hertel, P. J. Gerber, S. K. Rose, B. Sohngen, Global climate policy impacts on livestock, land use, livelihoods, and food security. *Proc. Natl. Acad. Sci. U. S. A.* **110**, 20894–20899 (2013).

52. M. Ludwig, A. Moreno-Martinez, N. Hölzel, E. Pebesma, H. Meyer, Assessing and improving the transferability of current global spatial prediction models. *Global Ecol. Biogeogr.* **32**, 356–368 (2023).

53. Y. Wang, Y. Zhu, S. C. Cook-Patton, W. Sun, W. Zhang, P. Ciais, T. Li, P. Smith, W. Yuan, X. Zhu, J. G. Canadell, X. Deng, Y. Xu, H. Xu, C. Yue, Z. Qin, Land availability and policy commitments limit global climate mitigation from forestation. *Science.* **389**, 931–934 (2025).

54. R. Sommer, D. Bossio, Dynamics and climate change mitigation potential of soil organic carbon sequestration. *J. Environ. Manage.* **144**, 83–87 (2014).

55. K. Georgiou, D. Angers, R. E. Champiny, M. F. Cotrufo, M. E. Craig, S. Doetterl, A. S. Grandy, J. M. Lavallee, Y. Lin, E. Lugato, C. Poeplau, K. S. Rocci, S. A. Schweizer, J. Six, W. R. Wieder, Soil Carbon Saturation: What Do We Really Know? *Glob. Chang. Biol.* **31**, e70197 (2025).

56. K. Georgiou, C. D. Koven, W. R. Wieder, M. D. Hartman, W. J. Riley, J. Pett-ridge, N. J. Bouskill, R. Z. Abramoff, E. W. Slessarev, A. Ahlström, W. J. Parton, A. F. A. Pellegrini, D. Pierson, B. N. Sulman, Q. Zhu, Emergent temperature sensitivity of soil organic carbon driven by mineral associations. *Nat. Geosci.* **17**, 205-212 (2024).

57. E. E. Rezaei, H. Webber, S. Asseng, K. Boote, J. L. Durand, F. Ewert, P. Martre, D. S. MacCarthy, Climate change impacts on crop yields. *Nat. Rev. Earth Environ.* **4**, 831–846 (2023).

58. C. M. Godde, R. B. Boone, A. J. Ash, K. Waha, L. L. Sloat, P. K. Thornton, M. Herrero, Global rangeland production systems and livelihoods at threat under climate change and variability. *Environ. Res. Lett.* **15**, 044021 (2020).

59. M. Tesfaye, L. Tessema, An overview of the status, productivity and determinants of improved forage technology adoption in Ethiopia: a review. *CABI Agr. Biosci.* **4**, 47 (2023).

60. R. Messner, C. Richards, E. Ransom, E. Mitchell, D. Rowlings, Holistic grazing management as a scalable niche? A systems perspective on transitions to increased sustainability in beef cattle grazing. *Sustain. Sci.* **20**, 2125–2139 (2025).

61. D. Y. Ayal, B. Mamo, Farmer's climate smart livestock production adoption and determinant factors in Hidebu Abote District, Central Ethiopia. *Sci. Rep.* **14**, 10027- (2024).

62. FAOSTAT, FAOSTAT statistical database of the Food and agriculture organization of the UN: Food Balance Sheet (2024). https://www.fao.org/faostat/en/#data/FBS.

63. A. Procton, "State of the Voluntary Carbon Market: Meeting the Moment Renewing Trust in Carbon Finance Editors: Researchers" (2025); www.forest-trends.org.

64. S. Roe, C. Streck, R. Beach, J. Busch, M. Chapman, V. Daioglou, A. Deppermann, J. Doelman, J. Emmet-Booth, J. Engelmann, O. Fricko, C. Frischmann, J. Funk, G. Grassi, B. Griscom, P. Havlik, S. Hanssen, F. Humpenöder, D. Landholm, G. Lomax, J. Lehmann, L. Mesnildrey, G. J. Nabuurs, A. Popp, C. Rivard, J. Sanderman, B. Sohngen, P. Smith, E. Stehfest, D. Woolf, D. Lawrence, Land-based measures to mitigate climate change: Potential and feasibility by country. *Glob. Chang. Biol.* **27**, 6025–6058 (2021).

65. P. Friedlingstein, M. O'Sullivan, M. W. Jones, R. M. Andrew, D. C. E. Bakker, J. Hauck, P. Landschützer, C. Le Quéré, I. T. Luijkx, G. P. Peters, W. Peters, J. Pongratz, C. Schwingshackl, S. Sitch, J. G. Canadell, P. Ciais, R. B. Jackson, S. R. Alin, P. Anthoni, L. Barbero, N. R. Bates, M. Becker, N. Bellouin, B. Decharme, L. Bopp, I. B. M. Brasika, P. Cadule, M. A. Chamberlain, N. Chandra, T. T. T. Chau, F. Chevallier, L. P. Chini, M. Cronin, X. Dou, K. Enyo, W. Evans, S. Falk, R. A. Feely, L. Feng, D. J. Ford, T. Gasser, J. Ghattas, T. Gkritzalis, G. Grassi, L. Gregor, N. Gruber, Ö. Gürses, I. Harris, M. Hefner, J. Heinke, R. A. Houghton, G. C. Hurtt, Y. Iida, T. Ilyina, A. R. Jacobson, A. Jain, T. Jarníková, A. Jersild, F. Jiang, Z. Jin, F. Joos, E. Kato, R. F. Keeling, D. Kennedy, K. K. Goldewijk, J. Knauer, J. I. Korsbakken, A. Körtzinger, X. Lan, N. Lefèvre, H. Li, J. Liu, Z. Liu, L. Ma, G. Marland, N. Mayot, P. C. McGuire, G. A. McKinley, G. Meyer, E. J. Morgan, D. R. Munro, S. I. Nakaoka, Y. Niwa, K. M. O'Brien, A. Olsen, A. M. Omar, T. Ono, M. Paulsen, D. Pierrot, K. Pocock, B. Poulter, C. M. Powis, G. Rehder, L. Resplandy, E. Robertson, C. Rödenbeck, T. M. Rosan, J. Schwinger, R. Séférian, T. L. Smallman, S. M. Smith, R. Sospedra-Alfonso, Q. Sun, A. J. Sutton, C. Sweeney, S. Takao, P. P. Tans, H. Tian, B. Tilbrook, H. Tsujino, F. Tubiello, G. R. van der Werf, E. van Ooijen, R. Wanninkhof, M. Watanabe, C. Wimart-Rousseau, D. Yang, X. Yang, W. Yuan, X. Yue, S. Zaehle, J. Zeng, B. Zheng, Global Carbon Budget 2023. *Earth Syst. Sci. Data* **15**, 5301–5369 (2023).

66. W. Willett, J. Rockström, B. Loken, M. Springmann, T. Lang, S. Vermeulen, T. Garnett, D. Tilman, F. DeClerck, A. Wood, M. Jonell, M. Clark, L. J. Gordon, J. Fanzo, C. Hawkes, R. Zurayk, J. A. Rivera, W. De Vries, L. Majele Sibanda, A. Afshin, A. Chaudhary, M. Herrero, R. Agustina, F. Branca, A. Lartey, S. Fan, B. Crona, E. Fox, V. Bignet, M. Troell, T. Lindahl, S. Singh, S. E. Cornell, K. Srinath Reddy, S. Narain, S. Nishtar, C. J. L. Murray, Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. Lancet Publishing Group [Preprint] (2019). https://doi.org/10.1016/S0140-6736(18)31788-4.
67. Powell, R. S., S. J. Davis, D. G. Encarnation, J. Piipponen, J. Chang, C. M. Currier, K.-H. Erb, S. Eze, C. Hong, P. Ploton, S. Ren, P. Smith, J. Su, G. Tempio, C. Terrer, D. Wisser, F. Xu, and A. F. A. Pellegrini. Assessing the net-climate benefits of improved grazing intensity in global rangelands. Dryad. https://doi.org/10.5061/dryad.h70rxwdzc.
68. J. Piipponen, M. Jalava, J. de Leeuw, A. Rizayeva, C. Godde, G. Cramer, M. Herrero, M. Kummu, Global trends in grassland carrying capacity and relative stocking density of livestock. *Glob. Chang. Biol.* **28**, 3902–3919 (2022).
69. K. Coleman, D. S. Jenkinson, "RothC-26.3 - a model for the turnover of carbon in soil" in *Evaluation of Soil Organic Matter Models Using Existing Long-Term Datasets (NATO ASI Series I, Vol. 38)*, D. S. Powlson, J. U. Smith, P. Smith, Eds. (Springer, Berlin, Berlin, 1996), pp. 237–246.
70. E. Hansis, S. J. Davis, J. Pongratz, Relevance of methodological choices for accounting of land use change carbon fluxes. *Global Biogeochem. Cycles* **29**, 1230–1246 (2015).
71. K. Hartung, A. Bastos, L. Chini, R. Ganzenmüller, F. Havermann, G. C. Hurtt, T. Loughran, J. E. M. S. Nabel, T. Nützel, W. A. Obermeier, J. Pongratz, Bookkeeping estimates of the net land-use change flux - A sensitivity study with the CMIP6 land-use dataset. *Earth Syst. Dynam.* **12**, 763–782 (2021).
72. A. Bastos, K. Hartung, T. B. Nützel, J. E. M. S. Nabel, R. A. Houghton, J. Pongratz, Comparison of uncertainties in land-use change fluxes from bookkeeping model parameterisation. *Earth Syst. Dynam.* **12**, 745–762 (2021).
73. A. Aguiar, M. Chepeliev, E. Corong, D. van der Mensbrugghe, The Global Trade Analysis Project (GTAP) Data Base: Version 11. *J. Glob. Econ. Anal.* **7**, 1–37 (2022).
74. C. Hong, H. Zhao, Y. Qin, J. A. Burney, J. Pongratz, K. Hartung, Y. Liu, F. C. Moore, R. B. Jackson, Q. Zhang, S. J. Davis, Land-use emissions embodied in international trade. *Science* **376**, 597-603 (2022).
75. R. J. Zomer, D. A. Bossio, R. Sommer, L. V. Verchot, Global sequestration potential of increased organic carbon in cropland soils. *Sci. Rep.* **7**, 15554 (2017).
76. M. Herrero, P. Havlík, H. Valin, A. Notenbaert, M. C. Rufino, P. K. Thornton, M. Blümmel, F. Weiss, D. Grace, M. Obersteiner, Biomass use, production, feed efficiencies, and greenhouse gas emissions from global livestock systems. *Proc. Natl. Acad. Sci. U. S. A.* **110**, 20888–20893 (2013).
77. C. Arndt, A. N. Hristov, W. J. Price, S. C. McClelland, A. M. Pelaez, S. F. Cueva, J. Oh, J. Dijkstra, A. Bannink, A. R. Bayat, L. A. Crompton, M. A. Eugéne, D. Enahoro, E. Kebreab, M. Kreuzer, M. McGee, C. Martin, C. J. Newbold, C. K. Reynolds, A. Schwarm, K. J. Shingfield, J. B. Veneman, D. R. Yáñez-Ruiz, Z. Yu, Full adoption of the most effective strategies to mitigate methane emissions by ruminants can help meet the 1.5 °C target by 2030 but not 2050. *Proc. Natl. Acad. Sci. U. S. A.* **119**, 1–10 (2022).
78. C. Milà, J. Mateu, E. Pebesma, H. Meyer, Nearest neighbour distance matching Leave-One-Out Cross-Validation for map validation. *Methods Ecol. Evol.* **13**, 1304–1316 (2022).
79. D. Sulla-Menashe, M. A. Friedl, "User Guide to Collection 6 MODIS Land Cover (MCD12Q1 and MCD12C1) Product" (2018); https://modis-land.gsfc.nasa.gov/pdf/MCD12Q2_Collection6_UserGuide.pdf.
80. L. A. (Laurence A. Stoddart, A. D. Smith, *Range Management* (New York : McGraw-Hill, 1955., New York, 2nd ed., 1955).

81. J. Wolf, M. Chen, G. R. Asrar, Global rangeland primary production and its consumption by livestock in 2000–2010. *Remote Sens.* **13**, 1–23 (2021).
82. F. Zabel, B. Putzenlechner, W. Mauser, Global agricultural land resources – A high resolution suitability evaluation and its perspectives until 2100 under climate change conditions. *PLoS One* **9**, e107522 (2014).
83. D. D. Briske, S. Vetter, C. Coetsee, M. D. Turner, Rangeland afforestation is not a natural climate solution. *Front. Ecol. Environ.* **22**, e2727 (2024).
84. K. Georgiou, R. B. Jackson, O. Vindušková, R. Z. Abramoff, A. Ahlström, W. Feng, J. W. Harden, A. F. A. Pellegrini, H. W. Polley, J. L. Soong, W. J. Riley, M. S. Torn, Global stocks and capacity of mineral-associated soil organic carbon. *Nat. Commun.* **13**, 1–12 (2022).
85. H. Ma, L. Mo, T. W. Crowther, D. S. Maynard, J. van den Hoogen, B. D. Stocker, C. Terrer, C. M. Zohner, The global distribution and environmental drivers of aboveground versus belowground plant biomass. *Nat. Ecol. Evol.* **5**, 1110–1122 (2021).
86. F. T. Maestre, Y. Le Bagousse-pinguet, M. Delgado-baquerizo, D. J. Eldridge, H. Saiz, M. Berdugo, B. Gozalo, V. Ochoa, E. Guirado, Grazing and ecosystem service delivery in global drylands. *Science* **378**, 915–920 (2022).
87. J. Su, F. Xu, Root, not aboveground litter, controls soil carbon storage under grazing exclusion across grasslands worldwide. *Land Degrad. Dev.* **32**, 3326–3337 (2021).
88. M. He, G. Zhou, T. Yuan, K. J. van Groenigen, J. Shao, X. Zhou, Grazing intensity significantly changes the C : N : P stoichiometry in grassland ecosystems. *Global Ecol. Biogeogr.* **29**, 355–369 (2020).
89. D. Xiong, P. Shi, X. Zhang, C. B. Zou, Effects of grazing exclusion on carbon sequestration and plant diversity in grasslands of China—A meta-analysis. *Ecol. Eng.* **94**, 647–655 (2016).
90. J. Sitters, E. R. J. Wubs, E. S. Bakker, T. W. Crowther, P. B. Adler, S. Bagchi, J. D. Bakker, L. Biederman, E. T. Borer, E. E. Cleland, N. Eisenhauer, J. Firn, L. Gherardi, N. Hagenah, Y. Hautier, S. E. Hobbie, J. M. H. Knops, A. S. MacDougall, R. L. McCulley, J. L. Moore, B. Mortensen, P. L. Peri, S. M. Prober, C. Riggs, A. C. Risch, M. Schütz, E. W. Seabloom, J. Siebert, C. J. Stevens, G. F. Veen, Nutrient availability controls the impact of mammalian herbivores on soil carbon and nitrogen pools in grasslands. *Glob. Chang. Biol.* **26**, 2060–2071 (2020).
91. S. Tang, K. Wang, Y. Xiang, D. Tian, J. Wang, Y. Liu, B. Cao, D. Guo, S. Niu, Heavy grazing reduces grassland soil greenhouse gas fluxes: A global meta-analysis. *Sci. Total Environ.* **654**, 1218–1224 (2019).
92. D. Tilman, Soil carbon: Herbivory by Nitrogen Interactive Effects on Community and Ecosystem Processes and Dynamics, *Environmental Data Initiative* (2018).
93. P. L. Stanley, C. Wilson, E. Patterson, M. Machmuller, M. F. Cotrufo, Ruminating on soil carbon: Applying current understanding to inform grazing management. *Glob. Chang. Biol.* **30**, 1–20 (2024).
94. R. C. Byrnes, D. J. Eastburn, K. W. Tate, L. M. Roche, A global meta-analysis of grazing impacts on soil health indicators. *J. Environ. Qual.* **47**, 758–765 (2018).
95. S. C. Cook-patton, S. M. Leavitt, D. Gibbs, N. L. Harris, K. Lister, K. J. Anderson-teixeira, R. D. Briggs, R. L. Chazdon, T. W. Crowther, P. W. Ellis, H. P. Griscom, V. Herrmann, K. D. Holl, Mapping carbon accumulation potential from global natural forest regrowth. *Nature* **585**, 545–550 (2020).
96. M. Dondini, M. Martin, C. De Camillis, A. Uwizeye, J.-F. Soussana, T. Robinson, H. Steinfeld, *Global Assessment of Soil Carbon in Grasslands: From Current Stock Estimates to Sequestration Potential* (FAO, 2023; https://doi.org/10.4060/cc3981en)vol. 187.
97. D. Bates, M. Mächler, B. M. Bolker, S. C. Walker, Fitting linear mixed-effects models using lme4. *J. Stat. Softw.* **67**, 1–48 (2015).
98. A. F. Zuur, E. N. Ieno, N. Walker, A. A. Saveliev, G. M. Smith, *Mixed Effects Models and Extensions in Ecology with R* (Springer New York, New York, NY, 2009; http://link.springer.com/10.1007/978-0-387-87458-6)*Statistics for Biology and Health*.

99. O. J. Schmitz, C. C. Wilmers, S. J. Leroux, C. E. Doughty, T. B. Atwood, M. Galetti, A. B. Davies, S. J. Goetz, Animals and the zoogeochemistry of the carbon cycle. *Science.* **362**, eaar3213 (2018).

100. D. Lüdecke, M. Ben-Shachar, I. Patil, P. Waggoner, D. Makowski, performance: An R Package for Assessment, Comparison and Testing of Statistical Models. *J. Open Source Softw.* **6**, 3139 (2021).

101. R. S. Bivand, D. W. S. Wong, Comparing implementations of global and local indicators of spatial association. *Test* **27**, 716–748 (2018).

102. A. Liaw, M. Wiener, The R Journal: Classification and regression by randomForest. *R Journal* **2**, 18–22 (2002).

103. M. Kuhn, Building predictive models in R using the caret package. *J. Stat. Softw.* **28**, 1–26 (2008).

104. H. Meyer, M. Ludwig, C. Milà, J. Linnenbrink, F. Schumacher, The CAST package for training and assessment of spatial prediction models in R. (2024).

105. H. Meyer, C. Reudenbach, S. Wöllauer, T. Nauss, Importance of spatial predictor variable selection in machine learning applications – Moving from data reproduction to spatial prediction. *Ecol. Modell.* **411**, 108815 (2019).

106. A. M. J. C. Wadoux, G. B. M. Heuvelink, S. de Bruin, D. J. Brus, Spatial cross-validation is not the right way to evaluate map accuracy. *Ecol. Modell.* **457**, 109692 (2021).

107. L. Breiman, “Random Forests” in *Machine Learning* (2001), pp. 5–32.

108. R. J. Telford, H. J. B. Birks, Evaluation of transfer functions in spatially structured environments. *Quat. Sci. Rev.* **28**, 1309–1316 (2009).

109. N. Karasiak, J. F. Dejoux, C. Monteil, D. Sheeren, Spatial dependence between training and test sets: another pitfall of classification accuracy assessment in remote sensing. *Mach. Learn.* **111**, 2715–2740 (2022).

110. B. Misiuk, M. Diesing, A. Aitken, C. J. Brown, E. N. Edinger, T. Bell, A spatially explicit comparison of quantitative and categorical modelling approaches for mapping seabed sediments using random forest. *Geosciences* **9**, 254 (2019).

111. L. Mo, C. M. Zohner, P. B. Reich, J. Liang, S. de Miguel, G.-J. Nabuurs, S. S. Renner, J. van den Hoogen, A. Araza, M. Herold, L. Mirzagholi, H. Ma, C. Averill, O. L. Phillips, J. G. P. Gamarra, I. Hordijk, D. Routh, M. Abegg, Y. C. Adou Yao, G. Alberti, A. M. Almeyda Zambrano, B. V. Alvarado, E. Alvarez-Dávila, P. Alvarez-Loayza, L. F. Alves, I. Amaral, C. Ammer, C. Antón-Fernández, A. Araujo-Murakami, L. Arroyo, V. Avitabile, G. A. Aymard, T. R. Baker, R. Bałazy, O. Banki, J. G. Barroso, M. L. Bastian, J.-F. Bastin, L. Birigazzi, P. Birnbaum, R. Bitariho, P. Boeckx, F. Bongers, O. Bouriaud, P. H. S. Brancalion, S. Brandl, F. Q. Brearley, R. Brienen, E. N. Broadbent, H. Bruelheide, F. Bussotti, R. Cazzolla Gatti, R. G. César, G. Cesljar, R. L. Chazdon, H. Y. H. Chen, C. Chisholm, H. Cho, E. Cienciala, C. Clark, D. Clark, G. D. Colletta, D. A. Coomes, F. Cornejo Valverde, J. J. Corral-Rivas, P. M. Crim, J. R. Cumming, S. Dayanandan, A. L. de Gasper, M. Decuyper, G. Derroire, B. DeVries, I. Djordjevic, J. Dolezal, A. Dourdain, N. L. Engone Obiang, B. J. Enquist, T. J. Eyre, A. B. Fandohan, T. M. Fayle, T. R. Feldpausch, L. V. Ferreira, L. Finér, M. Fischer, C. Fletcher, L. Frizzera, D. Gianelle, H. B. Glick, D. J. Harris, A. Hector, A. Hemp, G. Hengeveld, B. Hérault, J. L. Herbohn, A. Hillers, E. N. Honorio Coronado, C. Hui, T. Ibanez, N. Imai, A. M. Jagodziński, B. Jaroszewicz, V. K. Johannsen, C. A. Joly, T. Jucker, I. Jung, V. Karminov, K. Kartawinata, E. Kearsley, D. Kenfack, D. K. Kennard, S. Kepfer-Rojas, G. Keppel, M. L. Khan, T. J. Killeen, H. S. Kim, K. Kitayama, M. Köhl, H. Korjus, F. Kraxner, D. Kucher, D. Laarmann, M. Lang, H. Lu, N. V. Lukina, B. S. Maitner, Y. Malhi, E. Marcon, B. S. Marimon, B. H. Marimon-Junior, A. R. Marshall, E. H. Martin, J. A. Meave, O. Melo-Cruz, C. Mendoza, I. Mendoza-Polo, S. Miscicki, C. Merow, A. Monteagudo Mendoza, V. S. Moreno, S. A. Mukul, P. Mundhenk, M. G. Nava-Miranda, D. Neill, V. J. Neldner, R. V. Nevenic, M. R. Ngugi, P. A. Niklaus, J. Oleksyn, P. Ontikov, E. Ortiz-Malavasi, Y. Pan, A. Paquette, A. Parada-Gutierrez, E. I. Parfenova, M. Park, M. Parren, N. Parthasarathy, P. L. Peri, S. Pfautsch, N. Picard, M. T. F. Piedade, D. Piotto, N. C. A. Pitman, A. D. Poulsen, J. R. Poulsen, H.

Pretzsch, F. Ramirez Arevalo, Z. Restrepo-Correa, M. Rodeghiero, S. G. Rolim, A. Roopsind, F. Rovero, E. Rutishauser, P. Saikia, C. Salas-Eljatib, P. Saner, P. Schall, M.-J. Schelhaas, D. Schepaschenko, M. Scherer-Lorenzen, B. Schmid, J. Schöngart, E. B. Searle, V. Seben, J. M. Serra-Diaz, D. Sheil, A. Z. Shvidenko, J. E. Silva-Espejo, M. Silveira, J. Singh, P. Sist, F. Slik, B. Sonké, A. F. Souza, K. J. Stereńczak, J.-C. Svenning, M. Svoboda, B. Swanepoel, N. Targhetta, N. Tchebakova, H. ter Steege, R. Thomas, E. Tikhonova, P. M. Umunay, V. A. Usoltsev, R. Valencia, F. Valladares, F. van der Plas, T. Van Do, M. E. van Nuland, R. M. Vasquez, H. Verbeeck, H. Viana, A. C. Vibrans, S. Vieira, K. von Gadow, H.-F. Wang, J. V. Watson, G. D. A. Werner, S. K. Wiser, F. Wittmann, H. Woell, V. Wortel, R. Zagt, T. Zawiła-Niedźwiecki, C. Zhang, X. Zhao, M. Zhou, Z.-X. Zhu, I. C. Zo-Bi, G. D. Gann, T. W. Crowther, Integrated global assessment of the natural forest carbon potential. *Nature* **624**, 92–101 (2023).

112. S. de Bruin, D. J. Brus, G. B. M. Heuvelink, T. van Ebbenhorst Tengbergen, A. M. J. C. Wadoux, Dealing with clustered samples for assessing map accuracy by cross-validation. *Ecol. Inform.* **69**, 101665 (2022).
113. J. Pohjankukka, T. Pahikkala, P. Nevalainen, J. Heikkonen, Estimating the prediction performance of spatial models via spatial k-fold cross validation. *Int. J. Geogr. Inf. Sci.* **31**, 2001–2019 (2017).
114. D. R. Roberts, V. Bahn, S. Ciuti, M. S. Boyce, J. Elith, G. Guillera-Arroita, S. Hauenstein, J. J. Lahoz-Monfort, B. Schröder, W. Thuiller, D. I. Warton, B. A. Wintle, F. Hartig, C. F. Dormann, Cross-validation strategies for data with temporal, spatial, hierarchical, or phylogenetic structure. *Ecography* **40**, 913–929 (2017).
115. S. J. Wenger, J. D. Olden, Assessing transferability of ecological models: an underappreciated aspect of statistical validation. *Methods Ecol. Evol.* **3**, 260–267 (2012).
116. S. Ren, C. Terrer, J. Li, Y. Cao, S. Yang, D. Liu, Historical impacts of grazing on carbon stocks and climate mitigation opportunities. doi: 10.1038/s41558-024-01957-9 (2024).
117. M. C. Peel, B. L. Finlayson, T. A. McMahon, Updated world map of the Köppen-Geiger climate classification. *Hydrol. Earth Syst. Sci.* **11**, 1633–1644 (2007).
118. H. Meyer, C. Milà, M. Ludwig, J. Linnenbrink, CAST: “caret” Applications for Spatial-Temporal Models. (2023). https://CRAN.R-project.org/package=CAST.
119. J. H. Friedman, Greedy function approximation: A gradient boosting machine. *Ann. Stat.* **29**, 1189–1232 (2001).
120. B. M. Greenwell, pdp: An R package for constructing partial dependence plots. *R Journal* **9**, 421–436 (2017).
121. T. Fetzel, P. Havlik, M. Herrero, J. O. Kaplan, T. Kastner, C. Kroisleitner, S. Rolinski, T. Searchinger, P. M. Van Bodegom, S. Wirsenius, K. H. Erb, Quantification of uncertainties in global grazing systems assessment. *Global Biogeochem. Cycles* **31**, 1089–1102 (2017).
122. A. F. Bouwman, K. W. Van Der Hoek, B. Eickhout, I. Soenario, Exploring changes in world ruminant production systems. *Agric. Syst.* **84**, 121–153 (2005).
123. H. Haberl, K. H. Erb, F. Krausmann, V. Gaube, A. Bondeau, C. Plutzar, S. Gingrich, W. Lucht, M. Fischer-Kowalski, Quantifying and mapping the human appropriation of net primary production in earth’s terrestrial ecosystems. *Proc. Natl. Acad. Sci. U. S. A.* **104**, 12942–12947 (2007).
124. K. H. Erb, T. Fetzel, C. Plutzar, T. Kastner, C. Lauk, A. Mayer, M. Niedertscheider, C. Körner, H. Haberl, Biomass turnover time in terrestrial ecosystems halved by land use. *Nat. Geosci.* **9**, 674–678 (2016).
125. S. W. Running, M. Zhao, MOD17A3HGF MODIS/Terra Net Primary Production Gap-Filled Yearly L4 Global 500 m SIN Grid V006 [Data set], *NASA Land Processes Distributed Active Archive Center* (2019). https://doi.org/10.5067/MODIS/MOD17A3HGF.006.
126. J. T. Abatzoglou, S. Z. Dobrowski, S. A. Parks, K. C. Hegewisch, TerraClimate, a high-resolution global dataset of monthly climate and climatic water balance from 1958-2015. *Sci. Data* **5**, 1–12 (2018).

127. K. Petz, R. Alkemade, M. Bakkenes, C. J. E. Schulp, M. van der Velde, R. Leemans, Mapping and modelling trade-offs and synergies between grazing intensity and ecosystem services in rangelands using global-scale datasets and models. *Global Environ. Chang.* **29**, 223–234 (2014).

128. J. O. Sexton, X. P. Song, M. Feng, P. Noojipady, A. Anand, C. Huang, D. H. Kim, K. M. Collins, S. Channan, C. DiMiceli, J. R. Townshend, Global, 30-m resolution continuous fields of tree cover: Landsat-based rescaling of MODIS vegetation continuous fields with lidar-based estimates of error. *Int. J. Digit. Earth* **6**, 427–448 (2013).

129. W. P. Weiss, A. W. Tebbe, Estimating digestible energy values of feeds and diets and integrating those values into net energy systems. *Transl. Anim. Sci.* **3**, 953–961 (2019).

130. T. P. Robinson, P. K. Thornton, G. N. Francesconi, R. L. Kruska, F. Chiozza, A. M. O. Notenbaert, G. Cecchi, M. T. Herrero, M. Epprecht, S. Fritz, L. You, G. Conchedda, L. See, "Global livestock production systems" (FAO and ILRI, Rome, 2011); https://cgspace.cgiar.org/handle/10568/10537.

131. A. H. Andrews, R. W. Blowey, H. Boyd, R. G. Eddy, *Bovine Medicine Diseases and Husbandry of Cattle* (2004).

132. L. Zhang, H. Tian, H. Shi, S. Pan, J. Chang, S. R. S. Dangal, X. Qin, S. Wang, F. N. Tubiello, J. G. Canadell, R. B. Jackson, A 130-year global inventory of methane emissions from livestock: Trends, patterns, and drivers. *Glob. Chang. Biol.* **28**, 5142–5158 (2022).

133. J. Chang, S. Peng, Y. Yin, P. Ciais, P. Havlik, M. Herrero, The Key Role of Production Efficiency Changes in Livestock Methane Emission Mitigation. *AGU Advances* **2**, 1–16 (2021).

134. FAO, GLEAM 3 Dashboard in Shiny Apps (2022). https://foodandagricultureorganization.shinyapps.io/GLEAMV3_Public/.

135. FAO, "Global Livestock Environmental Assessment Model: Model Description" (2022).

136. R. Ehrhardt, Preparing rams for a successful breeding season - Sheep & Goats, *Michigan State University Extension*. https://www.canr.msu.edu/sheep_goats/reproduction/preparing-rams-for-a-successful-breeding-season.

137. Meat and Livestock Australia, "Factsheet 7: Production from a breeding doe" (2017); https://www.mla.com.au/globalassets/mla-corporate/extensions-training-and-tools/documents/fs07-production-from-a-breeding-doe-final.pdf.

138. Pregnant cows, timing of pregnancy, open cows, pregnancy rate | UNL Beef. https://beef.unl.edu/faq/pregnant-cows.

139. H. Andersen, M. Plum, Gestation Length and Birth Weight in Cattle and Buffaloes: A Review. *J. Dairy Sci.* **48**, 1224–1235 (1965).

140. F. M. Pate, W. E. Kunkle, Weaning Beef Calves At a Later Age To Increase Production. 1–5 (1989).

141. H. Wahid, Y. Rosnina, HUSBANDRY OF DAIRY ANIMALS | Buffalo: Asia. *Encyclopedia of Dairy Sciences*, 772 (2011).

142. P. Xu, Y. Liao, Y. Zheng, C. Zhao, X. Zhang, Z. Zheng, S. Luan, Northward shift of historical methane emission hotspots from the livestock sector in China and assessment of potential mitigation options. *Agric. For. Meteorol.* **272–273**, 1–11 (2019).

143. J. L. Holechek, R. Pieper, C. H. Herbel, *Range Management: Principles and Practices* (Pearson, ed. 6th, 2010).

144. K. E. Hales, C. A. Coppin, Z. K. Smith, Z. S. McDaniel, L. O. Tedeschi, N. A. Cole, M. L. Galyean, Predicting metabolizable energy from digestible energy for growing and finishing beef cattle and relationships to the prediction of methane. *J. Anim. Sci.* **100**, 1–11 (2022).

145. D. M. Olson, E. Dinerstein, E. D. Wikramanayake, N. D. Burgess, G. V. N. Powell, E. C. Underwood, J. A. D'Amico, I. Itoua, H. E. Strand, J. C. Morrison, C. J. Loucks, T. F. Allnutt, T. H. Ricketts, Y. Kura, J. F. Lamoreux, W. W. Wettengel, P. Hedao, K. R. Kassem, Terrestrial ecoregions of the world: a new map of life on Earth. *Bioscience* **51**, 933–938 (2001).

146. K. H. Erb, T. Kastner, C. Plutzar, A. L. S. Bais, N. Carvalhais, T. Fetzel, S. Gingrich, H. Haberl, C. Lauk, M. Niedertscheider, J. Pongratz, M. Thurner, S. Luyssaert, Unexpectedly large impact of forest management and grazing on global vegetation biomass. *Nature* **553**, 73–76 (2018).

147. A. Sanaei, E. J. Sayer, Z. Yuan, H. Saiz, M. Delgado-Baquerizo, M. Sadeghinia, P. Ashouri, S. Ghafari, H. Kaboli, M. Kargar, E. W. Seabloom, A. Ali, Grazing intensity alters the plant diversity–ecosystem carbon storage relationship in rangelands across topographic and climatic gradients. *Funct. Ecol.* **37**, 703–718 (2023).

148. F. Cao, W. Li, Y. Jiang, X. Gan, C. Zhao, J. Ma, Effects of grazing on grassland biomass and biodiversity: A global synthesis. *Field Crops Res.* **306**, 109204 (2024).

149. W. R. Wieder, J. Boehnert, G. B. Bonan, M. Langseth, Regridded Harmonized World Soil Database v1.2. ORNL DAAC. (2014).

150. H. Meyer, E. Pebesma, Predicting into unknown space? Estimating the area of applicability of spatial prediction models. *Methods Ecol. Evol.* **12**, 1620–1633 (2021).

151. IPCC, *IPCC Sixth Assessment Report: Climate Change* (Cambridge University Press, Cambridge, U.K., 2021).

152. R. Franz, C. R. Soliva, M. Kreuzer, P. Steuer, J. Hummel, M. Clauss, Methane production in relation to body mass of ruminants and equids. *Evol. Ecol. Res.* **12**, 727–738 (2010).

153. R. J. Zomer, J. Xu, A. Trabucco, Version 3 of the Global Aridity Index and Potential Evapotranspiration Database. *Sci. Data* **9**, 1–15 (2022).

154. P. K. Thornton, M. Herrero, Potential for reduced methane and carbon dioxide emissions from livestock and pasture management in the tropics. *Proc. Natl. Acad. Sci. U. S. A.* **107**, 19667–19672 (2010).

155. A. Suardi, S. Bergonzoli, V. Alfano, A. Scarfone, L. Pari, Economic distance to gather agricultural residues from the field to the integrated biomass logistic centre: A Spanish case-study. *Energies* **12**, 3086 (2019).

156. S. Avadhanam, S., Polumat, A. and Ellamraju, Usage of crop residue for making livestock feed. 1–25 (2020).

157. V. Heuze, G. Tran, D. Bastianelli, H. Archimede, D. Sauvant, "Feedipedia: an open access international ´encyclopedia on feed resources for farm animals" in *EAAP Annual Conference* (Wageningen Academic Publishers, 2013).

158. A. Kelly, W. Becker, E. Helsing, "Food Balance Sheets: A Handbook" (Rome, Italy, 2001).

159. J. Poore, T. Nemecek, Reducing food's environmental impacts through producers and consumers. *Science.* **360**, 987–992 (2018).

160. S. Gingrich, M. Theurl, K. H. Erb, J. Le Noë, A. Magerl, S. Bauernschuster, F. Krausmann, C. Lauk, Livestock increasingly drove global agricultural emissions growth from 1910-2015. *Environ. Res. Lett.* **19**, 024011 (2024).

161. FAOSTAT, FAOSTAT statistical database of the Food and agriculture organization of the UN: Food Production– Crops and Livestock (2023). https://www.fao.org/faostat/en/#data/QCL.

162. S. Lang, M. Mengel, S. Treu, M. Büchner, ISIMIP3a atmospheric climate input data (v1.1)., *ISIMIP Repository* (2022).

163. I. Harris, T. J. Osborn, P. Jones, D. Lister, Version 4 of the CRU TS monthly high-resolution gridded multivariate climate dataset. *Sci. Data* **7**, 109 (2020).

164. L. Poggio, L. M. De Sousa, N. H. Batjes, G. B. M. Heuvelink, B. Kempen, E. Ribeiro, D. Rossiter, SoilGrids 2.0: Producing soil information for the globe with quantified spatial uncertainty. *Soil* **7**, 217–240 (2021).

165. Earth Resources Observation And Science (EROS) Center, Global 30 Arc-Second Elevation (GTOPO30) [Data set] (2017). https://doi.org/10.5066/F7DF6PQS.

166. F. Tao, Y. Huang, B. A. Hungate, S. Manzoni, S. D. Frey, M. W. I. Schmidt, M. Reichstein, N. Carvalhais, P. Ciais, L. Jiang, J. Lehmann, Y.-P. Wang, B. Z. Houlton, B. Ahrens, U. Mishra, G. Hugelius, T. D. Hocking, X. Lu, Z. Shi, K. Viatkin, R. Vargas, Y. Yigini, C. Omuto, A. A. Malik, G. Peralta, R. Cuevas-Corona, L. E. Di Paolo, I. Luotto, C. Liao, Y.-S. Liang, V. S. Saynes, X.

Huang, Y. Luo, Microbial carbon use efficiency promotes global soil carbon storage. *Nature* **618**, 981–985doi: 10.1038/s41586-023-06042-3 (2023).

167. C. J. Still, J. A. Berry, G. J. Collatz, R. S. Defries, F. G. Hall, B. W. Meeson, S. O. los, E. Brown de Colstoun, D. R. Landis, ISLSCP II C4 Vegetation Percentage. (2009). https://doi.org/10.3334/ORNLDAAC/932.
168. S. E. Fick, R. J. Hijmans, WorldClim 2: new 1km spatial resolution climate surfaces for global land areas. *Int. J.l of Climatology* **37**, 4302–4315 (2017).
169. FAO, Global ecological zones for FAO forest reporting: 2010 Update. *Forest resources Assessment Working Paper 179*, 42 (2012).
170. I. P. Hartley, T. C. Hill, S. E. Chadburn, G. Hugelius, Temperature effects on carbon storage are controlled by soil stabilisation capacities. *Nat. Commun.* **12**, 1–7 (2021).
171. E. G. Jobbágy, R. B. Jackson, The vertical distribution of soil organic carbon and its relation to climate and vegetation. *Ecol. Appl.* **10**, 423–436 (2000).
172. Y. Zhao, Y. Ding, X. Hou, F. Y. Li, W. Han, X. Yun, Effects of temperature and grazing on soil organic carbon storage in grasslands along the Eurasian steppe eastern transect. *PLoS One* **12**, e0186980 (2017).
173. N. Herold, I. Schöning, B. Michalzik, S. Trumbore, M. Schrumpf, Controls on soil carbon storage and turnover in German landscapes. *Biogeochemistry* **119**, 435–451 (2014).
174. S. Xu, C. Sheng, C. Tian, Changing soil carbon: Influencing factors, sequestration strategy and research direction. *Carbon Balance Manag.* **15**, 1–9 (2020).
175. J. Hassink, The capacity of soils to preserve organic C and N by their association with clay and silt particles. *Plant Soil* **191**, 77–87 (1997).
176. S. A. Schweizer, C. W. Mueller, C. Höschen, P. Ivanov, I. Kögel-Knabner, The role of clay content and mineral surface area for soil organic carbon storage in an arable toposequence. *Biogeochemistry 2021 156:3* **156**, 401–420 (2021).
177. G. Y. K. Moinet, R. Hijbeek, D. P. Van Vuuren, K. E. Giller, Carbon for soils, not soils for carbon. *Glob. Chang. Biol.*, **29**, 2384-2398 (2023).
178. L. Brandt, F. Stache, C. Poll, D. S. Bramble, I. Schöning, M. Schrumpf, S. Ulrich, K. Kaiser, R. Mikutta, C. Mikutta, Y. Oelmann, A. Konrad, J. Siemens, E. Kandeler, Mineral type and land-use intensity control composition and functions of microorganisms colonizing pristine minerals in grassland soils. *Soil Biol. Biochem.* **182**, 109037 (2023).
179. K. A. Heckman, A. R. Possingerb, B. D. Badgleyc, M. M. Bowmand, A. C. Galloe, J. A. Hattene, L. E. Nave, M. D. SanClementsg, C. W. Swanston, T. L. Weiglein, W. R. Wieder., Brian D. Strahmb, Moisture-driven divergence in mineral-associated soil carbon persistence. *Proc. Natl. Acad. Sci. U. S. A.* **120**, e2210044120 (2023).
180. M. Reichenbach, P. Fiener, A. Hoyt, S. Trumbore, J. Six, S. Doetterl, Soil carbon stocks in stable tropical landforms are dominated by geochemical controls and not by land use. *Glob. Chang. Biol.* **29**, 2591–2607 (2023).
181. A. B. Keller, E. T. Borer, S. L. Collins, L. C. DeLancey, P. A. Fay, K. S. Hofmockel, A. D. B. Leakey, M. A. Mayes, E. W. Seabloom, C. A. Walter, Y. Wang, Q. Zhao, S. E. Hobbie, Soil carbon stocks in temperate grasslands differ strongly across sites but are insensitive to decade-long fertilization. *Glob. Chang. Biol.* **28**, 1659–1677 (2022).
182. M. F. Cotrufo, M. G. Ranalli, M. L. Haddix, J. Six, E. Lugato, Soil carbon storage informed by particulate and mineral-associated organic matter. *Nat. Geosci.* **12**, 989–994 (2019).
183. K. S. Rocci, K. S. Barker, E. W. Seabloom, E. T. Borer, S. E. Hobbie, J. D. Bakker, A. S. MacDougall, R. L. McCulley, J. L. Moore, X. Raynaud, C. J. Stevens, M. F. Cotrufo, Impacts of nutrient addition on soil carbon and nitrogen stoichiometry and stability in globally-distributed grasslands. *Biogeochemistry* **159**, 353–370 (2022).
184. R. F. Follett, C. E. Stewart, E. G. Pruessner, J. M. Kimble, Effects of climate change on soil carbon and nitrogen storage in the US Great Plains. *J. Soil Water Conserv.* **67**, 331–342 (2012).

185. M. Kleber, K. Eusterhues, M. Keiluweit, C. Mikutta, R. Mikutta, P. S. Nico, Mineral–organic associations: Formation, properties, and relevance in soil environments. *Adv. Agron.* **130**, 1–140 (2015).
186. C. Chenu, G. Stotzky, Interactions between microorganisms and soil particles: an overview. *Interactions between soil particles and microorganisms: impact on the terrestrial ecosystem*, 3–40 (2001).
187. A. Don, C. Rödenbeck, G. Gleixner, Unexpected control of soil carbon turnover by soil carbon concentration. *Environ. Chem. Lett.* **11**, 407–413 (2013).
188. M. Pinheiro, P. Garnier, J. Beguet, F. Martin Laurent, L. Vieublé Gonod, The millimetre-scale distribution of 2,4-D and its degraders drives the fate of 2,4-D at the soil core scale. *Soil Biol. Biochem.* **88**, 90–100 (2015).
189. J. Ruehlmann, M. Körschens, Calculating the effect of soil organic matter concentration on soil bulk density. *Soil Sci. Soc. Am. J.* **73**, 876–885 (2009).
190. A. F. A. Pellegrini, P. B. Reich, S. E. Hobbie, C. Coetsee, B. Wigley, E. February, K. Georgiou, C. Terrer, E. N. J. Brookshire, A. Ahlström, L. Nieradzik, S. Sitch, J. R. Melton, M. Forrest, F. Li, S. Hantson, C. Burton, C. Yue, P. Ciais, R. B. Jackson, Soil carbon storage capacity of drylands under altered fire regimes. *Nat. Clim. Chang.* **13**, 1089–1094 (2023).
191. R. B. Jackson, K. Lajtha, S. E. Crow, G. Hugelius, M. G. Kramer, G. Piñeiro, The Ecology of Soil Carbon: Pools, Vulnerabilities, and Biotic and Abiotic Controls. *Annu. Rev. Ecol. Evol. Syst.* **48**, 419–445 (2017).
192. I. Basile-Doelsch, J. Balesdent, S. Pellerin, Reviews and syntheses: The mechanisms underlying carbon storage in soil. *Biogeosciences* **17**, 5223–5242 (2020).
193. D. J. Kriticos, B. L. Webber, A. Leriche, N. Ota, I. Macadam, J. Bathols, J. K. Scott, CliMond: global high-resolution historical and future scenario climate surfaces for bioclimatic modelling. *Methods Ecol. Evol.* **3**, 53–64 (2012).
194. J. N. Galloway, F. J. Dentener, D. G. Capone, E. W. Boyer, R. W. Howarth, S. P. Seitzinger, G. P. Asner, C. C. Cleveland, P. A. Green, E. A. Holland, D. M. Karl, A. F. Michaels, J. H. Porter, A. R. Townsend, C. J. Vörösmarty, Nitrogen cycles: Past, present, and future. *Biogeochemistry* **70**, 153–226 (2004).
195. X. Xu, P. E. Thornton, W. M. Post, A global analysis of soil microbial biomass carbon, nitrogen and phosphorus in terrestrial ecosystems. *Global Ecol. and Biogeogr.* **22**, 737–749 (2013).
196. L. He, J. L. Mazza Rodrigues, N. A. Soudzilovskaia, M. Barceló, P. A. Olsson, C. Song, L. Tedersoo, F. Yuan, F. Yuan, D. A. Lipson, X. Xu, Global biogeography of fungal and bacterial biomass carbon in topsoil. *Soil Biol. Biochem.* **151**, 108024 (2020).
197. N. A. Soudzilovskaia, P. M. van Bodegom, C. Terrer, M. van't Zelfde, I. McCallum, M. Luke McCormack, J. B. Fisher, M. C. Brundrett, N. C. de Sá, L. Tedersoo, Global mycorrhizal plant distribution linked to terrestrial carbon stocks. *Nat. Commun.* **10**, 1–10 (2019).
198. B. Rabus, M. Eineder, A. Roth, R. Bamler, The shuttle radar topography mission—a new class of digital elevation models acquired by spaceborne radar. *ISPRS J. Photogramm. Remote Sens.* **57**, 241–262 (2003).
199. G. Amatulli, D. McInerney, T. Sethi, P. Strobl, S. Domisch, Geomorpho90m, empirical evaluation and accuracy assessment of global high-resolution geomorphometric layers. *Sci. Data* **7**, 1–18 (2020).
200. C. Beer, M. Reichstein, E. Tomelleri, P. Ciais, M. Jung, N. Carvalhais, C. Rödenbeck, M. A. Arain, D. Baldocchi, G. B. Bonan, A. Bondeau, C. Cescatti, G. Lasslop, A. Lindroth, M. Lomas, S. Luyssaert, H. Margolis, K. W. Oleson, O. Roupsard, E. Veenendaal, N. Viovy, C. Williams, F. I. Woodward, D. Papale, Terrestrial gross carbon dioxide uptake: Global distribution and covariation with climate. *Science* **329**, 834–839 (2010).
201. D. Hui, R. B. Jackson, Geographical and interannual variability in biomass partitioning in grassland ecosystems: A synthesis of field data. *New Phytol.* **169**, 85–93 (2006).

202. S. S. Saatchi, N. L. Harris, S. Brown, M. Lefsky, E. T. A. Mitchard, W. Salas, B. R. Zutta, W. Buermann, S. L. Lewis, S. Hagen, S. Petrova, L. White, M. Silman, A. Morel, Benchmark map of forest carbon stocks in tropical regions across three continents. *Proc. Natl. Acad. Sci. U. S. A.* **108**, 9899–9904 (2011).

203. J. de Leeuw, A. Rizayeva, E. Namazov, E. Bayramov, M. T. Marshall, J. Etzold, R. Neudert, Application of the MODIS MOD 17 Net Primary Production product in grassland carrying capacity assessment. *Int. J. Appl. Earth Obs. Geoinform.* **78**, 66–76 (2019).

Acknowledgements: We thank all scientists whose field-data were used in this study.

Funding: RSP was supported by the Natural Environment Research Council grant number NE/S007164/1. AFAP was supported by UKRI grant number EP/X042863/1. JP acknowledges the support of the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No. 819202).

Author Contributions Statement:
Conceptualization: RSP, AFAP, SJD
Methodology: RSP, AFAP, DGE, PP, JC, CH, SJD, JP, CMC, GT, DW, PS, CC
Investigation: RSP, CH, JC, SJD, FX, SE, SR, JS, KHE, SE, CT
Visualization: RSP, SJD
Funding acquisition: RSP, AFAP
Project administration: RSP
Supervision: AFAP
Writing – original draft: RSP, AFAP
Writing – review & editing: All authors

Competing Interests: S.J.D. is an advisor to Watershed Technology, Inc., a company that sometimes brokers sales of carbon credits generated by others' improved grazing projects, and have an ownership stake in the form of shares and/or options in the company.

Data, code, and materials availability:
All code and data to reproduce and extend this analysis can be found in the linked Dryad repository (*67*). The repository contains code used to analyse the data to produce our results as well as code to process the raw data. Processed and raw data inputs are included in the repository except where raw dataset size is very large (>10 GB), but download sources and/or instructions for downloading these raw data are provided. No new materials were created in this study.

Supplementary Materials

This PDF file includes:

- Materials and Methods
- Figs. S1 to S28
- Tables S1 to S11
- References (68-203)

Figure 1. Observed and modelled changes in soil carbon. Violin plots show the distribution of observed changes in total plant biomass due to categorical changes in grazing intensity (**A**) and the distribution of observed changes in soil organic carbon (SOC stocks n=677, SOC concentrations n=109) in top soils (0-30cm) among different quartiles of changes in total plant biomass (**B**) with grey points indicating median values and black points indicating response sizes from linear mixed effect models and whiskers extending to 95% confidence intervals. Sites that experienced greater increases in plant biomass often correspond to those with larger gains in SOC (e.g., -1.4% vs. +19.5% changes in SOC for the lowest and highest quartiles of plant biomass change, respectively). Variable importance for 10 'ecologically important' predictors (Methods (*37*)) for a spatially cross-validated random forest machine learning (ML) model with colours indicating variable type (**C**). Changes in SOC predicted by a random forest model with random cross-validated (log change ratios, gray squares, n=786) fitting observations better than predictions using a spatial buffered leave-one-out cross-validation approach (SBLOO-CV, red circles, n=530): R^2=0.43 and R^2=0.24, respectively, with dashed lines showing least squares regressions (**D**). Finally, bars in (**E**) compare our ML model predictions of SOC change (orange) with IPCC Tier 1 estimates (red) (*35*), statistical estimates from Ren et al. 2024 (yellow) (*7*), outputs of the GSOCseq v1.1 model (light blue) (*46*) and simulations of the ORCHIDEE-GM model (*45*) forced with changes in grazing intensity from our empirical model (Methods (*37*)). Error bars show standard deviations across Monte Carlo simulations (n=200).

Figure 2. Net-emissions mitigation potential with improved grazing intensity: Bars show the ecosystem carbon sequestration potential of improved grazing intensity potential by continent and the map shows ecosystem carbon sequestration potential (soil organic carbon (SOC) plus plant biomass) in global rangelands with improved grazing intensity (assuming dynamic responses of plant ANPP to grazing) **(A),** bars show the changes in 'other emissions' (feed emissions, livestock emissions and production emissions displacement) with improved grazing intensity broken down by flux type and the map shows total changes in other emissions (summed) **(B)**, bars show a comparison of ecosystem carbon sequestration potential (soil organic carbon plus plant biomass) and net-emissions changes or net-mitigation (negative emissions change values indicate an emissions sink or positive mitigation potential) and the map shows the difference or change in mitigation potential (%) between ecosystem carbon and net-emissions mitigation, with bar chart comparisons for countries at the extremes of mitigation potential change (negative % change values indicate net-emissions mitigation potential is lower than ecosystem carbon potential and vice versa), (**C**). All figures show emissions and sequestration annualized over an 11-year intervention period assuming livestock production is maintained at the country level and plant productivity responded dynamically to changes in grazing intensity (output of our 'core' scenario, see Methods *(37*)). Maps show median values, bars show mean values and error bars show standard deviations across Monte Carlo simulations (n=200).

Figure 3. Sensitivities to plant productivity response, spatial scales and trade assumptions: The effect of assumed grazing plant-productivity responses on distributions of plant-biomass consumed by livestock **(A),** ecosystem carbon sequestration potential **(B),** net-emissions changes **(C),** and livestock emissions changes **(D),** with improved grazing intensity globally across Monte Carlo simulations (n=200) (See Methods *(37*)). The Plant-Dynamic scenario assumes plant productivity is maximized at low-moderate grazing intensities, while the Plant-Proportional scenario assumes plant productivity remains constant across grazing intensities, with plant biomass stocks increasing or decreasing proportionally with changes in forage consumption. (See Figure S7 for further explanations of grazing-plant productivity relationships). The continent-level distributions of feed emissions changes when accounting for trade versus only considering the emissions intensity of domestic feed production **(E),** and the distribution of net-emissions changes across simulations when production is maintained at different spatial scales (local, country-level and global) **(F)**. Vertical colored bars show the mean of the distributions for Figures A-D, F and medians for Figure E, which span across Monte Carlo simulations (n=200) and are truncated for visualization.

Figure 4. Change in emissions mitigation potential across global grazing carbon credit projects: Map of change in emissions mitigation potential assuming livestock production is maintained under our 'core' scenario (Methods *(37*)) overlain with grazing carbon credit projects extracted from the Verified Carbon Standard Registry (*50*) (methodologies VM0032, VM0026, VM0042) where the size of points are scaled to the project-reported annual emissions reduction potential (carbon credit potential) and the shape of points

correspond with project status. Outset country values represent the change in emissions mitigation potential across a 100km radius buffer surrounding the centroid of Verified Carbon Standard grazing projects averaged across projects within each country and weighted by reported project emissions mitigation potential.