CLIMATE POLICY
https://doi.org/10.1080/14693062.2018.1528965

Taylor & Francis
Taylor & Francis Group

OUTLOOK ARTICLE

Including animal to plant protein shifts in climate change mitigation policy: a proposed three-step strategy

Helen Harwatt

Farmed Animal Law and Policy Fellow, Animal Law & Policy Program, Harvard Law School, Harvard University, Cambridge, MA, USA

ABSTRACT

Strong and rapid greenhouse gas (GHG) emission reductions, far beyond those currently committed to, are required to meet the goals of the Paris Agreement. This allows no sector to maintain business as usual practices, while application of the precautionary principle requires avoiding a reliance on negative emission technologies. Animal to plant-sourced protein shifts offer substantial potential for GHG emission reductions. Unabated, the livestock sector could take between 37% and 49% of the GHG budget allowable under the 2°C and 1.5°C targets, respectively, by 2030. Inaction in the livestock sector would require substantial GHG reductions, far beyond what are planned or realistic, from other sectors. This outlook article outlines why animal to plant-sourced protein shifts should be taken up by the Conference of the Parties (COP), and how they could feature as part of countries' mitigation commitments under their updated Nationally Determined Contributions (NDCs) to be adopted from 2020 onwards. The proposed framework includes an acknowledgment of 'peak livestock', followed by targets for large and rapid reductions in livestock numbers based on a combined 'worst first' and 'best available food' approach. Adequate support, including climate finance, is needed to facilitate countries in implementing animal to plant-sourced protein shifts.

ARTICLE HISTORY
Received 12 March 2018
Accepted 21 September 2018

KEYWORDS
Climate change mitigation; climate policy; Paris agreement; COP 24; animal to plant-protein shifts; animal agriculture

Key policy insights

- Given the livestock sector's significant contribution to global GHG emissions and methane dominance, animal to plant protein shifts make a necessary contribution to meeting the Paris temperature goals and reducing warming in the short term, while providing a suite of co-benefits.
- Without action, the livestock sector could take between 37% and 49% of the GHG budget allowable under the 2°C and 1.5°C targets, respectively, by 2030.
- Failure to implement animal to plant protein shifts increases the risk of exceeding temperate goals; requires additional GHG reductions from other sectors; and increases reliance on negative emissions technologies.
- COP 24 is an opportunity to bring animal to plant protein shifts to the climate mitigation table.
- Revised NDCs from 2020 should include animal to plant protein shifts, starting with a declaration of 'peak livestock', followed by a 'worst first' replacement approach, guided by 'best available food'.

1. Introduction

The Paris Agreement represents a landmark in international efforts to combat climate change, with almost all the world's nations pledging to keep global average temperature rise to 'well below' 2°C above pre-industrial levels, and ideally to no more than 1.5°C (UNFCCC, 2015). However, current unconditional commitments to

CONTACT Helen Harwatt hharwatt@gmail.com

the Paris Agreement are consistent with a 3.2°C rise this century, or a 3°C rise if conditional commitments are also factored in (UNEP, 2017), but could be as high as 3.7°C according to some climate prediction models (Brown & Caldeira, 2017).

If current commitments to the Paris Agreement are implemented, the greenhouse gas (GHG) emissions budget consistent with 1.5°C will be well depleted by 2030, by which point the budget consistent with staying below 2°C this century will be almost exceeded (UNEP, 2017). Hence, for the Paris goals to remain achievable, strong and rapid pre-2020 and pre-2030 mitigation is urgently required, in addition to enhanced longer term commitments (UNEP, 2017).

When emissions are assessed over this timeframe, that is, up to 2030, methane (CH_4) is slightly more abundant than carbon dioxide (CO_2) due to its relatively potent short-term warming impact (85 times greater Global Warming Potential than CO_2 over a 20 year time frame) (Myhre et al., 2013). CH_4 is responsible for around 24% of today's positive radiative forcing (proxy for today's warming) (Myhre et al., 2013), and CH_4 reduction has been identified as a relatively quick way of contributing to climate goals, due to its short atmospheric lifetime (∼10 years), and potential to reduce the risk of exceeding temperature goals (Montzka, Dlugokencky, & Butler, 2011; Ripple et al., 2014; Shindell et al., 2017). Hence, when assessing GHG reductions up to 2030, it is imperative to consider CH_4 emissions, in addition to CO_2. Achieving the central aim of the Paris Agreement will become increasingly difficult if reductions in CH_4 emissions are not also addressed strongly and rapidly (Saunois, Jackson, Bousquet, Poulter, & Canadell, 2016).

The main source of CH_4 emissions, the agricultural sector, has so far laid relatively low in the climate change policy arena, with the energy sector receiving most attention (Bajzelj et al., 2014). This is largely due to a focus on the most dominant GHG in terms of warming impact over the long term, CO_2 (IPCC, 2013). However, the scale of GHG reductions required leaves no sector to business as usual practices, including energy *and* agriculture (Blanco et al., 2014; Kuramochi et al., 2017; Richards, Wollenberg, & van Vuuren, 2018). An important consideration to support this statement is the assumed use of Negative Emissions Technologies (NETs) in the 2nd half of this century, to achieve the Paris Agreement. NETs are expected to remove carbon from the atmosphere and store it permanently, mainly via Bio Energy with Carbon Capture and Storage (BECCS), afforestation and reforestation, biochar, Carbon Capture and Storage (CCS), and enhanced soil carbon absorption. There are numerous challenges with NETs, including the large land requirements and competition for water resources, potentially threatening food security and biodiversity; the unproven and undeveloped nature of the technologies at the scale required; the risk of reversal/emissions release post-implementation (Larkin, Kuriakose, Sharmina, & Anderson, 2017; UNEP, 2016); and the strong possibility of overshooting the Paris temperature goals while waiting for NETs to become effective, in turn potentially triggering numerous system tipping points including the Greenland and West Antarctic ice sheets (Boysen et al., 2017; Rahmstorf & Levermann, 2017; Steffen et al., 2018). While NETs might be considered an important strategy to help achieve the Paris Agreement (particularly the 1.5°C goal), (van Vuuren et al., 2018), due to these severe trade-offs, large scale deployment of NETs cannot provide a viable alternative to steep and rapid emissions reductions through other means (Boysen et al., 2017). The precautionary principle states that '*Parties should take precautionary measures to anticipate, prevent or minimize the causes of climate change and mitigate its adverse effects*' (Article 3.3, UNFCCC, 1992). Hence, carbon budgets must be adhered to, and a wide range of mitigation options explored, without relying on uncertain measures such as NETs.

Meeting the Paris Agreement's temperature goal requires anthropogenic GHG emissions to peak as soon as possible, then achieve net zero levels this century, possibly by 2050, which implies deep reductions of not only CO_2 but also other major GHGs, CH_4 and N_2O. The updating of nationally-determined contributions (NDCs) from 2020 is a crucial step – this is the final opportunity to bring emissions in line with the Paris Agreement's temperature goals. A commitment to strong and rapid reductions up to 2030 must be included (UNEP, 2017). Subsequently, the following sections demonstrate the necessity of adopting near term mitigation options in the agricultural sector, and a proposed overarching approach. Co-benefits of, and support required to implement the proposed actions are also outlined. It is assumed throughout that the proposed actions in the agricultural sector are implemented in addition to, rather than instead of, strong action in other sectors.

2. The crucial role of agriculture in meeting the Paris Agreement

Agriculture is a prime option for GHG mitigation, accounting for 24% of total GHG emissions and being the main source of CH_4 and N_2O (Smith et al., 2014). GHG emissions from agriculture are dominated by livestock, which is itself the highest global source of CH_4 and N_2O. CH_4 emissions from the livestock sector are expected to increase by 60% by 2030 (Smith et al., 2007), the same time period when strong and rapid GHG reductions are needed (UNEP, 2017). Also problematic is a forecast growth in production across the entire livestock sector of 70% by 2050 (Alexandratos & Bruinsma, 2012).

In terms of temperature impact, the livestock sector is estimated to account for at least 23% of total warming in 2010 (positive radiative forcing in 2010 compared to pre-industrial conditions). This figure is an underestimate, omitting the majority of emissions related to feed production (including land use change), fertilizer use, energy and transport (Reisinger & Clark, 2017). Key traits position livestock reduction as an attractive option for both achieving long term GHG reduction goals and avoiding near term global temperature rise. These include the significant contribution of livestock production to global GHGs (at least 16.5% (FAO, 2018)), the dominance of CH_4 which has a relatively short atmospheric lifetime but potent warming impact, and the relatively short timeframe needed to achieve significant reductions. Livestock reduction should therefore feature centrally for climate mitigation policy in the agricultural sector.

While technological and management improvements could reduce livestock emissions by around a third, these benefits are being outpaced by increased demand for livestock products, and due to various adoption constraints, only around 10% of the potential livestock-related technical GHG mitigation is viable (Gerber et al., 2013; Herrero et al., 2016). A reduction in production levels is therefore needed to achieve greater GHG emission cuts (Bryngelsson, Wirsenius, Hedenus, & Sonesson, 2016; Hedenus, Wirsenius, & Johansson, 2014; Herrero et al., 2015; Herrero et al., 2016). The potential is substantial – full implementation of animal to plant protein shifts could reduce food related GHGs by 70% globally, by 2050 (Springmann, Godfray, Rayner, & Scarborough, 2016).

Without mitigation action, by 2030, the livestock sector could account for 27% to 49% of the emissions budget (19–34 billion metric tons CO_2e) associated with a >66% chance of achieving the 1.5°C target; assuming that emissions from the livestock sector increase at 0.07% per year, reaching 9.31 bmt CO_2e by 2030, which is likely an underestimated growth rate (Gerber et al., 2013; Smith et al., 2014; UNEP, 2017). For a >66% chance of staying below 2°C, the livestock sector could take 22–37% of the allowable emissions budget (25–43 bmt CO_2e) in 2030 (UNEP, 2017; Vrontisi et al., 2016). Hence, inaction in the livestock sector would require much steeper reductions from other sectors. This will be very challenging, especially given the long lock-in period associated with technology change in the fossil fuel sector (around 20 years) (IEA, 2013). Therefore, while countries plan their enhanced contributions to the Paris Agreement for 2020 onwards, livestock replacement should be included as a key measure. The following section sets out a potential overarching approach to this end.

3. An overarching three-step strategy for including animal to plant –sourced protein shifts in climate policy

The proposed course of action for tackling livestock replacement described here is guided by best available science to necessarily deliver large and rapid GHG reductions. Steps 1, 2 and 3 provide an overarching framework for addressing mitigation options in the short term and beyond, through animal to plant protein shifts. Policy makers can use the 3-step approach to structure animal to plant protein shifts, and subsequently identify context specific/relevant implementation policies.

3.1. Peak livestock – step 1

The global livestock population is at an all-time high of 28 billion animals, dominated by chickens which account for 82%. Over the past 20 years, the farmed chicken population has risen from 14 billion to 23 billion animals. Cattle have increased from 1.3 billion to 1.5 billion animals, sheep have increased from 1 billion to 1.2 billion animals, ducks from 0.9 billion to 1.2 billion animals, goats from 0.7 billion to 1 billion animals, and pigs from

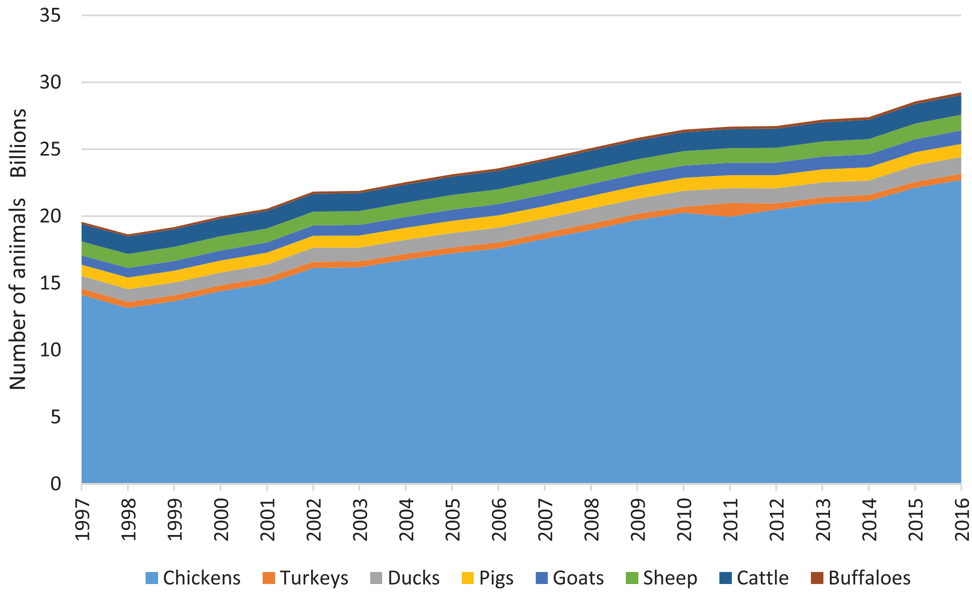

Figure 1. Number of farm animals (world total) 1997–2016.

0.8 billion to 1 billion animals (FAO, 2016) (Figure 1). These numbers continue to increase and are expected to rise substantially as global population grows and increasing affluence drives changes in consumer preferences, particularly in developing economies (Bajzelj et al., 2014; Godfray et al., 2018). The first step for policymakers in terms of making commitments for GHG emission reductions from livestock is to acknowledge 'peak' livestock, meaning that the current numbers are at their peak and will henceforth decline. In line with the Paris Agreement, it is recognized that peaking may take longer for developing countries (UNFCCC, 2015).

3.2. 'Worst first' approach – step 2

Following peak livestock, as a logical starting point in a transition away from livestock products, foods associated with the highest GHGs could be replaced first. This 'worst first' transition would therefore replace the highest emitting livestock product, and use the lessons learnt from this to assist in subsequent transitions away from the next largest emitter. For example, at the global level, beef accounts for the largest GHG footprint, followed by cow milk, pig meat, chicken meat, buffalo milk and chicken eggs (Table 1). Hence, the worst first approach based on global emissions would focus on beef, followed by cow milk and so on according to Table 1. At the country level, it is important to assess GHG inventories by animal species and products as it could be possible that, for example, sheep rather than cattle are the highest emitters in some places due to the amount of production. Replacement targets could be set according to GHG budgets, the potential for GHG reductions, and the pace of change that would be possible in terms of implementing animal to plant protein shifts.

3.3. Best available food – step 3

This concept is adopted from the pollution control strategy 'best available technology' and should accompany the 'worst first' approach to inform food replacement. For example, the suitability of replacements for livestock products can be assessed against a range of criteria including GHGs and other environmental impacts such as water and land use, and public health impacts. Nutritious foods high in protein are likely to be important replacements, such as beans which produce 46 times less GHGs in comparison to beef, on a protein equivalent basis (Gerber et al., 2013; Nijdam, Rood, & Westhoek, 2012). Replacing beef with beans can contribute significantly to GHG targets and provides an example of the 'worst first/best available food' approach. For example, in the

Table 1. Global greenhouse gas emissions (million metric tonnes CO_2e) from the 12 most highly produced livestock products.

Product	Quantity of production: million metric tonnes of carcass weight[a]	Greenhouse gases: CO_2e /kg (carcass weight meat and fat and protein corrected milk)[b]	Emissions (million metric tonnes CO_2e)[c]	Proportion of global CO_2e emissions (%)[d]
Beef (including veal)	66	46.2	3,048	5.86
Cow milk	659	2.8	1,846	3.55
Pig meat	118	6.1	721	1.39
Chicken meat	107	5.4	579	1.11
Buffalo milk	111	3.4	377	0.73
Chicken eggs	74	3.7	273	0.53
Sheep meat	9	23.8	222	0.43
Buffalo meat	4	53.4	204	0.39
Goat meat	6	23.8	134	0.26
Goat milk	15	6.5	99	0.19
Sheep milk	10	6.5	67	0.13
Turkey meat	6	5.4	33	0.06
Duck meat	5	5.4	24	0.05
Total			**7,627**	**14.7**

[a]Product yield data from FAOSTAT (FAO, 2016).
[b]GHG emission factors for each product from the FAO (Gerber et al., 2013), calculated using a 100 year accounting timeframe.
[c]Calculated by multiplying production weight by emissions factor.
[d]From a global total of 52,000 million metric tonnes CO_2e.

United States, substituting beans for beef at the national level could deliver up to 75% of the 2020 GHG reduction target and spare an area of land 1.5 times the size of California, with no loss of protein or calories to the food system (Harwatt, Sabaté, Eshel, Soret, & Ripple, 2017). On an equal protein basis, beans also have a very similar amino acid profile to beef, and contain more iron and calcium, provide fibre and no cholesterol (USDA, 2016a, 2016b). In situations where a like-for-like replacement is most suitable, plant-based meat and milk analogues that look and taste like their animal-sourced alternatives could play an important role and have a lower GHG footprint (similar to pulses) (Nijdam et al., 2012; Schösler, de Boer, & Boersema, 2012).

4. Co-benefits of including animal to plant –sourced protein shifts in climate policy

Climate change is expected to reduce food availability across the world, resulting in around half a million deaths by 2050 (Springmann, Mason-D'Croz, et al., 2016). Food security is a key consideration in the Paris Agreement: '*Recognizing the fundamental priority of safeguarding food security and ending hunger, and the particular vulnerabilities of food production systems to the adverse impacts of climate change*' (UNFCCC, 2015). Animal to plant-sourced protein shifts have the potential to increase food security in numerous ways. Globally, 77% of agricultural land is used for animal agriculture, which in turn provides 17% of calories and 33% of protein for global consumption (Roser & Ritchie, 2018). Crops grown for human consumption use 23% of agricultural land in exchange for 83% of calories and 67% of protein for global consumption (Roser & Ritchie, 2018). Plant-sourced alternatives to livestock products, such as beans, tend to require far fewer natural resources including land, nitrogen, phosphorus, water and energy, and result in lower GHG emissions (Eshel, Shepon, Makov, & Milo, 2014; Nijdam et al., 2012; Poore & Nemecek, 2018; Sabate, Sranacharoenpong, Harwatt, Wien, & Soret, 2014). Feed conversion is a major issue – globally a third of all calories produced are fed to animals with only 12% of those calories returning as livestock products such as meat and milk (Cassidy, West, Gerber, & Foley, 2013) – a loss of 29% of all calories produced globally. A recent analysis applied a health-sensitive approach to animal to plant-sourced food shifts and found this would involve changes in agricultural systems away from feed crops to crops that constitute healthy alternatives for human consumption, such as legumes, fruits and vegetables. Taking this approach in the US would feed an additional 350 million people, in comparison to the current food system (Shepon, Eshel, Noor, & Milo, 2018). At the level of individual foods, to deliver 1 calorie of beef to the food system requires 37 calories of plants, 1 calorie of pork requires 12 calories of plants, 1 calorie of chicken requires 9 plant calories, 1 calorie of eggs and 1 calorie of dairy each require 6 plant calories (Eshel et al., 2014). Switching from animal to plant proteins can actually increase, not decrease, global protein supply, in addition to reducing GHG emissions and land use (Bryngelsson et al., 2016).

Reducing the production of livestock and restoring land spared to its natural habitat can potentially contribute to carbon sequestration, as a supplement to strong and rapid GHG reductions. For example, in the UK, a 50% reduction in the production of calories from animal products combined with restoring the land to its natural habitat and vegetation could deliver an 80% reduction of UK GHGs from 1990 levels (Lamb et al., 2016). Bryngelsson et al. (2016) estimated the carbon sequestration potential of various dietary configurations and demonstrated that only shifting to a food system based entirely on plants in Sweden could deliver a net negative GHG balance, with sequestration of around 125 kg CO_2 per person per year over a 100 year time frame.

Since 1960, animal agriculture has caused 65% of land use change globally (Alexander et al., 2015), in order to grow feed crops for farmed animals, and to house farmed animals (in pasture and feedlots), at the expense of native forest, grasslands or savannah (Stoll-Kleemann & Schmidt, 2017). Animal agriculture is responsible for the majority of eutrophication and subsequent creation of 'dead zones', being linked to 72% of phosphorus and 63% of nitrogen pollution (from farm animal manure and chemical fertilizers applied to farm animal feed crops) (Pelletier & Tyedmers, 2010). A recent analysis estimates that a global shift from animal to arable agriculture could reduce the land use footprint of food by 76%, and eutrophication by 49% (using 2010 as the reference year) (Poore & Nemecek, 2018).

Animal to plant-sourced protein shifts can deliver numerous co-benefits to biodiversity and human health, in addition to financial cost savings through reduced health care requirements (Godfray et al., 2018; Machovina, Feeley, & Ripple, 2015; Springmann, Godfray, et al., 2016). Such co-benefits could form the basis of joined up policy making across multiple Sustainable Development Goals (SDGs), integrating climate, health and environmental policies.

5. Supporting measures required for implementing animal to plant-sourced protein shifts

Animal to plant-sourced protein shifts deliver maximum benefits if implemented in the near term, providing the greatest hedge against a high climate response and in turn reducing the adaptation and damage costs of climate change impacts. Early mitigation reduces the financial costs of implementation, in comparison to delaying action to the long term (Cai, Lenton, & Lontzek, 2016; Campbell et al., 2017; Millar et al., 2017). Hence, supporting measures should be provided in the near term, starting with a strategic focus on how best to facilitate animal to plant-sourced protein shifts at the 24th session of the Conference of the Parties (COP 24).

Countries should be permitted to request financial aid to adopt animal to plant-sourced protein shifts as a climate change mitigation measure, under the same process that they can request support for technologically-focused carbon reduction measures. For countries where climate finance is not required, a focus on subsidy restructuring to support livestock producers and feed growers to transition their businesses would most likely be needed. Ensuring food producers are adequately educated and skilled for the transition is a key support measure. Support and action should be inclusive of subnational and non-state actors, including regional and local governments and businesses (UNEP, 2017). Such actors could also adopt the three-step strategy (peak livestock, worst-first combined with best available food), in their production and/or purchasing policies. This might produce a different list of priorities, for example for a food service provider compared to a national GHG inventory, where chicken or pig meat might be an early focus due to purchase quantities.

Financial incentives for food manufacturers to supply adequate quantities and types of livestock replacement products, such as for meat and milk, could be important particularly in countries with high consumption of animal products. Educating consumers could support the global transition. People with an awareness of the environmental impacts of livestock products have a higher likelihood of having already reduced their consumption, or reducing in the future (Bailey, Froggatt, & Wellesley, 2014). Developing education materials for a range of audiences may be helpful, including the food industry and national curriculum programmes for schools, colleges and universities.

6. Conclusion

The agriculture sector offers substantial potential for greenhouse gas (GHG) emissions reductions, and numerous co-benefits, through animal to plant-sourced protein shifts. Unabated, the livestock sector could take between 37% and 49% of the emissions budget allowable under the 2°C and 1.5°C target, respectively, by the end of the next decade. Hence, inaction in the livestock sector means substantial GHG reductions, far beyond what is planned or realistic, for other sectors. The next 12 years are crucial – beginning the process of animal to plant-sourced protein shifts should be taken up at COP 24, and feature in countries' revised NDCs from 2020 onwards. Action on animal to plant protein shifts can also be spearheaded by subnational and non-state actors, including regional and local governments and businesses.

The global livestock population is at an all-time high – currently at 28 billion animals and rising. The proposed three-step strategy for including animal to plant-sourced protein shifts in climate policy begins with an acknowledgment of peak livestock, closely followed by large and rapid reductions in livestock numbers based on a combined 'worst first' and 'best available food' approach, replacing the highest emitting foods with alternatives that provide maximum environmental and health benefits. At the global level, this would firstly entail a 'beans for beef' switch, or similar, as beef currently has the largest GHG footprint in the livestock sector, followed by cow milk. The order of 'worst first' may differ between countries and should be identified through national GHG inventories. The key recommendation is to base animal to plant-sourced protein shifts on a science-guided approach for achieving large and rapid GHG reductions together with maximum provisions for supplementary carbon sequestration through restoring ecosystems to their natural states, and delivery of co-benefits in relation to biodiversity, food security and public health. Such co-benefits provide opportunities for joined up policy making across multiple SDGs. Adequate support will be needed to facilitate countries in implementing animal to plant-sourced protein shifts. Future research needs include the identification of detailed transition pathways for animal to plant-sourced protein shifts, including targets, policy measures, time-frames, and quantification of co-benefits.

Acknowledgements

I am grateful to three anonymous reviewers and Dr Depledge for their careful reviews and suggestions.

Disclosure statement

No potential conflict of interest was reported by the author.

References

Alexander, P., Rounsevell, M. D. A., Dislich, C., Dodson, J. R., Engström, K., & Moran, D. (2015). Drivers for global agricultural land use change: The nexus of diet, population, yield and bioenergy. *Global Environmental Change*, *35*, 138–147.

Alexandratos, N., & Bruinsma, J. (2012). *World agriculture towards 2030/2050: The 2012 revision* (ESA Working paper No. 12-03). Rome: FAO.

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

Bajzelj, B., Richards, K. S., Allwood, J. M., Smith, P., Dennis, J. S., Curmi, E., & Gilligan, C. A. (2014). Importance of food-demand management for climate mitigation. *Nature Climate Change*, *4*, 924–929.

Blanco, G., Eby, M., Edmonds, J., Fleurbaey, M., Gerlagh, R., Kartha, S., … Yohe, G. (2014, November 1). *Climate change 2014 synthesis report*. Intergovernmental Panel on Climate Change. Fifth Assessment. Approved Summary for Policymakers.

Boysen, L. R., Lucht, W., Gerten, D., Heck, V., Lenton, T. M., & Schellnhuber, H. J. (2017). The limits to global-warming mitigation by terrestrial carbon removal. *Earth's Future*, *5*, 463–474.

Brown, P. T., & Caldeira, K. (2017). Greater future global warming inferred from Earth's recent energy budget. *Nature*, *552*, 45–50.

Bryngelsson, D., Wirsenius, S., Hedenus, F., & Sonesson, U. (2016). How can the EU climate targets be met? A combined analysis of technological and demand-side changes in food and agriculture. *Food Policy*, *59*, 152–164.

Cai, Y., Lenton, T. M., & Lontzek, T. S. (2016). Risk of multiple interacting tipping points should encourage rapid CO_2 emission reduction. *Nature Climate Change*, *6*, 520–525.

Campbell, B. M., Beare, D. J., Bennett, E. M., Hall-Spencer, J. M., Ingram, J. S. I., Jaramillo, F. … Shindell, D. (2017). Agriculture production as a major driver of the Earth system exceeding planetary boundaries. *Ecology and Society*, *22*(4). doi:10.5751/ES-09595-220408

Cassidy, E., West, P., Gerber, J., & Foley, J. (2013). Redefining agricultural yields: From tonnes to people nourished per hectare. *Environmental Research Letters*, *8*, 034015.

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. *Proceedings of the National Academy of Sciences*, *111*, 11996–12001.

FAO. (2016). *FAOSTAT*. Live animals 2016. Retrieved from http://www.fao.org/faostat/en/#data/QA
FAO. (2018). *Global Livestock Environmental Assessment Model*. Version 2.0. Revision 5. July 2018. United Nations Food and Agriculture Organization.
Gerber, P., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., … Tempio, G. (2013). *Tackling climate change through livestock – A global assessment of emissions and mitigation opportunities*. Rome: Food and Agriculture Organization.
Godfray, H. C. J., Aveyard, P., Garnett, T., Hall, J. W., Key, T. J., Lorimer, J. … Jebb, S. A. (2018). Meat consumption, health, and the environment. *Science*, *361 (6399)*, pii: eaam5324.
Harwatt, H., Sabaté, J., Eshel, G., Soret, S., & Ripple, W. (2017). Substituting beans for beef as a contribution toward US climate change targets. *Climatic Change*, *143*, 261–270.
Hedenus, F., Wirsenius, S., & Johansson, D. A. (2014). The importance of reduced meat and dairy consumption for meeting stringent climate change targets. *Climatic Change*, *124*, 1–13.
Herrero, M., Henderson, B., Havlik, P., Thornton, P. K., Conant, R. T., Smith, P., … Stehfest, E. (2016). Greenhouse gas mitigation potentials in the livestock sector. *Nature Climate Change*. advance online publication.
Herrero, M., Wirsenius, S., Henderson, B., Rigolot, C., Thornton, P., Havlík, P., … Gerber, P. J. (2015). Livestock and the environment: What have we learned in the past decade? *Annual Review of Environment and Resources*, *40*, 177–202.
IEA. (2013). Key World Energy Statistics 2012, IEA, Paris, https://doi.org/10.1787/key_energ_stat-2012-en.
IPCC. (2013). Summary for policymakers. In T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, & A. Nauels (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, UK and New York, NY: Cambridge University Press.
Kuramochi, T., Höhne, N., Schaeffer, M., Cantzler, J., Hare, B., Deng, Y., … Blok, K. (2017). Ten key short-term sectoral benchmarks to limit warming to 1.5°C. *Climate Policy*, *18*, 287–305.
Lamb, A., Green, R., Bateman, I., Broadmeadow, M., Bruce, T., Burney, J., … Balmford, A. (2016). The potential for land sparing to offset greenhouse gas emissions from agriculture. *Nature Climate Change*. advance online publication
Larkin, A., Kuriakose, J., Sharmina, M., & Anderson, K. (2017). What if negative emission technologies fail at scale? Implications of the Paris Agreement for big emitting nations. *Climate Policy*, *18*, 1–25.
Machovina, B., Feeley, K. J., & Ripple, W. J. (2015). Biodiversity conservation: The key is reducing meat consumption. *Science of The Total Environment*, *536*, 419–431.
Millar, R. J., Fuglestvedt, J. S., Friedlingstein, P., Rogelj, J., Grubb, M. J., Matthews, H. D., … Allen, M. R. (2017). Emission budgets and pathways consistent with limiting warming to 1.5°C. *Nature Geoscience*, *10*, 741–747.
Montzka, S. A., Dlugokencky, E. J., & Butler, J. H. (2011). Non-CO_2 greenhouse gases and climate change. *Nature*, *476*, 43–50.
Myhre, G., Shindell, D., Bréon, F. M., Collins, W., Fuglestvedt, J., Huang, J. … Zhang, H. (2013). Anthropogenic and natural radiative forcing. In T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, & P. M. Midgley (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* (pp. 659–740). Cambridge, UK and New York, NY: Cambridge University Press.
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.
Pelletier, N., & Tyedmers, P. (2010). Forecasting potential global environmental costs of livestock production 2000–2050. *Proceedings of the National Academy of Sciences*, *107*, 18371–18374.
Poore, J., & Nemecek, T. (2018). Reducing food's environmental impacts through producers and consumers. *Science*, *360*, 987–992.
Rahmstorf, S., & Levermann, A. (2017). *2020: The climate turning point*. Potsdam, Germany: Potsdam Institute for Climate Impact Research.
Reisinger, A., & Clark, H. (2017). How much do direct livestock emissions actually contribute to global warming? *Global Change Biology*, *24*, 1749–1761.
Richards, M. B., Wollenberg, E., & van Vuuren, D. (2018). National contributions to climate change mitigation from agriculture: Allocating a global target. *Climate Policy*, *18*, 1271–1285.
Ripple, W. J., Smith, P., Haberl, H., Montzka, S. A., McAlpine, C., & Boucher, D. H. (2014). Ruminants, climate change and climate policy. *Nature Climate Change*, *4*, 2–5.
Roser, M., & Ritchie, H. (2018). "Yields and land use in agriculture". Published online at OurWorldInData.org. Retrieved from https://ourworldindata.org/yields-and-land-use-in-agriculture [Online Resource]
Sabate, J., Sranacharoenpong, K., Harwatt, H., Wien, M., & Soret, S. (2014). The environmental cost of protein food choices. *Public Health Nutrition*, *18*, 1–7.
Saunois, M., Jackson, R. B., Bousquet, P., Poulter, B., & Canadell, J. G. (2016). The growing role of methane in anthropogenic climate change. *Environmental Research Letters*, *11*, 120207.
Schösler, H., de Boer, J., & Boersema, J. J. (2012). Can we cut out the meat of the dish? Constructing consumer-oriented pathways towards meat substitution. *Appetite*, *58*, 39–47.
Shepon, A., Eshel, G., Noor, E., & Milo, R. (2018). The opportunity cost of animal based diets exceeds all food losses. *Proceedings of the National Academy of Sciences of the United States of America*, *115*, 3804–3809.
Shindell, D., Borgford-Parnell, N., Brauer, M., Haines, A., Kuylenstierna, J. C. I., Leonard, S. A., … Srivastava, L. (2017). A climate policy pathway for near- and long-term benefits. *Science*, *356*, 493–494.
Smith, P., Bustamante, H., Ahammad, H., Clark, H., Dong, E. A., Elsiddig, H. … Tubiello, F. (2014). Agriculture, forestry and other land use (AFOLU). In O. Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, & J. C. Minx (Eds.), *Climate change 2014:*

Mitigation of climate change. Contribution of working group III to the fifth assessment report of the intergovernmental panel on climate change (pp. 811–922). Cambridge, UK and New York, NY: Cambridge University Press.

Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P. … Sirotenko, O. (2007). Agriculture. In B. Metz, O. R. Davidson, P. R. Bosch, R. Dave, & L. A. Meyer (Eds.), *Climate change 2007: Mitigation. Contribution of working group III to the fourth assessment report of the intergovernmental panel on climate change* (pp. 498–540). Cambridge, UK and New York, NY: Cambridge University Press.

Springmann, M., Godfray, H. C. J., Rayner, M., & Scarborough, P. (2016). Analysis and valuation of the health and climate change cobenefits of dietary change. *Proceedings of the National Academy of Sciences*, *387*, 1937–1946.

Springmann, M., Mason-D'Croz, D., Robinson, S., Garnett, T., Godfray, H. C., Gollin, D., … Scarborough, P. (2016). Global and regional health effects of future food production under climate change: A modelling study. *Lancet (London, England)*, *387*, 1937–1946.

Steffen, W., Rockstrom, J., Richardson, K., Lenton, T. M., Folke, C., Liverman, D. … Schellnhuber, H. J. (2018). Trajectories of the Earth System in the Anthropocene. *Proceedings of the National Academy of Sciences of the United States of America*, *115*, 8252–8259.

Stoll-Kleemann, S., & Schmidt, U. J. (2017). Reducing meat consumption in developed and transition countries to counter climate change and biodiversity loss: A review of influence factors. *Regional Environmental Change*, *17*, 1261–1277.

UNEP. (2016). *The emissions gap report 2016*. Nairobi: United Nations Environment Programme (UNEP).

UNEP. (2017). *The emissions gap report 2017*. Nairobi: United Nations Environment Programme (UNEP).

UNFCCC. (1992). *Framework convention on climate change*. New York, NY: United Nations.

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

USDA. (2016a). USDA National Nutrient Database for Standard Reference 28 slightly revised May 2016 Software v.3.7.1 2017-03-29. Nutrient data for: 13495, Beef, ground, 70% lean meat / 30% fat, loaf, cooked, baked.

USDA. (2016b). USDA National Nutrient Database for Standard Reference 28 slightly revised May 2016 Software v.3.7.1 2017-03-29. Nutrient data for: 16015, Beans, black, mature seeds, cooked, boiled, without salt.

van Vuuren, D. P., Stehfest, E., Gernaat, D. E. H. J., van den Berg, M., Bijl, D. L., de Boer, H. S., … van Sluisveld, M. A. E. (2018). Alternative pathways to the 1.5°C target reduce the need for negative emission technologies. *Nature Climate Change*, *8*, 391–397.

Vrontisi, Z., Luderer, G., Saveyn, B., Bertram, C., De Boer, H. S., Drouet, L., … Van Vuuren, D. P. (2016). Report containing an economic analysis of a set of sectoral impacts, Deliverable No. 6.4, ADVANCE, Advanced Model Development and Validation for Improved Analysis of Costs and Impacts of Mitigation Policies.