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Livestock intensification and the influence of dietary change: A calorie-based assessment of competition for crop production

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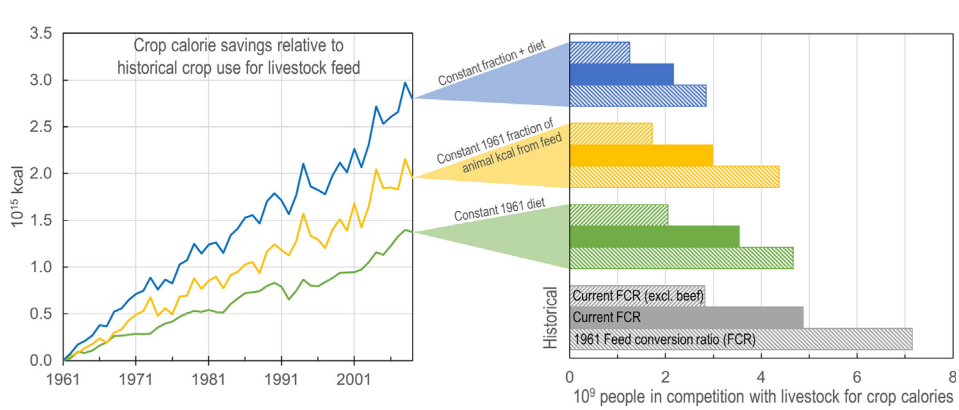
HIGHLIGHTS

- We examine the historical competition for crop use between food and feed.
- Currently, 56% of animal calories are 'free' to humans in terms of crop use.
- A constant per capita diet would mean 1.38×10^{15} fewer crop calories needed for feed.
- Crops lost via consumer waste of animal foods could feed 235 million people.

GRAPHICAL ABSTRACT



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ABSTRACT

Animal production exerts significant demands on land, water and food resources and is one of the most extensive means by which humans modify natural systems. Demand for animal source foods has more than tripled over the past 50 years due to population growth and dietary change. As a result, the livestock sector has transitioned towards intensive and concentrated production systems. Typically, studies have divided types of animal production into intensive, mixed and grazing production systems. However, because a large percentage of animal production originates from mixed systems, dividing by such production types can make it difficult to quantify competition for crop production between direct human consumption and use as feed. To this end we employ a calorie-based approach to determine which animal calories were 'free' – in that they did not compete with human consumption for crop use – and consider to what extent alternative scenarios could have reduced this competition between food and feed. We find that growth in non-feed animal systems has only been able to keep pace with population growth and that feed-fed production has necessarily met increases in human dietary demand for animal products. Through solutions such as moderating diets for animal calories, choosing less resource-demanding animal products and maintaining the relative contribution of non-feed systems, between 1.3 and 3.6 billion fewer people would be in competition with feed for crop use. We also estimate that the feed crop calories required to support consumer waste of animal calories could feed an additional 235 million people. With human demand for animal products expected to continue increasing in the coming decades, the findings here provide insights into

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potential solutions and what the magnitude of their effect may be and suggest that there exist real opportunities for humankind to substantially reduce competition for crop use.

1. Introduction

Global livestock production has rapidly increased over the past 50 years in order to meet the rising demands from population growth and dietary change (Delgado, 2005; Thornton, 2010). In this time both the global demand for animal products and the amount of crop production used for feed have approximately tripled (330% and 300% respectively) (Food and Agriculture Organization of the United Nations, 2014). While livestock production has been able to keep pace with human demand, its increase has had significant implications for food security and the environment (Tilman et al., 2002; Bouwman et al., 2013). Using roughly 30% of global ice-free land for grazing and the cultivation of feed (Steinfeld et al., 2006; Erb et al., 2007; Ramankutty et al., 2008), not only has livestock production played a major role in humankind's modification of Earth's surface but it is also one of several substantial and unprecedented demands being placed on crop production worldwide. This is particularly true given the recent growth in demand for animal feed as a result of livestock intensification and commodification (Steinfeld et al., 2006; Delgado et al., 1999). However, rangelands and other non-feed systems continue to play an integral role in global food supply (Godfray et al., 2010; Davis et al., 2014) while providing their own socio-economic and ecosystem services (Thornton, 2010; Herrero et al., 2009) as well as environmental impacts (Steinfeld et al., 2006).

Each system of animal production (e.g. feed-fed, rangelands, grass feeding, mixed crop-livestock) offers unique benefits and shortcomings. Feed-fed animal production typically produces animals more efficiently (Pimentel and Pimentel, 2008) and separates livestock production from a number of local resource constraints (Steinfeld and Gerber, 2010). Because the recent intensification of animal production is mostly attributable to non-ruminant species (e.g. poultry, pigs) (Food and Agriculture Organization of the United Nations, 2014), this means that more animals can be raised in a smaller area (Cassidy et al., 2013). On the other hand, this form of animal production can mean greater competition for land use between food and feed production (Naylor et al., 2005), a separation of consumption from its environmental impacts (e.g. virtual nitrogen trade (Galloway et al., 2007)), a higher concentration of waste per area (Tilman et al., 2002) and issues of animal welfare and disease (Thornton, 2010). Conversely, animal production from other types of systems (hereafter referred to as 'non-feed' systems) offers a distinct advantage in that it does not reduce humankind's crop resource base and instead often makes use of crop residues as well as biomass on "marginal lands" where crop cultivation would not be possible (Tilman et al., 2002; Pimentel and Pimentel, 2008; Herrero et al., 2013). However, systems that rely more heavily on non-feed sources also typically require larger areas to produce the same amount of animal calories, as forage does not have the same nutritional value as animal feed (Krausmann et al., 2008). In addition, a more direct reliance on land also means that animal production from many non-feed systems is tied to local climate and affected by its uncertainty. Moreover the use of and conversion to grassland and rangeland can carry its own set of environmental consequences (e.g. desertification, deforestation, greater total GHG emissions) (Steinfeld et al., 2006; Asner et al., 2004; McMichael et al., 2007).

Indeed there exists a rich literature exploring the various production systems of the livestock sector and their role in global food security (Thornton, 2010; Steinfeld et al., 2006; Delgado et al., 1999; Herrero et al., 2013; Kastner et al., 2012). While livestock have historically ensured food security in numerous ways (e.g. human consumption, transport, manure for fertilizer) (Galloway et al., 2007), their direct use as food has recently grown in importance while their indirect roles have become secondary. The emerging human demand for animal products, how it may be expected to grow in the future and how supply will need to increase have all been thoroughly studied (Tilman et al., 2002; Wint and Robinson, 2007; Robinson and Pozzi, 2011; Pradhan et al., 2013). In addition, recent detailed studies and life-cycle assessments have quantified the distribution of major types of animal production as well as their environmental impacts (Steinfeld et al., 2006; Steinfeld and Gerber, 2010; Food and Agriculture Organization of the United Nations, 2013a,b). However, the reliance of the livestock sector on crop production – and how this has changed through time – has not been quantified to date. This is largely due to the difficulty in distinguishing between livestock production derived from feed and non-feed sources particularly given that a large portion of animal production is the result of mixed feed/grass feeding (Food and Agriculture Organization of the United Nations, 2013a,b; Sere and Steinfeld, 1996).

A calorie-based approach offers an alternative perspective in that it gives a clearer picture of which animal calories are 'free' to the agricultural system in terms of crop use. Specifically here we employ an approach in which animal calorie production is converted to equivalent animal biomass demand and compared to the calories present in feed crops. In this way, we can determine what portion of animal biomass demand was met by feed – as well as in competition with direct human consumption of crop production – and in turn quantify the fraction of animal calories that originated from non-feed biomass. While we expect that non-feed biomass has contributed substantially to historical animal production, we posit that scenarios in which animal production either relied more heavily on non-feed biomass or in which growth in human demand was reduced could have further reduced competition for crop use between food and feed. By examining past changes along with alternative scenarios, it is possible to gain a better understanding of the interplay between feed-fed and non-feed animal supply, the capacity of each to react to demand over the past half-century and the potential crop calorie savings that could have been realized under situations of less intensive production and moderated dietary demand. This study therefore provides a simple and effective approach for evaluating potential pathways with which to minimize human impacts from the livestock sector.

2. Methods

We defined animal production as calories from bovine meat, pig meat, poultry meat, eggs and milk. Collectively these animal food groups comprised 76% of global human demand for animal calories (including for seafood) (Food and Agriculture Organization of the United Nations, 2014). We included 40 feed products – each contributing at least 100,000 tonnes to global feed use in the year 2009 – in our study (Table S1); these products made up ~93% of global feed production in any given year (Food and Agriculture Organization of the United Nations, 2014). Data for animal production, caloric content and crops/products used for feed for 1961 through 2009 came from FAOSTAT. Oilcake production for feed was transformed to its equivalent primary crop based on cake-to-crop conversion factors (Table S2), calculated as the tonnes of total oil cake production in equivalent primary crop units divided by the tonnes of total oil cake production (Food and Agriculture Organization of the United Nations, 2014). Data on animal and feed crop production were converted from tonnes to calories using the FAO Food Balance Sheets (Food and Agriculture Organization of the United Nations, 2014). Calories from each animal product were then converted to equivalent plant calories (i.e., total animal demand for plant calories) using sub-regional product-specific plant-to-animal feed conversion ratios (FCRs), derived from dry matter intake values reported in a recent study by Herrero et al. (Herrero et al., 2013). These values were converted from total kilograms DM per Tropical Livestock Unit (FCR_{kg}; kg DM TLU^{-1}) to calories DM per animal calorie (FCR; kcal DM animal kcal^{-1}) by:

$$FCR_x = \frac{FCR_{kg,x} ME_x}{w_x k_x}$$

where ME_x is the metabolizable energy (in calories) of a kilogram of feed dry matter consumed by animal x (Herrero et al., 2013), w_x is the kilograms of animal product per TLU (Herrero et al., 2013) and k_x is the calories per kilogram of animal x (Food and Agriculture Organization of the United Nations, 2014) (Table S3-S4). Because ME_x was not reported for poultry, eggs or pigs, we calculated these values for each sub-region using:

$$ME_x = \frac{\sum g_i k_i}{\sum g_i}$$

where k_i is the global average calories per kilogram of feed crop i (Food and Agriculture Organization of the United Nations, 2014) and g_i is the kilograms of grain i per TLU (Herrero et al., 2013).

We also account for improvements in livestock production efficiency through time, assuming linear improvements in all conversion factors based on product-specific values published by van der Steen et al. (Van der Steen et al., 2005) and Capper (Capper, 2011) (Table S5). We estimate the current global plant-to-animal calorie conversion factor to be 11.5:1, a value largely in agreement with those reported by Pimentel and Pimentel (Pimentel and Pimentel, 2008) and Godfray et al. (Godfray et al., 2010). Feed conversion ratio (FCR) without beef was determined as a production-weighted average of the conversion ratios for poultry, pig, eggs and milk. Finally, animal demand for non-feed plant calories was calculated as the difference between total animal demand for plant calories and animal demand for feed calories (i.e., crop calories from the 40 feed products). Under this definition, fodder crops (e.g., alfalfa, clover, green maize), crop residues and permanent grasslands are considered as non-feed products – even though their production may compete with other uses of cultivatable land – because human and animal demands do not compete over the consumption of most of these crops. In addition, because some of these crops (e.g. alfalfa) can also be directly consumed by humans, our method of calculation means that, to a limited extent, we underestimate the feed calories available for animal consumption. Further, what we draw from our results is limited to a certain extent by the use of calories. This is because when using our methodology it is not possible to know what amount of feed calories is dedicated to producing each animal product.

Information on consumer waste came from Gustavsson et al. (2011) (see Table S6). The minimized waste scenario followed methods of Kummu et al. (2012) who assumed that, for any step along the food supply chain, the lowest waste percentage of any region was applicable to all regions. As FAO Food Balance Sheets and FAOSTAT production data already account for any pre-consumer waste, we only apply the Kummu et al. (2012) methodology to consumer waste and determine that demand for the animal products considered in this study could be reduced from 384 kcal cap^{-1} day^{-1} to 366 kcal cap^{-1} day^{-1} if consumer waste was minimized. The number of people, P, fed by this minimized consumer waste was then calculated as:

$$P = \frac{a\left(1 - \frac{d_{a,min}}{d_a}\right)}{d_{total}}$$

where a is the feed calorie demand of animal production, d_a is the daily per capita animal calorie demand, $d_{a,min}$ is the daily per capita calorie demand when consumer waste is minimized and d_{total} is the total daily per capita calorie demand.

Lastly, we consider several alternative scenarios of how human demand for animal calories (and the crop calories required to produce them) might have been historically reduced. In Scenario A1, per capita dietary demand for the considered animal products is held constant at 1961 levels – 232 kcal cap^{-1} day^{-1}; all other variables (i.e., population, FCR, non-feed fraction (NFF)) remained dynamic. In Scenario A2, NFF was held constant at its 1961 value while population, FCR and diet were allowed to vary. In Scenario A3, both diet and NFF were held constant at 1961 levels, while only population and FCR varied with time. Using these scenarios, we were able to examine the effect that reduced human demand and/or greater reliance on non-feed sources might have had in reducing competition for crop calories.

3. Results

Global animal biomass demand increased from 5.34×10^{15} kcal to 11.13×10^{15} kcal over the 49 year study period (Fig. 1a). The percentage of global animal demand met by non-feed sources (hereafter referred to as the "non-feed fraction" or NFF) has steadily decreased throughout the time period from 73% to 56% (Figs. 1b, S1d), though we observed stark regional contrasts (Fig. S1). We also found that – while animal calorie production more than tripled (210% relative change) – animal biomass demand grew more modestly (122% relative change) (Fig. 1c–d). In addition, animal production from non-feed sources and total animal biomass demand experienced approximately the same relative growth as population. We estimate that animal biomass demand met by non-feed sources in 2009 was enough to meet the animal portion of daily dietary demand for 4.0 billion people. Had this animal biomass demand instead been met by feed sources, the feed calories required to do so would equate to an additional 62% of total calorie production from major crops.

We also considered several alternative scenarios of animal production. In holding diet constant (A1), we find that this alone would have meant a feed crop calories savings of 1.38×10^{15} kcal (Fig. 2a, b). Alternatively, a constant NFF resulted in a savings of 1.96×10^{15} kcal (A2). When these two elements are taken together (A3), an estimated 2.80×10^{15} kcal could have been saved. Overall, we calculated that between 2.2 and 3.5 billion people could be fed by the feed crop calories required for these different scenarios (Fig. 2c). We also estimate that improving FCR has markedly reduced the competition for crop use, historically eliminating the need for enough crops to feed 2.3 billion people. In addition, by removing beef from the current diet, it is possible to further reduce competition for crop use by an additional 2.0 billion people. Lastly, we find a crop savings (0.24×10^{15} kcal) when consumer waste of animal products is minimized. Though modest in comparison to the other scenarios, this savings alone would be able to feed 235 million people.

4. Discussion

Population growth, dietary changes (Alexandratos and Bruinsma, 2011) and increasing biofuel use (Organization for Economic Cooperation and Development/Food and Agriculture Organization of the United Nations, 2014) are expected to place unprecedented demands on the global agricultural system in the coming decades. Despite this ever steeper competition for crop resources, it appears that feed-fed animal production will play an increasingly important role in meeting demand for animal-source goods. By examining historical trends from a calorie perspective, our study sheds light not only on how the use of crop production for feed may be expected to change but also suggests effective mechanisms by which reduced competition can be achieved. What is most apparent from this study is that growth in non-feed animal production was only able to keep pace with population growth (Fig. 1d). The same was true for total animal biomass demand (Fig. 1c). As a result, the increasing demand

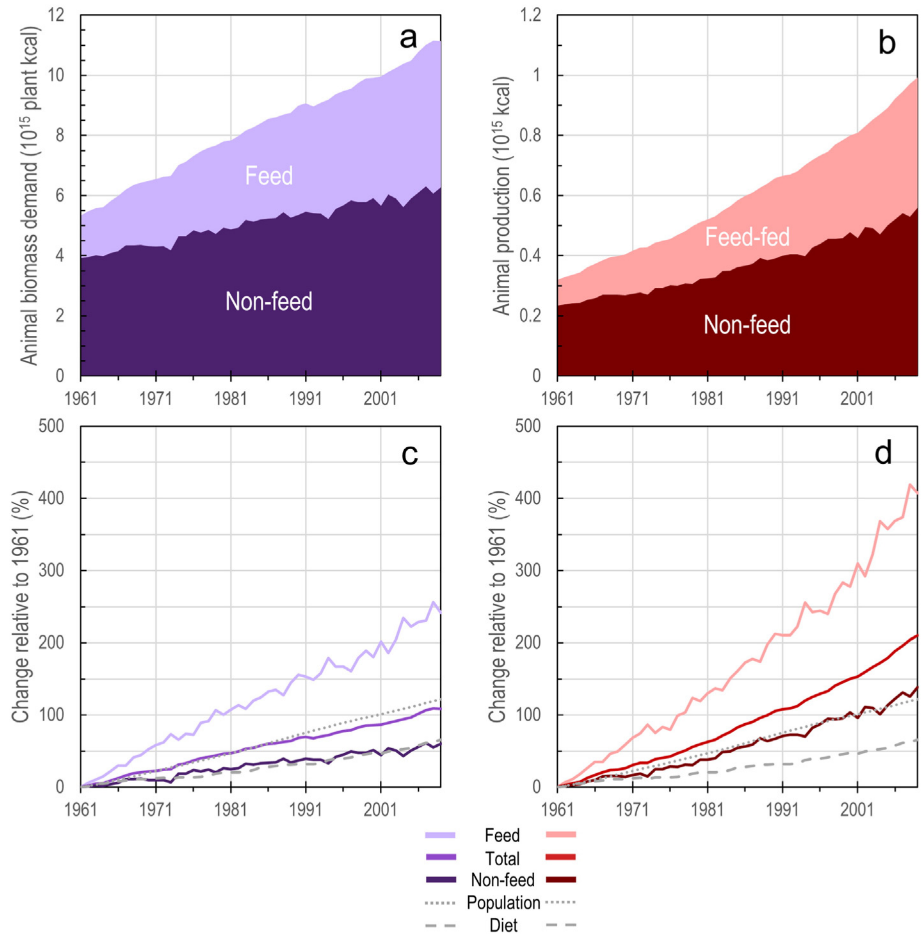

Fig. 1. Livestock demand, production and relative change. a) Calories demanded by animals, disaggregated between feed and non-feed sourced plant calories. b) Amount of animal calorie production derived from feed and non-feed sources. c) Relative change in calories demanded by animals compared to growth in population and human dietary demand for animal calories. d) Relative change in animal calorie production. Please note that the y-axis scales for panels a and b are different.

from dietary change was necessarily met by feed-fed systems, which are typically not limited by local climatic variability. Concurrently, the rapid increase in crop yields as a result of the Green Revolution is what enabled the global food system to accommodate these richer diets. Regardless of the causality between diets and feed use, growing evidence of plateauing yields (Lobell et al., 2009; Ray et al., 2012) means that the world's crop resources will become increasingly strained. This is cause for concern considering that per capita demand – especially for animal products – is expected to continue increasing in the coming decades (Robinson and Pozzi, 2011).

One important way to minimize the competition for crop production while still meeting demand is to improve the efficiency with which input resources can be converted into animal calories. While selective breeding has played an important role in reducing the amount of resources required to produce an animal, transitioning from a livestock system comprised of resource-intensive animal goods to less resource-demanding ones can still help to reduce stress on agricultural resources as well as the environment (Thornton, 2010). In this regard the ongoing transition away from ruminant species towards monogastrics is encouraging. As the production of the former is generally more environmentally burdensome (Eshel et al., 2014), this trend means that the production of an animal calorie has become less demanding in many ways (e.g., land use, carbon emissions) though it has not necessarily minimized the additional required crop production. In the USA for example, Eshel et al. (Eshel et al., 2014) determined the overall caloric FCRs of beef, pork and poultry to be 36, 11 and 9, respectively; only considering the portion of the animal diet met by feed concentrates dropped the beef FCR to 8. However, when protein conversion ratios from another recent study by Tilman and Clark (Tilman and Clark, 2014) are converted to calorie FCRs (not including calories from non-feed sources), beef is 5 to 10 times more calorie demanding than other animal products. Thus in terms of preserving crop production for direct human consumption, the benefits of changing what animals comprise overall production remain unclear. These two main mechanisms – improved efficiency of a species and the composition of animal calorie production – are what influence changes in the overall FCR of the livestock sector through time. From our results it is clear that – had the overall FCR instead remained constant – competition between direct human consumption and crop use for feed would have been substantially greater (Fig. 2c). Conversely, eliminating beef (and its inefficient FCR) could substantially improve crop availability for direct human consumption (Fig. 2c).

Efficiency represents an important mechanism by which the impact of animal production has improved and may continue to do so. In addition, our results demonstrate that changes to patterns of human consumption can be an effective means for reducing competition for crop production (Scenario A1; Fig. 2b), though historically this has not been the case (Alexandratos and Bruinsma, 2011; Tilman and Clark, 2014). If per capita dietary demand for animal calories had remained constant, this alone could potentially reduce the number of people in competition with feed by 27%. This reduction is even greater when combined with a non-feed dominated livestock system. However, such pathways would have only been possible with a more equitable distribution of animal goods and diets. Indeed, there continues to be a large disparity between countries in terms of per capita calorie consumption. For instance, in sub-Saharan Africa there is a persistent need to increase availability of and access to animal products (or other protein sources)

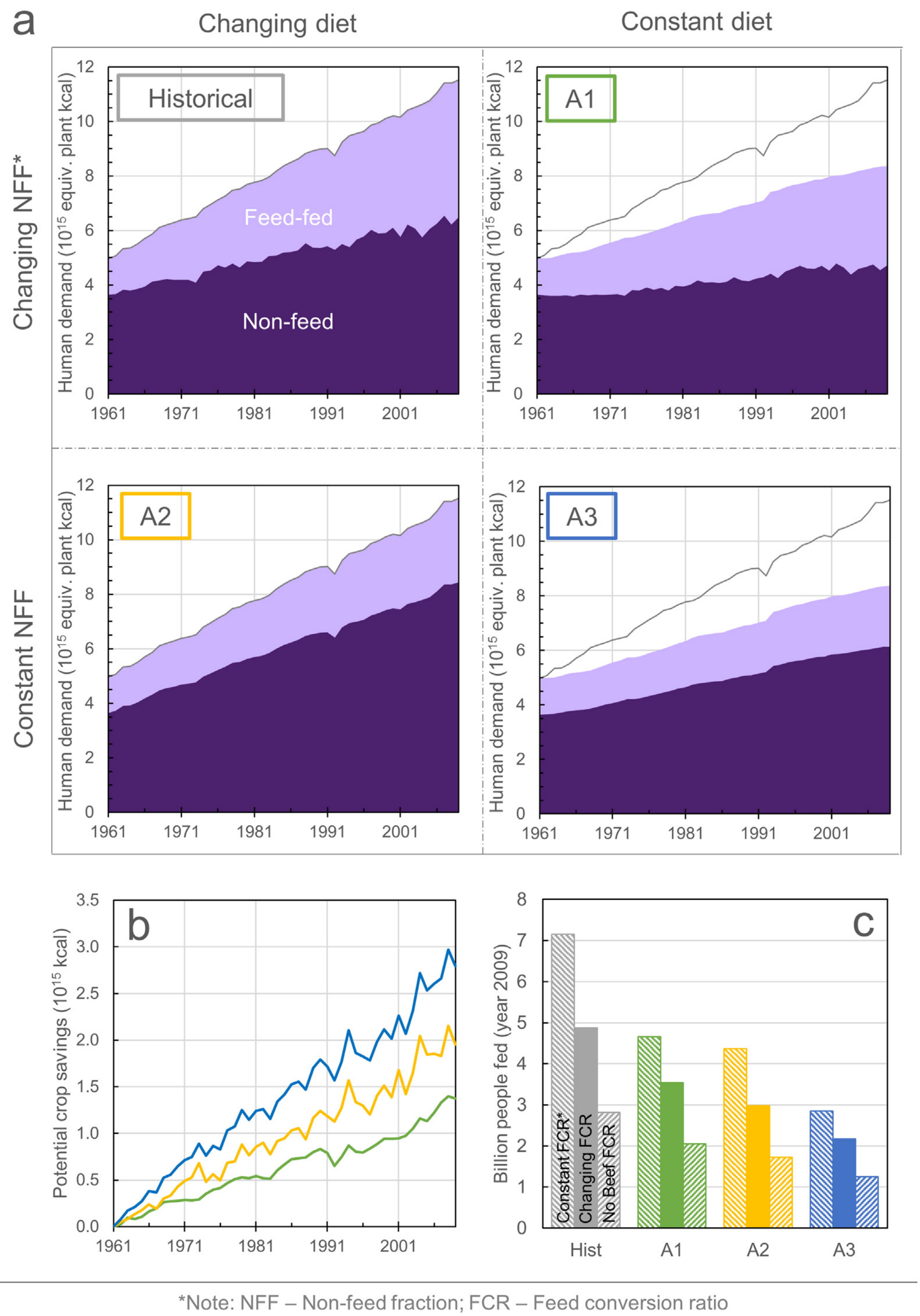

Fig. 2. Alternative scenarios and calorie savings. a) Human demand for animal calories – expressed in equivalent plant calories – sourced from feed-fed and non-feed sources. Alternative scenarios hold dietary demand (A1), non-feed fraction (A2) or both (A3) constant at 1961 levels. Gray line represents historical human demand. b) Crop calories savings resulting from alternative scenarios reduced feed demand. Crop calorie savings was calculated as the historical feed calorie use minus the feed calorie use of the respective scenario. c) The number of people potentially fed by crop calories that were instead used for animal feed. Production-weighted FCR from 1961 was used for 'Constant FCR'. Production-weighted FCR from 2009 (excluding beef production and beef FCR) was used for 'No Beef FCR'. The average global calorie demand for the year 2009 (2800 kcal cap^{-1} day^{-1}) (Food and Agriculture Organization of the United Nations, 2014) was used to calculate the number of people able to be fed if feed calories were instead used for direct human consumption. Thus, the smaller a column is, the less competition that scenario would have with crop use for food.

to address issues of undernourishment. Such places – many of which have undergone prolonged drought in recent decades – may well benefit from a greater reliance on feed in order to increase the productivity of their livestock systems and reduce the impacts of local climate. In contrast, there are compelling health and environmental reasons for countries in the developed world – places that historically overconsume animal products – to reduce their meat consumption and, in turn, their demand for feed (McMichael et al., 2007; Tilman and Clark, 2014). Thus a shift towards a globally adequate diet – where the consumption of agricultural production is more equitably distributed and the range of per capita animal calorie consumption is tightened towards the global average – would seem to offer great benefits in a number of ways. Yet while the increasing globalization of the food system makes such an approach more feasible (Fader et al., 2013), wealth inequality, increasing food prices and the uncertainty of climate change present major obstacles. Still, targeted trade decisions (Carr et al., 2015) as well as more open sharing and distribution of agricultural technologies to underperforming regions can all help to make progress in addressing food inequality.

Lastly, large amounts of animal production are wasted at various steps of the food supply chain (Gustavsson et al., 2011). Because of the resources required to produce them, the waste of animal products is far more costly to crop production and the environment than is the waste of crop production directly (West et al., 2014). In any region, approximately 20% of meat production is currently lost or wasted throughout the food supply chain (Gustavsson et al., 2011). For example in sub-Saharan Africa, almost all of these losses occur during production and transport as a result of high livestock mortality and lack of refrigeration. Thus, improved access to technology (e.g., animal vaccinations) and adequate infrastructure (e.g., storage freezers) would help to greatly reduce losses in this region and better ensure that dietary requirements are met and natural resources minimally stressed. Animal waste in industrialized countries has a far different complexion. Different from the developing world, consumer waste accounts for a much larger percentage of lost animal production in industrialized countries. As Gustavsson et al. (2011) found, in the U.S. and Europe, approximately half of all wasted meat production and as much as two-thirds of wasted dairy production occurs at the level of the consumer (or retailer). Minimizing consumer waste of animal products in industrialized regions therefore represents an important approach to reducing stress on crop production. In fact, our results demonstrate this, showing that curtailing consumer waste of animal-source foods would mean approximately 235 million less people would need to compete with feed for crop use. Though modest in comparison to the food security benefits of moderating diets, efforts directed towards reducing consumer waste of animal products may be more effective than attempting to alter people's dietary choices, as many of the possible improvements (e.g., eliminating arbitrary ‘sell by’ dates, chronic overstocking in supermarkets) would not require a change in human behavior or personal habits.

5. Conclusion

Livestock intensification has proven beneficial especially for countries with low crop production, as they can substantially increase their domestic supply of feed through trade (e.g. Japan, Netherlands, Spain) and therefore operate independent of local climatic impacts and resource constraints. However, this option may not be as readily available in the coming decades. Recent evidence shows that an increasingly connected global food trade has also left the system more vulnerable to shocks and conditions of crises and may therefore leave exporting countries more reluctant to participate in trade in order to ensure domestic food self-sufficiency (Suweis et al., 2015). In addition, global demand for major crops may double by mid-century (Tilman et al., 2011) and future climate change is expected to adversely impact crop yields in much of the world (Wheeler and von Braun, 2013). In turn, competition for the various uses of crop production will intensify and, with half of the world's crop calorie production already being used for feed, this may have serious implications for animal production and consumption.

It is clear from this study that dietary demand for animal products is closely related to the intensification of the livestock system. Therefore, an effort to moderate diets would seem to be an effective means for reducing competition for crop use, especially considering the rising demand for crop-based biofuels. Such a dietary shift would be most effective in developed countries where not only is the overconsumption of meat linked to rising health costs (Tilman and Clark, 2014) but is also where consumer waste is highest (Gustavsson et al., 2011). However, political and cultural hurdles continue to make solutions involving diet difficult. Thus approaches that utilize global food trade to address hunger or that promote the choice of animal products with lower resource requirements may be the most useful and impactful in coming decades.

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Appendix A. Supplementary data

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