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Substituting beans for beef as a contribution toward US climate change targets

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Abstract Shifting dietary patterns for environmental benefits has long been advocated. In relation to mitigating climate change, the debate has been more recent, with a growing interest from policy makers, academics, and society. Many researchers have highlighted the need for changes to food consumption in order to achieve the required greenhouse gas (GHG) reductions. So far, food consumption has not been anchored in climate change policy to the same extent as energy production and usage, nor has it been considered within the context of achieving GHG targets to a level where tangible outputs are available. Here, we address those issues by performing a relatively simple analysis that considers the extent to which one food exchange could contribute to achieving GHG reduction targets in the United States (US). We use the targeted reduction for 2020 as a reference and apply published Life Cycle Assessment data on GHG emissions to beans and beef consumed in the US. We calculate the difference in GHGs resulting from the replacement of beef with beans in terms of both calories and protein. Our results demonstrate that substituting one food for another, beans for beef, could achieve approximately 46 to 74% of the reductions needed to meet the 2020 GHG target for the US. In turn, this shift would free up 42% of US cropland (692,918 km^2). While not currently recognized as a climate policy option, the "beans for beef" scenario offers significant climate change mitigation and other environmental benefits, illustrating the high potential of animal to plant food shifts.

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1 Introduction

Climate change is one of the defining public issues of our time, threatening crop yield in some regions, reducing access to water, increasing human toll due to weather extremes, and increasing the spread of infectious disease among a myriad of other, mostly adverse, effects (Stern 2007; Blanco et al. 2014). The Copenhagen Accord and Paris Agreement acknowledge that limiting global mean temperature rise to ≤2 °C above pre-industrial levels requires deep cuts in global greenhouse gas (GHG) emissions (UNEP 2011; UNFCCC 2015). Additionally, the Paris Agreement states that efforts to limit warming to no more than 1.5 °C are needed to significantly reduce the risks and impacts of climate change (UNFCCC 2015), requiring deeper cuts in global GHGs. Currently, climate change policy largely focuses on reducing carbon dioxide (CO_2) emissions, the dominant anthropogenic GHG (Solomon et al. 2007). Yet realizing ≤2 °C warming also requires major reductions in non-CO_2 GHG emissions (primarily methane (CH_4) and nitrous oxide (N_2O)) (Stehfest et al. 2009; Popp et al. 2010; Bajzelj et al. 2014; Blanco et al. 2014), especially in the near term (Ripple et al. 2014; Pierrehumbert and Eshel 2015). Globally, livestock farming accounts for ~15% of total anthropogenic GHG emissions (Gerber et al. 2013) and is the primary anthropogenic source of CH_4 and N_2O emissions, producing around 50 and 60%, respectively (Smith et al. 2007). This is particularly significant given that on a mass basis, CH_4 and N_2O have 25 and 298 times the centennial-mean global warming potential of CO_2 (Myhre et al. 2013). In addition, CH_4 has a much shorter atmospheric lifetime than CO_2 (9–12 years), enhancing its near-term prominence (Myhre et al. 2013) and highlighting the importance of early focus on livestock.

Livestock accounts for up to half of the technical GHG mitigation potential of the agriculture, forestry, and land-use sectors (Herrero et al. 2016). Yet even the most technologically possible GHG reductions (32%) are outpaced by increasing demand for meat (Gerber et al. 2013). In addition, due to adoption constraints, costs and numerous trade-offs only 10% of the livestock-related technical GHG mitigation potential is viable (Herrero et al. 2016). Without significant dietary shifts, food-related GHG emissions in 2050 would constitute half of the total emissions budget imposed by the 2 °C target (Springmann et al. 2016). Hedenus et al. (2014) have shown that food-related emissions could exceed the full emissions budget by as early as 2070. Hence, a dietary shift away from livestock products is most likely required in addition to technological reduction of agricultural GHG emissions (Hertwich et al. 2010; Popp et al. 2010; Bajzelj et al. 2014; Hedenus et al. 2014).

Modifying diets for environmental benefits has long been advocated (Gussow and Clancy 1986) and has been enjoying considerable attention recently (Stehfest et al. 2009; Scarborough et al. 2014; Green et al. 2015; Machovina et al. 2015; Lamb et al. 2016; Springmann et al. 2016). Despite this growing interest, so far, dietary choices have not been as central in climate change discourse as energy production and usage (Stehfest et al. 2009; Bailey et al. 2014; Bajzelj et al. 2014). The analysis presented here seeks to specifically assess the potential contribution of simple dietary changes toward achieving the US GHG emissions target for 2020, which we use as a reference. To keep the analysis tractable, we consider replacing one item, beef, the highest GHG emitting food item (Nijdam et al. 2012; Eshel et al. 2014), with beans, a lower GHG intensity food (Nijdam et al. 2012). This work is novel in that no other analysis has placed potential diet changes in the context of meeting country-wide GHG reduction targets.

2 Methods

The US President's Climate Change Plan sets out to reduce net US GHG emissions by 17% below 2005 levels (6438 million metric tons, mmt, of CO_2 equivalent, denoted CO_2e) by the year 2020 (EOP 2013). This target requires net 2020 GHG levels to remain below 5344 mmt CO_2e, a 7% reduction from current net emissions of 5791 mmt CO_2e (EPA 2015) (as the most recent data available, we refer to 2013 levels as "current emissions").

This analysis is based on replacing beef consumption with beans. Beef is the most GHG-intensive food item, with emissions ranging from 9 to 129 kg CO_2e/kg, whereas comparatively legumes result in 1–2 kg CO_2e/kg (Nijdam et al. 2012). In addition, legumes are a high protein food currently consumed at levels well below the US government's dietary recommendations (USDA 2012c; Moore and Thompson 2015). Legumes are therefore a natural option for substantially reducing GHG emissions while improving nutrition. We calculate the net emission change by taking the averted beef emissions and subtracting the emissions associated with producing the legume replacement. We use emission factors from US Life Cycle Assessments (LCA) of 40.2 kg CO_2e/kg beef and 0.8 kg CO_2e/kg beans (Nijdam et al. 2012). The beef LCA reflects typical US beef production, Midwestern feedlot finishing of range-weaned calves (Pelletier et al. 2010). Live to retail weight loss is accounted for, using a factor of 2.7 (Nijdam et al. 2012). As a sensitivity analysis, we also use a global average from Nijdam et al. (2012), of 25.5 kg CO_2e/kg beef and 1.1 kg CO_2e/kg beans, derived from a review of 52 LCA studies of meat and its alternatives (Nijdam et al. 2012). Because beef emission estimates vary widely, we use their geometric mean. The 52 LCAs included CO_2e emissions from the cultivation/farming process and transportation to retail. Additionally, the beef LCAs include direct and indirect N_2O emissions from feed production, CH_4 from enteric fermentation, N_2O and CH_4 from manure management, and carbon (C) emissions due to the slaughter process. GHGs from the production of farm machinery, changes in soil C emissions, and emissions related to land use change are not considered here. For both beans and beef, the bulk (>90%) of emissions occur during production (Nijdam et al. 2012). We consider the mass necessary to fully replace both kcals and protein delivered by beef with beans, using nutritional information for both beef (USDA 2015a) and beans (USDA 2015b), and report each separately. Beef provides 332 kcals and 14.4 g protein per 100 g of raw weight (USDA 2015a), and raw beans' corresponding values per 100 g are 341 kcals and 21.6 g protein (USDA 2015b) (we use raw weights because the emissions data apply to the retail level). The corresponding moisture content of the raw weights of beef and beans is 54 and 11%, respectively. The caloric equivalence ratio of substituting beans for beef is 0.97 (332 beef kcals divided by 341 bean kcals), and the protein mass ratio is 0.66 (14.4 g beef protein divided by 21.6 g bean protein). Consequently, we derive energy (kcal) and protein equivalence emissions factors using:

- US emissions, energy equivalence: 40.2 kg CO_2e/kg—(0.8 kg CO_2e/kg $\times 0.97$) = 39.4 kg CO_2e/kg
- US emissions, protein equivalence: 40.2 kg CO_2e/kg—(0.8 kg CO_2e/kg $\times 0.66$) = 39.7 kg CO_2e/kg
- Global emissions, energy equivalence: 25.5 kg CO_2e/kg—(1.1 kg CO_2e/kg $\times 0.97$) = 24.4 kg CO_2e/kg
- Global emissions, protein equivalence: 25.5 kg CO_2e/kg—(1.1 kg CO_2e/kg $\times 0.66$) = 24.8 kg CO_2e/kg

We next use US beef consumption data (USDA 2012b), converting carcass to retail weights following Nijdam et al. (2012). Finally, we obtain emission savings due to substituting beans for beef in the energy and protein equivalence by applying the above factors to US annual beef consumption, 8.4 mmt. We report results using both US specific and global GHG emission factors for beef and beans. As the US is a net exporter of beans (USDA 2012c) and beef (USDA 2012a), we assume that the consumption amounts in this analysis are relevant to the US GHG inventory and hence our "beans for beef" scenario is appropriate for considering as part of US GHG reduction efforts. We treat the envisioned dietary change in isolation, quantifying its effect as the only emission reduction measure implemented toward the 2020 target. We do not consider land use changes associated with converting pasture and cropland from beef into beans.

3 Results and discussion

Substituting beans for beef in the US diet would reduce CO_2e emissions by 334 mmt, accomplishing 75% of the 2020 reduction target. Using global emissions factors, the figures reduce to 209 mmt CO_2e and 47%, respectively (Table 1), due to large differences between US and global emissions factors (Fig. 1). The results are almost identical when conserving either protein mass or energy (Table 1).

Our findings demonstrate that substituting plant sourced foods for animal sourced foods can play an important role in climate change mitigation. While substituting beans for beef does not entirely satisfy the US GHG reduction targets, it could be combined with mitigation efforts for other major emitters such as power generation or transportation. While our estimate represents the upper bound, given the sizable contribution to the GHG reduction target, a lower level of uptake, i.e., less than 100%, would still provide an important contribution.

The example analyzed is particularly impactful for mitigating near-term global temperature rise (Rockstrom et al. 2009; Ripple et al. 2014). Radiative forcing in the short-term, i.e., over the next several decades, will be dominated by CH_4 due to its relatively short atmospheric lifetime (~9 years) in comparison to CO_2 (~100 years) and its much higher global warming potential (Myhre et al. 2013). Because we replace beef, a high CH_4 source, with beans, a relatively much lower CH_4 source, the expected resultant decline in radiative forcing and decline in decadal scale warming will be greater than that expected from current policies,

Table 1 Actual CO_2e reduction and percent of the US 2020 CO_2e target achieved by substituting beans for beef in the calorie and protein mass equivalence

Scenario	Beans for beef: energy equivalent		Beans for beef: protein mass equivalent	
	% contribution to 2020 US climate change target	CO_2e reduction (million metric tons)	% contribution to 2020 US climate change target	CO_2e reduction (million metric tons)
US specific LCA emissions factors	74	332	75	334
Global LCA emissions factors	46	206	47	209

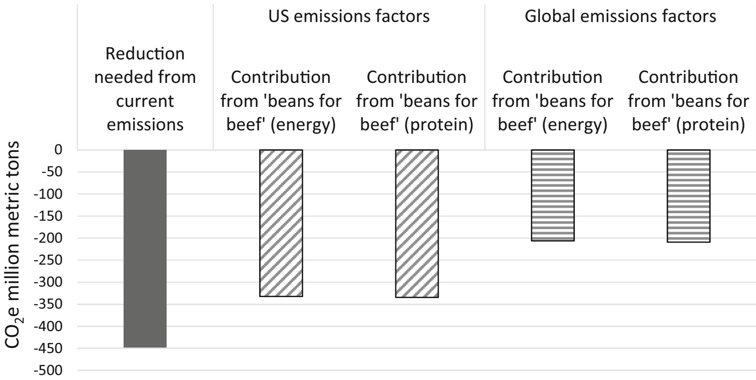

Fig. 1 Greenhouse gas reductions. CO_2e reductions needed to achieve US climate change targets set for 2020 (*solid box*), in comparison to the CO_2e reductions achieved from substituting beans for beef, by energy equivalence and protein weight equivalence using US emission factors (*diagonally hatched boxes*) and global emission factors (*horizontally hatched boxes*)

which focus almost exclusively on reducing CO_2 emissions (Pierrehumbert and Eshel 2015). However, to meet long-term GHG reduction targets, significant reductions of both CO_2 and non-CO_2 emissions are required (Blanco et al. 2014).

Although the goal of our analysis is to assess the potential of conceptually simple food substitutions to contribute to climate change goals, the resultant shifts—requiring societal level behavior change (Popp et al. 2010; Green et al. 2015)—are non-trivial and unprecedented at the national level. Policy innovation and experimentation, and economic incentives (Ripple et al. 2014) will likely be required to propel such shifts (Bajzelj et al. 2014). While a national substitution of beans for beef would be socially demanding, a strong willingness to make dietary changes for environmental improvements, including eliminating red meat, has been demonstrated (Bailey et al. 2014). For example, in 2014, Ipsos MORI (Market & Opinion Research International) conducted an online survey of at least 1000 individual consumers from each of the following countries: Brazil, China, France, Germany, India, Italy, Japan, Poland, Russia, South Africa, the UK, and the US (Bailey et al. 2014). Among those aware of the climate impact of meat, 44% were likely to reduce their meat consumption and 15% had already reduced their meat consumption. A public survey conducted by the UK government revealed that from over 3000 participants, 85% stated that they will or maybe will change their diets for environmental improvements, and 53% were willing to give up red meat (DEFRA 2011). Furthermore, consumer acceptance could possibly be increased by plant-based beef analogs (Hoek et al. 2011; Bailey et al. 2014) that have become more palatable, available and accepted, now being regularly availed by a third of US consumers (Mintel 2015). Because these meat analogs have very similar GHG emissions to the beans used in our analysis (Nijdam et al. 2012), if beef is replaced by meat analogs, we expect similar GHG reductions to those presented for replacing beef with beans. To further ease the implementation of such a policy, increasing awareness of the impacts food choices have on climate change and also on the urgency and importance of reducing the impacts of climate change are likely to be crucial (Stern 2007; Ripple et al. 2014; Bailey et al. 2014). Recent findings have demonstrated that people who are the most aware of the related climate impacts have a greater likeliness of having already reduced their meat consumption and a greater likeliness of reducing meat consumption in the future (Bailey et al. 2014). Highlighting the human health benefits related to such a policy could increase consumer interest (Stehfest et al. 2009; Bailey et al. 2014), particularly as health benefits have been a strong motivator for consumers purchasing meat analog products (Sadler 2004).

To provide further context to the analysis, replacing daily calories from beef could be achieved with 188 g (0.8 of a cup) of cooked black beans, which 87% of Americans currently consume below recommended levels (Moore and Thompson 2015). This shift will also reduce chronic disease burdens including heart disease, diabetes, and some meat-related cancers (Bouvard et al. 2015; Orlich et al. 2013) and increase dietary fiber intake, currently also below recommended or protective levels (Anderson et al. 2009; Orlich et al. 2013).

The GHG targets assessed here are less demanding in comparison to those recommended to stabilize global temperature increase below 2 °C (Gupta et al. 2007; UNEP 2011; UNFCCC 2015). We analyze beef-to-beans in this analysis purely as an illustration of the substantial emission reduction potential of a conceptually simple dietary shift. Future assessments could compare more stringent GHG reductions or sweeping dietary shifts.

The actual emission reduction needed to meet the 2020 target depends on the considered baseline emissions. For example, if we instead use the 2020 forecast (6206 mmt CO_2e) (USDS 2010), as the baseline, and estimate beef consumption for 2020 by applying current per capita consumption (8,428,000 metric tons for 308,745,538 people) to the projected 2020 US population (334,503,000 people) (USCB 2014), we get 9.1 mmt of beef (27.3 kg cap^{-1}×334,503,000 people). Inputting these figures into the methodology of section 2 changes our estimated contribution to meeting the 2020 target from 46–74 to 26–42%.

Given the focus on GHG reduction targets, the current analysis included GHG emissions as the sole environmental metric. A more comprehensive assessment would include the likely very significant impacts of substituting beans for beef on other resource use. For example, using the mean for US specific land-use factors from a published meta-analysis for beef (86.5 m^2/kg) and beans (4.4 m^2/kg) (Nijdam et al. 2012), substituting beans for beef in the US on a calorie equivalent basis will spare 692,918 km^2 of land, as an upper bound estimate. This land area is equivalent to 42% of cropland in the contiguous US, which is 1,650,745 km^2 (USDA 2011), and roughly 1.6 times the surface area of California. This type of land sparing is particularly relevant to climate change goals given the potential for enhancing carbon sequestration, which will likely augment GHG reductions (Lamb et al. 2016). By removing cattle from rangelands and pastures, the beef-to-beans shift would also benefit woody plant recruitment and biodiversity (Mishra et al. 2003; Pelletier and Tyedmers 2010; Phalan et al. 2011; Batchelor et al. 2015; Lamb et al. 2016), and substantially reduce water needs (Marlow et al. 2015), an increasingly important conservation issue under climate change (IPCC 2007; Cisneros et al. 2014). Beyond calories and protein, and the general health co-benefits mentioned above, our analysis did not rigorously account for any health and/or nutritional factors related to substituting "beans for beef." Future assessments could usefully include such health factors in an integrated assessment with environmental factors (Stehfest et al. 2009; Sabate et al. 2014; Green et al. 2015; Springmann et al. 2016).

While some have argued that there are climate and environmental benefits associated with livestock production in certain locales and practices (de Oliveira Silva et al. 2016; Teague et al. 2016), others have forcefully demonstrated the factual inconsistencies in these arguments (Beschta et al. 2013; Briske et al. 2013; Carter et al. 2014; Phalan et al. 2016).

One of the key strategies for effective climate change mitigation is informing, educating, and persuading individuals about what they can do (Stern 2007). Dietary shift is ideal in this respect as it ascribes a pivotal role to personal choice in achieving GHG reduction targets. Further strategies will likely prove necessary to assist consumer choice regarding dietary shifts, including gaining support from the food service industry and retail markets.

4 Conclusions

Key traits position livestock production as a prime target for climate policy. The significant contribution to global GHGs, the dominance of short-lived methane, and thus the relatively immediate impact compel dietary shifts away from livestock products as important tools for mitigating anthropogenic climate change and particularly for avoiding near-term global temperature rise. We further demonstrate this through our analysis, showing the significant GHG reductions deliverable through simple food substitutions such as "beans for beef," meeting up to 74% of the reductions needed to reach the 2020 GHG target for the US. Additional benefits include the sparing of 692,918 km^2, equivalent to 42% of US cropland.

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Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

References

Anderson JW, Baird P, Davis RH Jr, Ferreri S, Knudtson M, Koraym A, Waters V, Williams CL (2009) Health benefits of dietary fiber. Nutr Rev 67:188–205

Bailey R, Froggatt A, Wellesley L (2014) Livestock—climate change's forgotten sector global public opinion on meat and dairy consumption. Chatham House, London

Bajzelj B, Richards KS, Allwood JM, Smith P, Dennis JS, Curmi E, Gilligan CA (2014) Importance of food-demand management for climate mitigation. Nature Clim. Change 4:924–929

Batchelor J, Ripple W, Wilson T, Painter L (2015) Restoration of riparian areas following the removal of cattle in the Northwestern Great Basin. Environ Manag:1–13

Beschta RL, Donahue DL, DellaSala DA, Rhodes JJ, Karr JR, O'Brien MH, Fleischner TL, Deacon Williams C (2013) Adapting to climate change on western public lands: addressing the ecological effects of domestic, wild, and feral ungulates. Environ Manag 51:474–491

Blanco G, Eby M, Edmonds J, Fleurbaey M, Gerlagh R, Kartha S, Kunreuther H, Rogelj J, Schaeffer M, Sedláček J, Sims R, Ürge-Vorsatz D, Victor D, Yohe G (2014) Climate change 2014 synthesis report. Intergovernmental Panel on Climate Change. Fifth Assessment. Approved Summary for Policymakers, 1 November 2014

Bouvard V, Loomis D, Guyton KZ, Grosse Y, Ghissassi FE, Benbrahim-Tallaa L, Guha N, Mattock H, Straif K (2015) Carcinogenicity of consumption of red and processed meat. Lancet Oncol 16:1599–1600

Briske DD, Bestelmeyer BT, Brown JR, Fuhlendorf SD, Wayne Polley H (2013) The savory method can not green deserts or reverse climate change: a response to the Allan Savory TED video. Rangelands 35:72–74

Carter J, Jones A, Brien M, Ratner J, Wuerthner G (2014) Holistic management: misinformation on the science of grazed ecosystems. International Journal of Biodiversity 2014:10

Cisneros J, Oki BET, Arnell NW, Benito G, Cogley JG, Döll P, Jiang T, Mwakalila SS (2014) Freshwater resources. In: Field CB, Barros VR, Dokken DJ, Mach KJ, Mastrandrea MD, Bilir TE, Chatterjee M, Ebi KL, Estrada YO, Genova RC, Girma B, Kissel ES, Levy AN, MacCracken S, Mastrandrea PR, White LL (eds) In: Climate change 2014: impacts, adaptation, and vulnerability. Part A: global and sectoral aspects.

Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge and New York, pp 229–269

de Oliveira Silva R, Barioni LG, Hall JAJ, Folegatti Matsuura M, Zanett Albertini T, Fernandes FA, Moran D (2016) Increasing beef production could lower greenhouse gas emissions in Brazil if decoupled from deforestation. Nature Clim. Change 6:493–497

DEFRA (2011) Attitudes and behaviors around sustainable food purchasing. Department for Environment, Food, and Rural Affairs. Report (SERP 1011/10). April 2011

EOP (2013) The President's climate action plan. Executive office of the President. June 2013. The White House. Washington, US

EPA (2015) Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2013. U.S. Environmental Protection Agency. 1200 Pennsylvania Ave., N.W. Washington, DC 20460, U.S.A. April 15, 2015

Eshel G, Shepon A, Makov T, Milo R (2014) Land, irrigation water, greenhouse gas, and reactive nitrogen burdens of meat, eggs, and dairy production in the United States. Proc Natl Acad Sci 111:11996–12001

Gerber P, Steinfeld H, Henderson B, Mottet A, Opio C, Dijkman J, Falcucci A, Tempio G (2013) Tackling climate change through livestock—a global assessment of emissions and mitigation opportunities. Food and Agriculture Organization, Rome

Green R, Milner J, Dangour A, Haines A, Chalabi Z, Markandya A, Spadaro J, Wilkinson P (2015) The potential to reduce greenhouse gas emissions in the UK through healthy and realistic dietary change. Clim Chang 129:253–265

Gupta S, Tirpak D, Burger N et al (2007) Policies, instruments and co-operative arrangements. In: Metz B, Davidson OR, Bosch PR, Dave R, Meyer LA (eds) Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge

Gussow JD, Clancy KL (1986) Dietary guidelines for sustainability. J Nutr Educ 18:1–5

Hedenus F, Wirsenius S, Johansson DA (2014) The importance of reduced meat and dairy consumption for meeting stringent climate change targets. Clim Chang 1–13

Herrero M, Henderson B, Havlik P, Thornton PK, Conant RT, Smith P, Wirsenius S, Hristov AN, Gerber P, Gill M, Butterbach-Bahl K, Valin H, Garnett T, Stehfest E (2016) Greenhouse gas mitigation potentials in the livestock sector. Nature Clim. Change advance online publication

Hertwich E, van der Voet E, Tukker A (2010) Assessing the environmental impacts of consumption and production. Priority products and materials. United Nation Environment Program

Hoek AC, van Boekel MAJS, Voordouw J, Luning PA (2011) Identification of new food alternatives: how do consumers categorize meat and meat substitutes? Food Qual Prefer 22:371–383

IPCC (2007) Climate change 2007: impacts, adaptation and vulnerability. In: Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE (eds) Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge 976 pp

Lamb A, Green R, Bateman I, Broadmeadow M, Bruce T, Burney J, Carey P, Chadwick D, Crane E, Field R, Goulding K, Griffiths H, Hastings A, Kasoar T, Kindred D, Phalan B, Pickett J, Smith P, Wall E, zu Ermgassen EKHJ, Balmford A (2016) The potential for land sparing to offset greenhouse gas emissions from agriculture. Nature Clim. Change advance online publication

Machovina B, Feeley KJ, Ripple WJ (2015) Biodiversity conservation: the key is reducing meat consumption. Sci Total Environ 536:419–431

Marlow HJ, Harwatt H, Soret S, Sabaté J (2015) Comparing the water, energy, pesticide and fertilizer usage for the production of foods consumed by different dietary types in California. Public Health Nutr 18:2425–2432

Mintel (2015) Meat alternatives - US - June 2013. Mintel, London

Mishra C, Allen P, McCarthy TOM, Madhusudan MD, Bayarjargal A, Prins HHT (2003) The role of incentive programs in conserving the Snow Leopard el Papel de Programas de Incentivos en la Conservación del *Uncia uncia*. Conserv Biol 17:1512–1520

Moore LV, Thompson FE (2015) Adults meeting fruit and vegetable intake recommendations—United States, 2013. US Centers for Disease Control and Prevention. Morbidity and Mortality Weekly Report July 10 2015/64 (26); 709–713

Myhre G, Shindell D, Bréon FM, Collins W, Fuglestvedt J, Huang J, Koch D, Lamarque JF, Lee D, Mendoza B, Nakajima T, Robock A, Stephens G, Takemura T, Zhang H (2013) Anthropogenic and natural radiative forcing. In: Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds) Climate change 2013: the Physical Science Basis. Contribution of Working Group I to the Fifth assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge and New York

Nijdam D, Rood T, Westhoek H (2012) The price of protein: review of land use and carbon footprints from life cycle assessments of animal food products and their substitutes. Food Policy 37:760–770

Orlich MJ, Singh PN, Sabate J, Jaceldo-Siegl K, Fan J, Knutsen S, Beeson WL, Fraser GE (2013) Vegetarian dietary patterns and mortality in Adventist Health Study 2. JAMA Intern Med 173:1230–1238

Pelletier N, Tyedmers P (2010) Forecasting potential global environmental costs of livestock production 2000–2050. Proc Natl Acad Sci 107:18371–18374

Pelletier N, Pirog R, Rasmussen R (2010) Comparative life cycle environmental impacts of three beef production strategies in the Upper Midwestern United States. Agric Syst 103:380–389

Phalan B, Onial M, Balmford A, Green RE (2011) Reconciling food production and biodiversity conservation: land sharing and land sparing compared. Science 333:1289–1291

Phalan B, Ripple WJ, Smith P (2016) Increasing beef production won't reduce emissions. Glob Chang Biol 22: 3255–3256

Pierrehumbert RT, Eshel G (2015) Climate impact of beef: an analysis considering multiple time scales and production methods without use of global warming potentials. Environ Res Lett 10:085002

Popp A, Lotze-Campen H, Bodirsky B (2010) Food consumption, diet shifts and associated non-CO2 greenhouse gases from agricultural production. Glob Environ Chang 20:451–462

Ripple WJ, Smith P, Haberl H, Montzka SA, McAlpine C, Boucher DH (2014) Ruminants, climate change and climate policy. Nature Clim Change 4:2–5

Rockstrom J, Steffen W, Noone K, Persson A, Chapin FS 3rd, Lambin EF, Lenton TM, Scheffer M, Folke C, Schellnhuber HJ, Nykvist B, de Wit CA, Hughes T, van der Leeuw S, Rodhe H, Sorlin S, Snyder PK, Costanza R, Svedin U, Falkenmark M, Karlberg L, Corell RW, Fabry VJ, Hansen J, Walker B, Liverman D, Richardson K, Crutzen P, Foley JA (2009) A safe operating space for humanity. Nature 461:472–475

Sabate J, Sranacharoenpong K, Harwatt H, Wien M, Soret S (2014) The environmental cost of protein food choices. Public Health Nutr 1–7

Sadler MJ (2004) Meat alternatives—market developments and health benefits. Trends Food Sci Technol 15:250–260

Scarborough P, Appleby P, Mizdrak A, Briggs AM, Travis R, Bradbury K, Key T (2014) Dietary greenhouse gas emissions of meat-eaters, fish-eaters, vegetarians and vegans in the UK. Climat Chang 1–14

Smith P, D. Martino, Z Cai, D Gwary, H Janzen, P Kumar, B McCarl, S Ogle, F O'Mara, C Rice, B Scholes, O Sirotenko (2007) Agriculture. In: Metz B, Davidson OR, Bosch PR, Dave R, Meyer LA (eds) Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA

Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (2007) Climate Change 2007: The Physical Science Basis. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, IPCC Cambridge, United Kingdom and New York, USA, p 996

Springmann M, Godfray HCJ, Rayner M, Scarborough P (2016) Analysis and valuation of the health and climate change cobenefits of dietary change. Proc Natl Acad Sci

Stehfest EBL, van Vuuren DP, den Elzen MGJ, Eickhout B, Kabat P (2009) Climate benefits of changing diet. Climate Change 95:83–102

Stern N (2007) The economics of climate change: the Stern review. Cambridge University Press, Cambridge and New York

Teague WR, Apfelbaum S, Lal R, Kreuter UP, Rowntree J, Davies CA, Conser R, Rasmussen M, Hatfield J, Wang T, Wang F, Byck P (2016) The role of ruminants in reducing agriculture's carbon footprint in North America. J Soil Water Conserv 71:156–164

UNEP (2011) The emissions gap report: are the Copenhagen Accord pledges sufficient to limit global warming to 2 °C or 1.5 °C? A preliminary assessment. United Nations Environment Programme

UNFCCC (2015) Conference of the parties. Twenty-first session. United Nations Framework Convention on Climate Change. Paris, 30 November to 11 December 2015

USCB (2014) Unites States Census Bureau. 2014 National Population Projections: Summary Tables. Table 1. Projections of the Population and Components of Change for the United States: 2015 to 2060. Available at: http://www.census.gov/population/projections/data/national/2014/summarytables.html

USDA (2011) Cropland, 1945–2007, by State: the sum of cropland used for crops, cropland idled, and cropland used for pasture. Dataset. United States Department of Agriculture Economic Research Service. Available at: http://www.ers.usda.gov/data-products/major-land-uses/.aspx#25964

USDA (2012a) U.S. Department of Agriculture, Foreign Agricultural Service, Livestock and Poultry: World Markets and Trade, annual. Table 1376. Meat Production by Type and Country: 2009 and 2010. In: U.S. Census Bureau, Statistical Abstract of the United States: 2012. See also <http://www.fas.usda.gov/currwmt.asp>

USDA (2012b) U.S. Department of Agriculture, Foreign Agricultural Service, Livestock and Poultry: World Markets and Trade, annual. Table 1377. Meat Consumption by Type and Country: 2009 and 2010. In: U.S. Census Bureau, Statistical Abstract of the United States: 2012. See also <http://www.fas.usda.gov/currwmt.asp>

USDA (2012c) Vegetables and pulses. Dry beans. United States Department of Agriculture Economic Research Service. http://www.ers.usda.gov/topics/crops/vegetables-pulses/dry-beans.aspx

USDA (2015a) National Nutrient Database for Standard Reference Release 27. Basic Report: 13498, Beef, ground, 70% lean meat / 30% fat, raw. United States Department of Agriculture. Agricultural Research Service

USDA (2015b) National Nutrient Database for Standard Reference Release 27. Basic Report: 16014, Beans, black, mature seeds, raw. United States Department of Agriculture. Agricultural Research Service

USDS (2010) United States Department of State. U.S. Climate Action Report 2010. Washington: Global Publishing Services, June 2010