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Could consumption of insects, cultured meat or imitation meat reduce global agricultural land use?

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Highlights

- Review of alternatives to conventional animal products, e.g. cultured meat and insects
- Imitation meat and insects have the highest land use efficiency
- Land use requirements are only slightly greater for eggs and poultry meat
- Cultured meat does not seem to offer substantial benefits over poultry meat or eggs
- Mix of small changes in consumer behaviour would help to achieve a sustainable diet

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Abstract

Animal products, i.e. meat, milk and eggs, provide an important component in global diets, but livestock dominate agricultural land use by area and are a major source of greenhouse gases. Cultural and personal associations with animal product consumption create barriers to moderating consumption, and hence reduced environmental impacts. Here we review alternatives to conventional animal products, including cultured meat, imitation meat and insects (i.e. entomophagy), and explore the potential change in global agricultural land requirements associated with each alternative. Stylised transformative consumption scenarios where half of current conventional animal products are substituted to provide at least equal protein and calories are considered. The analysis also considers and compares the agricultural land area given shifts between conventional animal product consumption. The results suggest that imitation meat and insects have the highest land use efficiency, but the land use requirements are only slightly greater for eggs and poultry meat. The efficiency of insects and their ability to convert agricultural by-products and food waste into food, suggests further research into insect production is warranted. Cultured meat does not appear to offer substantial benefits over poultry meat or eggs, with similar conversion efficiency, but higher direct energy requirements. Comparison with the land use savings from reduced consumer waste, including over-consumption suggests greater benefits could be achieved from alternative dietary transformations considered. We conclude that although a diet with lower rates of animal product consumption is likely to create the greatest reduction in agricultural land, a mix of smaller changes in consumer behaviour, such as replacing beef with chicken, reducing food waste and potentially introducing insects more commonly into diets, would also achieve land savings and a more sustainable food system.

Keywords

Land use; Animal products; Livestock; Dietary change; Entomophagy; Cultured meat

1. Introduction

Livestock provides a quarter of all the protein (and 15% of energy) consumed in food, but also creates substantial environmental impacts (FAO, 2012; Herrero et al., 2016). The area of global pasture is more than twice that of cropland, with livestock animals additionally consuming around a third of the crops harvested as feed (FAO, 2006). Despite rises in crop yields and in the efficiency of livestock production, global agricultural land area has been expanding, increasing by 464 Mha between 1961 and 2011 (Alexander et al., 2015). Land use change in recent decades has accounted for 10-12% of total anthropogenic carbon dioxide emissions, and a third since 1850 (Houghton et al., 2012; Le Quéré et al., 2015). Livestock production also contributes to atmospheric greenhouse-gas (GHG) emissions, due to methane from enteric fermentation (presently 2.1 Gt CO_2 eq year^{-1} (Gerber et al., 2013)), and nitrous oxide emissions from fertiliser use on pasture and croplands in fodder production (Smith et al., 2014). In total, livestock is responsible for 12% of global anthropogenic GHG emissions (Havlík et al., 2014). A larger global population consuming a diet richer in meat, eggs and dairy (Kearney, 2010; Keyzer et al., 2005; Popkin et al., 1999; Tilman et al., 2011) has meant that agricultural land use change in the past 50 years has been dominated by the expansion of livestock production (Alexander et al., 2015). Besides the direct GHG emissions, agriculture also has large indirect emissions (e.g. from agrochemicals production and fossil fuel used) (Smith and Gregory, 2013). The combination of land use change and other emissions increases the share of agriculture in all global anthropogenic GHG emissions to between 17% and 32% (Smith and Gregory, 2013). Therefore, changing demands on agricultural production, and in particular for animal products (i.e. meat, milk and eggs), has the potential to substantially alter GHG emissions (Bustamante et al., 2014; Havlík et al., 2014). Additionally, the sparing of agricultural land provides options for further climate change mitigation measures, including afforestation or bioenergy (Humpenöder et al., 2014).

The projected rise in global population and higher per capita rates of animal product consumption, arising from higher incomes and urbanisation, suggests that livestock production will continue to increase (Tilman et al., 2011). Changes in production practices and animal genetics that increase efficiencies may help to offset some of the potential land use and associated environmental impacts (Havlík et al., 2014; Le Cotty and Dorin, 2012). Nevertheless, demand-side measures to reduce animal product consumption may be necessary to meet climate change targets (UNFCC, 2015), while helping to achieve food security (Bajželj et al., 2014; Lamb et al., 2016; Meadu et al., 2015; Smil, 2013). High levels of meat consumption are also detrimental to human health, with links to obesity, cardiovascular diseases and cancer (Bouvard et al., 2015; Hu, 2011; NCD Risk Factor Collaboration, 2016; Popkin and Gordon-Larsen, 2004). Despite both the health and environmental benefits, changing consumer preferences towards a low meat diet is difficult because of cultural, social and personal associations with meat consumption (Graça et al., 2015; Macdiarmid et al., 2016). Although there is some evidence for increasing rates of vegetarianism and reduced meat diets in western countries (Leahy et al., 2011; Vinnari et al., 2010), the global average per capita rate of animal product consumption has continued to increase (FAOSTAT, 2015a).

Studies of the food system that include the impact of dietary change typically assume the continuation of existing consumption patterns and income and price elasticity relationships (e.g. Engström et al., 2016a, 2016b; Schmitz et al., 2014; Tilman et al., 2011), implicitly discounting the possibility of major shocks or transformative changes in diets. There has also been an increasing number of studies considering the impact of alternative assumptions regarding future diets, such as lower animal product consumption, healthy diets, vegetarianism or veganism, e.g. (Bajželj et al., 2014; Erb et al., 2016; Haberl et al., 2011; Mora et al., 2016; Popp et al., 2010; Stehfest et al., 2009)

However, technology changes or radical alteration of consumer preferences, which could be transformative for the food system, remain unexplored. New technologies raise the possibility of supplying high quality food from novel sources, e.g. cultured meat, also known as *in vitro* meat (Thornton, 2010). Also, behaviour, preferences and social norms change over time, such that food previously considered unacceptable or undesirable (e.g. insects, in western countries) could become a more common part of future diets (van Huis, 2013). There are historical precedents for foods becoming acceptable after long periods of rejection; for example, tomatoes in Britain were widely viewed with suspicion and dismissed for over 200 years (Bir, 2014; K. A. Smith, 2013). Similarly, lobster in America was initially a poverty food eaten by slaves and prisoners, and used as fertiliser and fish bait, due to their abundance (Dembosky, 2006). It wasn't until the late nineteenth century that lobster developed a status as a luxury food, supported by the expansion of the US railway network giving access to new markets (Townsend, 2012). But while alternative food sources may become technologically feasible or publically acceptable in the future, their potential contributions to sustainability remains unclear.

This study addresses this research gap by reviewing and comparing the potentially transformative alternatives to conventional animal products, including cultured meat, imitation meat and insects, and consider the implications for global agricultural land use requirements given widespread adoption. The approach is explorative, rather than predictive, and assumes half of existing animal products are substituted by each alternative food, to provide at least equal energy and protein. The objective is to compare the alternatives on an equal basis and to assess their potential to reduce agricultural land requirements, and contribute to food system sustainability. To allow comparison with more typical dietary change, several other scenarios were also included using the same methodology. These scenarios include shifts in conventional animal product consumption, changes to high and low animal product diets (based on average consumption in India and the USA), and reductions in consumer waste. The focus is on animal products due to their dominance in the food system for land use and environmental impacts (Herrero et al., 2016), and because of their relative inefficiency in converting inputs into human-edible food (FAO, 2006; Mottet et al., 2017). The premise is that due to the cultural and personal associations with animal product consumption (Graça et al., 2015; Macdiarmid et al., 2016), consumers with higher incomes continue to eat large quantities of animal products and consumers currently eating at lower rates will increase their consumption as incomes increase. This assumption combined with population growth, also underlies the projections of substantial increases (from 76 to 133%) in global animal product demand (Alexandratos and Bruinsma, 2012; Bodirsky et al., 2015). Therefore, alternatives that mimic aspects of these products in a manner that is acceptable to consumers need to be explored for environmental sustainability.

2. Alternatives to current animal products

There are several alternatives to existing animal products as food protein and energy sources:

(a) Insects

Edible insects have the potential to become a major source of human nutrition, and can be produced more efficiently than conventional livestock, i.e. in terms of converting biomass into protein or calories (Tabassum-Abbasi et al., 2016; van Huis, 2013). They are high in fat, protein and micronutrients (Persijn and Charrondiere, 2014; Rumpold and Schlüter, 2013), and can be produced with lower levels of GHG emissions and water consumption (van Huis, 2013). The efficiency of insects to convert feed into edible food is in part due to the higher fraction of insect consumed (up to 100%), compared to conventional meat (e.g. 40% of live animal weight is consumed with cattle). Insects are poikilothermic, so they do not use their metabolism to heat or cool themselves, reducing energy usage. They tend to have higher fecundity than conventional livestock, potentially producing thousands of offspring (Premalatha et al., 2011). Efficiency is also increased by rapid growth rates and the ability of insects to reach maturity in days rather than months or years.

Isotope analysis of bones indicates that insectivorous diets are entrenched in human evolution (De-Magistris et al., 2015; Ramos-Elorduy, 2009), and a variety of species are currently consumed (>2000 species (Rumpold and Schlüter, 2013)) across many regions of the world (119 countries (Rumpold and Schlüter, 2013)). But issue of limited consumer acceptability is prevalent particularly in western countries. These are also the countries with high animal product consumption rates per capita, and are therefore where a switch from animal product to insect consumption would have the greatest impact. There are already signs that consumer attitudes in developed countries such as the USA and the UK may be starting to change (Jamieson, 2015), and there may be less of a barrier to including insect-derived materials in other products, for example in powdered form (Little, 2015). However, in some jurisdictions, there are legal barriers. For example, within the European Union, regulations on novel food and the legal status of insect-based foods means that insects cannot be processed, and must be marketed whole (De-Magistris et al., 2015).

(b) Cultured meat

Cultured meat, also termed *in vitro*, 'lab-based', or synthetic meat, refers to meat produced outside of a living animal. The meat is produced by culturing animal stem cells in a medium that contains nutrients and energy sources required for the division and differentiation of the cells into muscle cells that form into tissue (Bhat et al., 2015), with commercial scale production anticipated by 2021 (Verstrate, 2016). The tissue produced can be separated for further processing and packaging. The amount of nutrients and energy needed may be relatively small, as only muscle tissue develops, without the need for biological structures such as respiratory, digestive or nervous systems, bones or skin (Bhat et al., 2014). Rapid growth rates mean that tissue is maintained for a shorter time than for animal rearing, further reducing required inputs.

Cell and tissue culture are currently not efficient processes in terms of energy, water and feedstock expenditure, and have been primarily employed in scientific and medical applications (Moritz et al., 2015). The financial and sustainability advantages are also unclear as the reductions in some inputs may be offset by the extra costs of a stricter hygiene regime and other energy inputs (Bhat et al., 2014). The cell culture medium can be produced from materials of animal origin (e.g. bovine serum), but this defeats many of the sustainability benefits of cultured meat (Bhat et al., 2014). Although suitable culture medium can be produced from non-animal sources (e.g. hydrolysed cyanobacteria, sometimes known as blue-green algae (Tuomisto and de Mattos, 2011) and Maitake mushroom extract (Bhat et al., 2014)), an efficient process to manufacture animal-free media is still viewed as a major challenge, and a barrier to cultured meat adoption (Mattick et al., 2015a). Consumer perceptions are also a potential barrier (Hocquette, 2016). The product needs to be of sufficiently similar taste, texture and appearance to livestock meat for wide acceptance, and this is currently difficult to achieve (Moritz et al., 2015).

(c) Imitation meat

Imitation meat or meat analogues attempt to mimic specific types of meat, including the aesthetic qualities (e.g. texture, flavour and appearance) and the nutrient qualities, without using meat products. Soy based products, such as tofu or tempeh, are perhaps the most widely known imitation meats (Malav et al., 2015). Tofu is soybean curd, made from coagulated soy milk, and has been prepared and consumed in Asia for centuries. It can be further prepared to approximate meat products in flavour and texture, e.g. with flavouring added to make it taste like chicken, beef, lamb, ham or sausage (Malav et al., 2015). Soy and tofu contain high levels of protein, while being low in fat (Sahirman and Ardiansyah, 2014). Beef and soy have a similar Protein Digestibility–Corrected Amino Acid Score (PDCAAS), indicating that they have similar protein values in human nutrition (Schaafsma, 2000). More recent imitation meats include mycoprotein-based Quorn (Finnigan et al., 2010), and textured vegetable protein, again often made from soy.

(d) Aquaculture

Global aquaculture is already a major source of food, and has grown substantially over the past 50 years to produce around 61.9 Mt in 2011 (FAO, 2016), which is similar to the quantity of bovine meat (FAOSTAT, 2015b). As a global per capita average, protein from fish contribute 10% (2.72 g/capita/day) of that from meat, milk and eggs; 27.69 g/capita/day (FAOSTAT, 2015b), around half of which is from aquaculture. Asia dominates aquaculture production (accounting for 89 per cent by mass), with 62.4% produced in China alone, due to pre-existing aquaculture practices and a relaxed regulatory framework (Bostock et al., 2010). Carnivorous fish, such as salmon, can consume up to 5 times the quantity of fish (as feed) than they ultimately provide (Naylor et al., 2009). Therefore, limitations on the sustainable sourcing of feed represents a barrier to increases in farmed carnivorous fish (Diana, 2009), making substantial substitution with existing animal products less likely. This issue is less acute for herbivorous and omnivorous species, as they have much lower 'fish-to-fish' conversion ratios, e.g. carp currently has a ratio of 0.1, with further reductions predicted (Tacon and Metian, 2008) as fish derived feed consumption is not essential for their nutrition (Bostock et al., 2010). Freshwater aquacultural systems dominate production, accounting for around two thirds of all outputs from aquaculture. The main species are herbivorous or omnivorous, with largest production from carp, although tilapia and catfish production have increased more recently (Bostock et al., 2010).

3. Comparison of land requirements

To provide an assessment of the consequences of adoption of above alternative protein sources on agricultural land requirements separate scenarios for each were considered, assuming replacement of 50% of current animal products. These scenarios assume that perceptions and diets alter over time, such that current animal product (i.e. meat, milk and eggs) consumption declines and is substituted by a replacement food that provides nutritional content at least as equal in both energy and protein terms. The 50% replacement assumption is largely arbitrary, but is simply used as a reference point against which to compare alternative diets. It would have been equally accurate to select an alternative value, and the relative changes between these substitution scenarios would not have been impacted, i.e. the changes would scale proportionately. Further scenarios considered conventional animal products in the same manner (i.e. 50% replacement), to provide a basis for comparison with the transformative scenarios. The scales of animal product substitution tested is not highly relevant, but rather the comparative outcomes between the substitution scenarios. The scenarios of reduced consumer waste (including both food waste and consumption in excess of nutritional requirements) and global adoption of the current average per capita diets in India and the United States of America were also constructed. These scenarios are not chosen to be equally probable or desirable, but rather to provide a broad comparison between the impacts of potential transformations in consumer behaviour.

3.1. Human appropriation of land for food

Results are expressed using the Human Appropriation of Land for Food (HALF) index (Alexander et al., 2016), giving the percentage of global land surface required to supply the world's population with a particular diet, under current production efficiencies. The baseline 2011 HALF index was calculated from FAO country-level panel data for crop areas, production quantities, commodity uses and nutrient values (FAOSTAT, 2015a, 2015c, 2015d, 2015e, 2015f, 2015g). Following the approach of Alexander *et al.* (2016), 90 commodities (50 primary crops that are directly grown, 32 processed commodities derived from them, and 8 livestock products (2016)), representing 99.4% of global food consumption by calorific value, were considered.

The areas associated with primary crops production were determined using yields adjusted to include losses in storage and transport (overall around 5%), calculated by *pro rata* allocation of these losses to subsequent uses. These yields were multiplied by the quantity of each commodity used as food for human consumption, processing and animal feed (FAOSTAT, 2015a, 2015d) to obtain an associated production area. The areas for the processed primary crops were mapped to the commodities produced, and allocated by economic value (e.g. soybeans processed into soybean oil and meal) (Alexander et al., 2016). The feed use was divided between animal products using estimated feed requirements. Monogastric livestock (i.e. poultry and pigs) nutrition was assumed to be met solely from feed, while feed and grazed pasture is used for ruminant species (e.g. cattle and sheep). Feed requirements were calculated using feed conversion ratios (FCRs), which express the efficiency of converting biomass inputs into animal products (Little, 2014; Macleod et al., 2013; Opio et al., 2013; Smil, 2013). The feed requirements for monogastrics were assigned first, and remaining feed and the total pasture area were then allocated *pro rata* by feed requirements to the ruminant products.

This approach provides the yields for primary crops, processed commodities and livestock products, using 2011 global average production efficiencies. These were used to estimate the cropland and pasture areas needed for diets containing these commodities, with the resulting areas expressed through the HALF index, i.e. as the percentage of total land area required for food production. The HALF index does not provide a land use footprint for particular countries or regions, but addresses questions such as "how much land would be used if the global population adopted diet X". The approach provides a comparative metric of the land requirements of different diets, and a way to consider the impacts from changes in dietary patterns. The inclusion of local production systems within a land footprint would tend to obscures the understanding of the role of diet in the global food system.

3.2. Alternative animal product scenarios

The alternative animal product scenarios assume that 50% of current animal products, evenly distributed across existing sources, are replaced by one commodity, while being constrained to maintaining at least equal quantities of energy and protein within the diet. Nutrient contents and FCRs were estimated for the substitute commodities (Table 1, with assumptions below). The protein and energy contents were used to calculate the mass of the commodity required to replace the conventional foods removed. FCRs were applied to evaluate the feed requirements to produce the substitute product. The feed was assumed to be provided from the current mix and yields of animal feeds, except for imitation meat, which was calculated using soybean production. The net changes in cropland and pasture areas were then calculated assuming the conventional livestock area reduces by 50% (assuming constant production practices) plus the requirements from the replacement commodity.

Table 1. Feed conversion efficiencies, in dry matter (DM) weight of feed required per unit edible weight (EW), for alternatives to convention animal products considered. For conventional livestock feed conversion efficiencies data used and sources are given in Table 1, Alexander et al. (2016)*.*

Commodity	**Percentage edible (% EW of LW)**	**Feed conversion by mass (kg DM feed/kg EW) [uncertainty range]**	**Energy content (MJ/kg EW)**	**Protein content (g / kg EW)**	**Energy feed conversion efficiency [a] (%)**	**Protein feed conversion efficiency [a] (%)**	**Direct energy for housing and processing (MJ / kg EW)**	**Data sources**
Mealworm: larvae (*Tenebrio molitor*)	100	1.8 [b] [1.6-2.1]	8.9	179	33	50	7.3	(Oonincx and de Boer, 2012; Persijn and Charrondiere, 2014; Spang, 2013)
Crickets: adults (*Acheta domesticus*)	80	2.1 [1.9-2.4]	5.9	205	19	49	No data	(Finke, 2002; van Huis, 2013)
Cultured meat	100	4 [2-8]	8.3	190	17	24	18-25 [c]	(Tuomisto and de Mattos, 2011)
Imitation meat (based on soybean curd) [d]	-	0.29 [0.27-0.35]	3.2	81	47	72	11.4	(Sahirman and Ardiansyah, 2014; USDA, 2015; Wang and Cavins, 1989)
Tilapia	37	4.6 [3.7-5.5]	4.0	201	5.8	21.8	5.4	(Pelletier and Tyedmers, 2010; USDA, 2015)
Chinese Carp	37	4.9 [3.9-5.9]	5.3	178	7.3	18.3	5.4 [e]	(Bauer and Schlott, 2009; Tacon and Metian, 2008; USDA, 2015)

Notes:

a. Energy and protein conversion efficiency based on feed content of 15 MJ/kg DM and 200 g/kg protein.
b. Mealworm feed efficiency adjusted from Spang (2013), assuming 62% moisture content (Persijn and Charrondiere (2014).
c. Excluding production of biomass feedstock.
d. Feed columns relates to inputs of soy to tofu production process.
e. Based on Tilapia production.

(a) Insect consumption

Mealworm larvae and adult crickets were selected to assess the impact of insect consumption, based on the availability of data for these species (Table 1). Protein from conventional livestock and insects were considered substitutable on an equal mass basis, as all essential amino acids for humans are available from insects, although profiles differ between species (Persijn and Charrondiere, 2014; van Huis, 2013). Insects are also high in a variety of micronutrients such as the minerals copper, iron, magnesium, manganese, phosphorous, selenium, and zinc and the vitamins riboflavin, pantothenic acid, biotin, and in some cases folic acid (Persijn and Charrondiere, 2014; Rumpold and Schlüter, 2013). However, the analysis is limited to considering equivalence of protein and energy only. Although insects can be produced from organic wastes, given the high levels of production required under this scenario, it is assumed that production is from purpose-grown feed, rather than waste sources.

(b) Cultured (in vitro) meat

Process efficiency values from Tuomisto & de Mattos (2011) were used as FCR, but assuming that the raw materials for the production of the culture medium is from conventional livestock feeds (Table 1). Tuomisto & de Mattos (2011) suggest 99% less land is required to produce cultured meat rather than livestock meat, but this assumes production of biomass for the culture medium using an algae-based system. This increases direct energy requirements while reducing land requirements, but depends upon a conflation of two novel technologies; production of algae biomass and cell culturing of meat. Producing feed from algae is likely to reduce the land required for conventional livestock production, while increasing other inputs, and therefore we consider only the cultured meat aspect. Production of the nutrient 'broth' in which the cells are cultured (Mattick et al., 2015a; Verbeke et al., 2015) is possible from different inputs. However, as commercial-scale processes for cultured meat are not yet available (Mattick et al., 2015a), the assessment of which feedstock would be selected to produce the culture media in the required quantities, and the associated efficiency are both uncertain. To represent this uncertainty the conversion efficiency range tested is large (Table 1).

(c) Imitation meat

The calculation was based on the use of soybean curd, i.e. tofu, for imitation meat. Manufacturing soybean curd from soybeans creates some losses in protein and energy content (Wang and Cavins, 1989), for example during the washing, grinding, boiling and pressing involved (Sahirman and Ardiansyah, 2014), and also requires direct input of energy to these operations (Table 1). The production of the soybean curd was considered analogously to livestock production, with soy being used to produce soybean curd, rather than livestock inputs producing animal products. The losses in preparation of imitation meat from the soybean curd are expected to be low, and given the relatively simple processes, such as extrusion (Malav et al., 2015), have substantially lower direct energy inputs in comparison to cultured meat.

(d) Aquaculture

Production of Chinese carp and tilapia were taken as examples in the analysis, due to their high contribution to current aquaculture and, compared to carnivorous fish (e.g. salmon), their low requirements for fishmeal or fish oil as feeds, and more advantageous FCR. The feed conversion ratios to live weight for tilapia and carp are 1.7 and 1.8 respectively (Tacon and Metian, 2008), but given that only 37% of the fish by weight is fillet (Bauer and Schlott, 2009; Pelletier and Tyedmers, 2010), this leads to a FCR to edible weight of 4.6 to 4.9 (Table 1). Although some fishmeal and fish oil are currently used as feed for these species, these are not essential for nutrition in herbivorous and omnivorous species (e.g. carp and tilapia) (Bostock et al., 2010). Therefore, the assumption is that all feed is provided from land-based production (e.g. soybeans and cereals). Any contribution from fishmeal and fish oil, that could be provided sustainably from fish processing by-products is neglected (Bostock et al., 2010; Tacon and Metian, 2008). The 50% replacement scenario would imply an approximately 10-fold increase in protein terms.

(e) Conventional livestock consumption changes

Each of the conventional animal products was also considered as replacements for 50% of the current mix. Thus, more than half of calories or protein were assumed to be provided by the commodity being considered in each of these scenarios. For example, poultry meat currently provides 24% of all animal proteins, which reduces to 12% under all the other protein meat substitution scenarios except the poultry meat scenario. Under this scenario 62% of animal product consumption is from poultry, i.e. the 12% of unchanged poultry consumption plus the 50% substituted for the current animal product mix. The feed and pasture area requirements were calculated using the results derived from the FAO data (FAOSTAT, 2015a, 2015c, 2015d, 2015e, 2015f, 2015g), as described above.

3.3. Waste and other dietary change scenarios

Scenarios for food waste reduction and for global adoption of the average diets in India and the USA were included from previously calculated results (Alexander et al., 2017, 2016).

(a) Waste reduction

The waste reduction scenario uses losses from Alexander *et al.* (2017). The scenario assumes that the combination of food discarded by consumers and due to over-consumption halves from the 2011 rates to 11% of energy and 26% of protein (assuming requirements of 9.8 MJ/person/day of energy and 52 g/day of protein (Institute of Medicine, 2005; SACN, 2011)). The reduction in this waste was applied equally across all commodities. Losses during production, processing and distribution were not changed, as the focus here is on the impact of consumer behaviour on the food system.

(b) High and low animal product diets

To assess the impact of diets with high and low rates of animal products consumption, the average per capita consumption in the USA and India were chosen, respectively. Alexander *et al.* (2016) used the average consumption per capita for each commodity in these countries to calculate the HALF index for their diets. Additionally, the difference between the global average diet and the diets in each of the countries was decomposed into two parts (Alexander et al., 2016). The first represents a shift in the total quantity of nutrients consumed while holding the proportional contribution of each commodity constant. The second represents a shift in the profile of commodities consumed, while holding the total nutrient level constant.

3.4. Uncertainty quantification

A number of the parameter values used are uncertain, with perhaps the most influential ones being the livestock feed conversion ratios and the food nutrient contents. To assess the impact of these uncertainties, these parameters were randomly sampled from assigned uncertainty ranges (i.e. a Monte Carlo uncertainty method). The range of FCR for conventional livestock was taken as -20% to +20% of the assumed value (Alexander et al., 2016, Table 1), and for the alternative commodities the ranges are given in Table 1. The ranges for protein and energy contents were -10% to + 10% for the 90 agricultural commodities, carp, tilapia, soybean curd and cultured meat. However, the nutrient content of the insect species appears to be less certain, so a -30% to + 30% range was used. All of these uncertainty ranges are indicative of qualitative levels of confidence in the default values used in the absence of relevant quantitative data. Uniform distributions were used for all parameter uncertainties, sampled 500 times. The initial allocation of land use to commodities, using the methodology of (Alexander et al. (2016), was re-run for each sampled set of FCR.

3.5. Yields of alternatives to animal product

The energy and protein produced per unit of agricultural area were found to vary by more than 100-fold across conventional animal products and the alternatives considered (Figure 1). Soybean curd had the highest energy and protein yields (2.2 MJ/m^2 and 57 g/m^2) and beef the lowest (0.02 MJ/m^2 and 0.4 g/m^2). After soybean curd, the two insect species gave the next highest yields. The yields for cultured meat were similar to eggs, and also relatively close to those for poultry. The order of commodities by yield differed between protein and energy, due to the differences in nutrient contents. For example, tilapia has a higher protein, but a lower energy yield, than carp. The areas for the ruminant derived products (i.e. mutton and goat meat, milk, and beef) include both cropland to produce feed and pasture area for grazing, while the other products use only feeds from cropland.

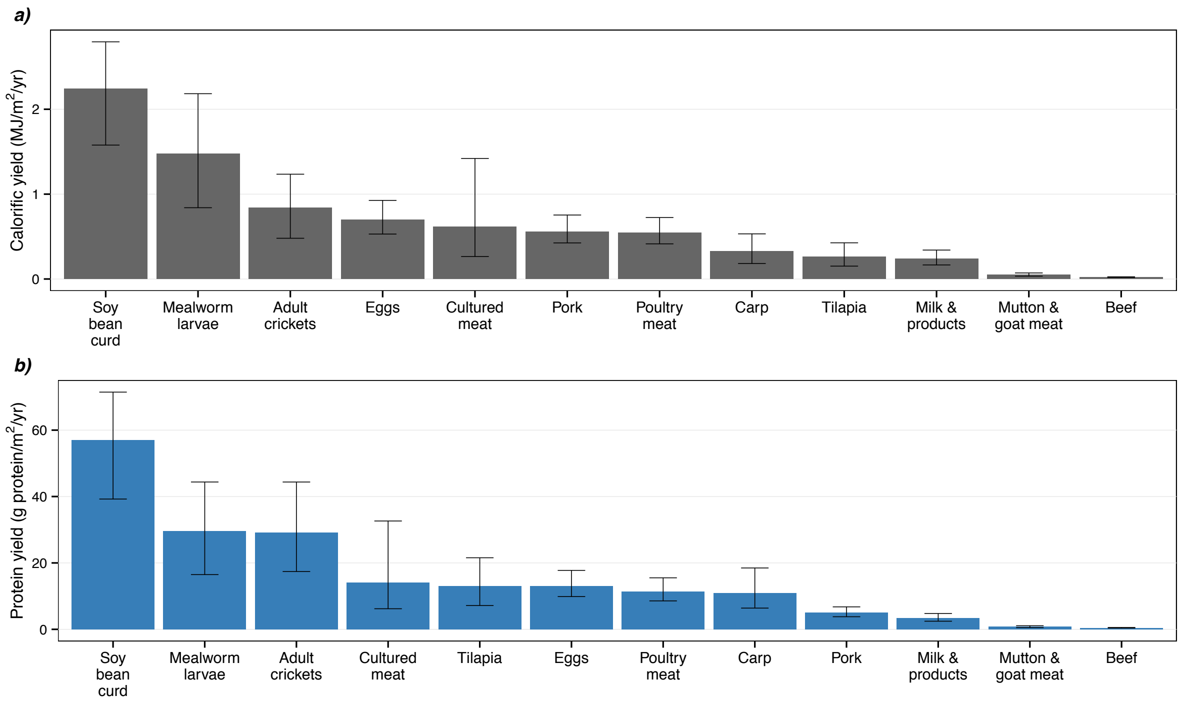

Figure 1. Energy and protein per unit area of agricultural land for conventional and alternatives to animal production. Error bars show the yield range from uncertainty in feed conversion ratios and nutrient contents.

3.6. Land requirements of scenarios

Global cropland and pasture areas vary substantially under the scenarios (Figure 2). The animal product substitute scenarios suggest that the HALF index (i.e. the percentage of land area required for food production), is 21.8 for soybean curd, and 112.2 for beef, compared to a baseline of 35.1 in 2011. There is also considerable variability in the cropland areas. The highest cropland requirement occurs in the tilapia scenario, where an additional 709 Mha of cropland is needed for feed, a 46% increase in the total cropland area. However, total agricultural land area reduces by 18% or 892 Mha, as cropland increases are more than offset by a 1601 Mha drop in pasture area. For the animal product replacement scenarios, the lowest cropland area is for milk with the cropland reducing by 217 Mha (14%) of cropland and 590 Mha (18%) of pasture, due to higher feed conversion ratios than the current mix of animal products, and because nutrients are also derived from pasture. Pasture changes dominate the results, with the cropland changes for most of the other scenarios being more modest. For example, the results with the largest agricultural area change have only a 7-9% change in cropland, with soybean curd decreasing by 137 Mha and beef increasing by 110 Mha, while the pasture areas decrease by 1601 Mha and increase by 9916 Mha, respectively.

The animal production replacement scenarios all provide at least the same amount of both energy and protein. The binding constraints were by energy for all scenarios except pork. In these scenarios the replacement food provides an equal amount of energy, but a greater quantity of protein. Conversely, for pork the binding constrained was on protein, due to the relatively low ratio of protein to energy in pork compared to the other animal products (FAOSTAT, 2015e).

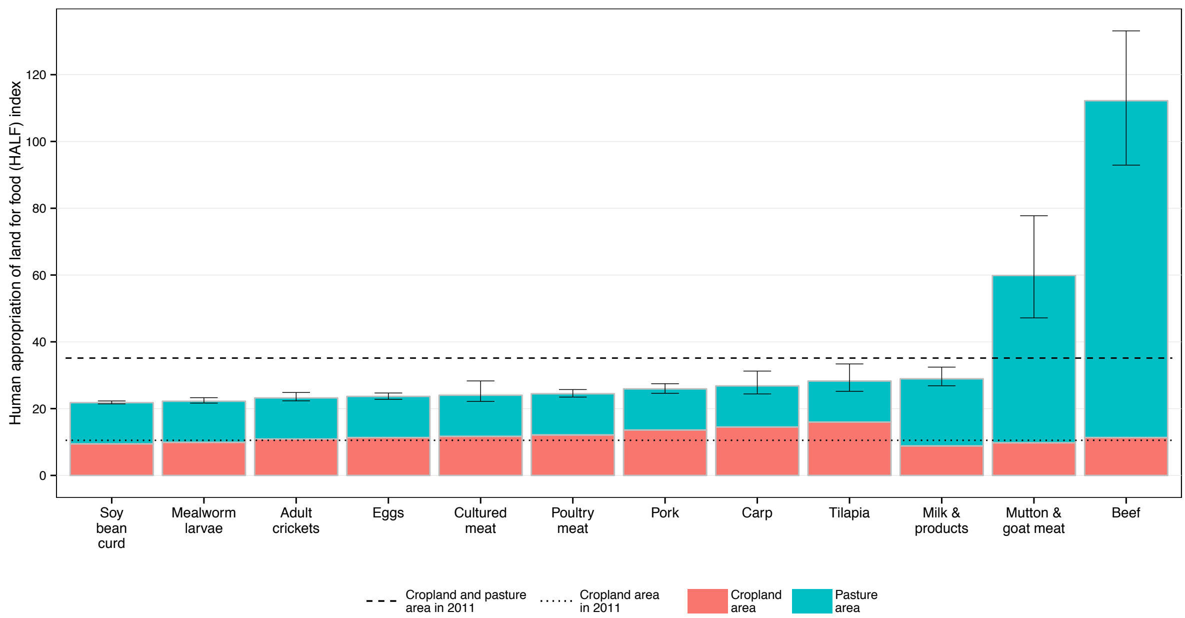

Figure 2. Total cropland and pasture areas for food production under scenarios assuming 50% of current nutrients from animal productions are substituted with the indicated food, to provide at least equal energy and protein. The results are expressed as the percentage of global land required, or HALF index, based on 2011 population and food production systems. Error bars show the HALF range from uncertainty in feed conversion ratios and nutrient contents.

The range of agricultural land areas required based on uncertainty in FCRs and food nutrients (Figure 2, error bars) are small for the animal product scenarios with low HALF indices (e.g. soybean curd and insects). This is because the uncertainty from new food commodities, e.g. for soybean curd, is only a small proportion of the total agricultural area, therefore a large percentage uncertainty (Figure 1) only produces a small absolute uncertainty in land area (Figure 2). The opposite is the case for the results with higher HALF (e.g. beef), where the areas for replacement production are large and so, therefore, are the associated uncertainties. Figure 1 shows uncertainty for each scenario per unit of energy or protein.

The similarity in land requirements between the commodities with low HALF indices (Figure 2) suggests that substantial land use and associated environmental benefits could be achieved from the adoption of any of them individually or in combination. Land requirements are always reduced by further increases in efficiencies of production per unit area. For example, a doubling of efficiency between two alternative scenarios always produces a halving of land use requirements. However, as the land use requirements decrease, the differences in the absolute areas also decrease, creating diminishing returns from increasing efficiency. The selection of the most appropriate mix of the more efficient products (Figure 2) may therefore be more greatly influenced by other production externalities, e.g. biodiversity or water usage, rather than the land requirements.

Table 2 summarises these meat substitution scenario results and also includes the results from the consumer waste and scenarios from adoption of high and low animal product diets (based on average consumption in India and the USA) (Alexander et al., 2017, 2016). As these additional scenarios involve different assumptions, i.e. they do not consider a 50% substitute of animal products, direct comparisons between these two scenario groups must be limited. However, the high and low animal product diets (based on USA and India), respectively, were found to have higher and lower land impacts than the meat alternatives, with the exception of beef (Table 2). This is because the diets include both a shift in the amounts of food consumed and, more importantly, in the types of food consumed (Alexander et al., 2016). These diets involve different rates of meat consumption, and therefore are not restricted to maintain 50% of the current animal products as in the other scenarios. The consumer waste scenario, halving foods discarded and lost due to over-consumption, was found to spare 9% of agricultural land.

Table 2. Summary of results across all scenarios, ordered by increasing agricultural land use.

Scenario	Description	Percentage change in required agricultural area for food	HALF index	Comments
Low animal product diet	Average diet globally becomes that of the average diet in India	-55	15.7	Influenced by lower overall consumption, and lower rates of meat in the diet. In both these aspects global diets are changing in the opposite direction of current trends, making this scenario of low plausibility.
Soybean curd	Soybean curd replaces 50% of current animal products	-35	21.7	Increase in direct energy inputs in comparison to animal products, but less substantial than for cultured meat. 50% uptake seems unlikely to be acceptable to consumers.
Insects	Mealworm larvae replaces 50% of current animal products	-34	22.2	Consumer acceptability barriers in some regions. A lower level of uptake in combination, perhaps as an ingredient, e.g. in pre-packaged foods, seems more likely.
Most efficient conventional animal products	Eggs or chicken replaces 50% of current animal products	-30 to -28	23.7 to 24.4	The direction of recent changes, with rapid growth in the consumption rates for chicken in particular, supported by intensification in production.
Cultured meat	Cultured meat replaces 50% of current animal products	-29	24.0	Technology still rather uncertain (Bhat et al., 2014), and benefits compared to other sources of nutrients currently are not well demonstrated. The high direct energy used in production also a concern.
Most efficient aquacultural product	Carp replaces 50% of current animal products	-22	26.8	Potential for environmental pollution issues with large-scale production, although this is also the case with other intensive animal production.
Milk and products	Milk and products replaces 50% of current animal products	-16	28.9	Associated with the largest reduction of cropland, while still providing material reduction in overall agricultural area.
Reduction in waste	Consumer waste, including food discard and due to over-consumption is halved	-9	32.0	Feasible, but opposite to current direction of change, particularly with respect to over-consumption. Health, as well as environmental, benefits for policies or social changes to reverse these changes.
High animal product diet	Average diet globally becomes that of the average diet in the USA	+178	97.7	Not possible given production systems currently used. Direction of recent changes for overall nutrients and rates of animal products consumption. Approaching this consumption globally would be expected to increase food price, suppress demand and intensify production practices.
Least efficient conventional animal product	Beef replaces 50% of current animal products	+204	112.2	Physically impossible with production systems currently used, and contrary to current trends of average per capita consumption falling since 1970s.

4. Discussion

(a) Limitations of the analysis

A stylised and exploratory approach is used to better understanding and ensure comparison on a like-for-like basis of potential land use outcomes across a range of scenarios, from the more unusual and transformational (e.g. insects and cultured meat), to the more conventional (e.g. changes in proportions of livestock demand). The replacement of at least equal quantities of protein and calories has been considered, leaving the potential for reductions in micronutrients between the scenarios. The results are not intended as predictive, nor are they presented to suggest equal plausibility, but rather to allow comparisons in land use requirements between the scenarios.

Fixed global average production figures based on 2011 were used and no spatial variation in production practices are taken into account. These production practices would be expected to respond to the substantial changes considered in these scenarios, mediated by international trade in agricultural commodities. For example, increased agricultural land requirement would tend to intensify production, with higher rates of inputs used to achieve greater yields. Conversely, if less agricultural land is needed for food, this may cause a lowering of the production intensity. In both cases, such adaptation in production moderates the land use consequences, but alters the resource requirements for other inputs, e.g. fertiliser or pesticide use (Hertel et al., 2016; P. Smith, 2013). However, the results do characterise the demands placed on agricultural production, which can be interpreted as implying an increase in agricultural areas, an equivalent increase in productive efficiency (perhaps through greater inputs, i.e. higher intensity), or some combination of the two. Nonetheless, comparison with previous more complex model results suggests that the outcomes here are broadly equivalent. For example the vegan and vegetarian diets in Erb et al. (2016) have a central value for cropland area of approximately 1200 and 1000 Mha, respectively, compared to the low meat diet used here (based on the average diet in India) of 1022 Mha. As expected, for the reasons given above, changes in intensity considered in Erb et al. (2016) but not here appear to moderate the land use outcomes, i.e. for less agricultural land to be relinquished, but coupled with a decrease in intensity of production. Therefore, although the adopted approach neglects aspects that would allow robust spatial or temporal predictions of land use, it does provide a consistent methodology across scenarios allowing comparisons between them, a primary aim of the study.

The results demonstrate that milk production is more efficient that the current animal product mix, with the milk scenario showing a decrease in land requirements (Table 1). Cull dairy cows and male dairy calves could also be used to produce beef, which is not accounted for in these results. If the additional beef production from an expanded dairy sector were considered, the land requirements in the milk scenario would be further reduced, as less land would be required to produce the remaining beef consumed. The magnitude of this bias is perhaps moderate, as the fraction of emissions from the dairy herd currently assigned to milk rather than meat production is between 90-96% (Opio et al., 2013).

(b) Imitation meat and soybean production

The imitation meat scenario, based on soybean curd, implies that more cropland is used for growing soybeans, while the other meat replacement scenarios use a more diverse mix of feeds. The additional soybean areas may be less suited to the crop and so would have lower yields than existing production, potentially leading to an underestimate of the area needed when using average yields. An additional 111 Mha of soybean area was calculated as needed (i.e. a doubling of 2013 area (FAOSTAT, 2015c)), while 248 Mha of cropland currently used for animal feed is spared. Therefore, the net cropland area decreases in this scenario suggest that suitable land may be available, although this would also be constrained by climatic suitability. However, higher soybean yields would be anticipated to have only a small impact on the results as the net percentage agricultural area change is dominated by the change in pasture area. The expansion of soybean area may have substantial local impacts, e.g. on biodiversity and soil quality, due to the intensity of production. However, the land spared from agricultural production by the transition could be potentially used to offset such negative outcomes. This would be a form of 'land sparing', i.e. separation of land for conservation and food production, in contrast to 'land sharing' with integration of conservation and production (Phalan et al., 2011). However, attempting to account for the associated trade-offs and scale effects, as well as the challenges and controversy involved (Fischer et al., 2014), are out of scope for consideration here.

(c) Cultured meat and energy

The results suggest that the benefits claimed for cultured meat (Tuomisto and de Mattos, 2011) may not be justified. Although cultured meat was found to have a lower land footprint than beef, it had a similar efficiency to poultry meat (Figure 1 and 2), but with substantially higher direct energy requirements (Table 1 and S1). Direct energy inputs are needed for cultured meat to process raw biomass material into the cell medium, to then culture the cells and process them into a consumable product, including sterilisation and hydrolysis (Tuomisto and de Mattos, 2011). Conventional livestock use direct energy primarily in housing, e.g. lighting, heating and cooling (Macleod et al., 2013). Direct energy inputs for cultured meat (18-25 GJ/t (Tuomisto and de Mattos, 2011), Table 1) are higher than any of the other foods considered here (at least four times the highest conventional animal product, poultry meat (4.5 GJ/t (Macleod et al., 2013)). This suggests that a low-cost and low-carbon source of energy may be a prerequisite for cultured meat to be economically and environmentally viable. Furthermore, the provision of growth factors, vitamins and trace elements, e.g. B12, will also have an impact on the resources used for cultured meat, although the scale of this is unclear. However, the overall primary energy used in the production of cultured meat production was shown to be 46% lower than for beef production (e.g. including energy in fertiliser production and machinery), but 38% higher than for poultry meat. Given the relative novelty of this technology, further development and optimisation may be able to reduce these energy and cost requirements and increase the efficiency of production (Bhat et al., 2017). These improvements would potentially involve development of improved methods for producing the cell culture medium beyond that assumed here. The types of feed used may not match the current animal feed mix, although the land use consequences of such differences are likely to be lower than that associated with the uncertainty in efficiency of cultured meat production, and would not be expected to alter our conclusions. Overall, currently cultured meat could provide some benefits (e.g. land use savings compared to beef), but result in higher direct energy requirements and also potentially primary energy (e.g. in comparison to poultry meat). This conclusion concurs with a more recent anticipatory life cycle analysis of culture meat production (Mattick et al., 2015b).

(d) Insects, promising but more research needed

Insects are the most efficient animal production system considered, although less so than soybean curd. However, insects have the additional advantage that they are able to use a wide variety of feeds, including by-products and waste (Ocio and Vinaras, 1979; van Broekhoven et al., 2015). The results here assume that insect feed uses the same mix of feeds currently used for conventional livestock. However, if half of food discarded by consumers (from Alexander et al. (2017)) could be used as feed for mealworms, this would replace 8.1% of current animal production. Where the total feed is reduced there is potential for this to occur primarily for food commodities (e.g. cereals), and thereby increase the proportion of by-products. Although by-products are ascribed some value when considering their impacts (Elferink et al., 2008), the system efficiency increases by replacing lower yielding conventional livestock with insects (Figure 1). For instance, soybeans could be used to produce soybean curd, and then feed insects from the residues.

More research is needed to understand how the large scale production of insects could be achieved, the inputs required, the suitability of feeds, and other constraints (e.g. location) (van Huis, 2013). There is little published data on the feed efficiency of insect production. However direct energy inputs for intensive insect production appears comparable to intensive conventional livestock production (Oonincx and de Boer, 2012). Perhaps the biggest barrier to the large scale global adoption of insects as a food source is consumer acceptability (Looy et al., 2013; Shelomi, 2015), where again further research is required to understand how best to increase adoption and what rate and levels of consumption might be possible.

(e) A future for ruminants?

The land use footprint of ruminant meat production is high, and therefore consuming more beef and sheep meat requires large increases in land areas (Figure 2). Although ruminants are less efficient converters of feed to edible foods than monogastrics (Table 1), their high reliance on forage that is inedible to humans from non-arable land reduces their claim for feeds produced on cropland (Smil, 2013). Livestock production can also provide a range of other benefits, e.g. recycling plant nutrients, maintaining ecosystems and providing social benefit (Janzen, 2011; Oltjen and Beckett, 1996). Therefore, ruminants that are mainly grass-fed from land that is unsuitable for the production of other crops may provide substantial benefits, but this implies a move away from intensive production practices, i.e. that use large quantities of feed produced from cropland. Such extensive grazing based systems are likely to produce a reduced quantity of livestock, and therefore per capita consumption rates of ruminant meat would have to continue to fall to avoid unsustainable land use change. Additionally, changes towards consumption of diets with lower land use requirements also provide the prospect of reduced competition for land between food production and climate change mitigation measures, e.g. bioenergy or afforestation (Smith et al., 2014).

5. Conclusions

These results suggest that alternatives to the current mix of livestock production systems could substitute current animal products and substantially reduce the current agricultural land use footprint from food production. Reducing meat consumption overall is likely to have the greatest effect on the land use footprint, but replacing beef or lamb with any of the foods considered here has the potential for substantial sustainability benefits. Although, the two most efficient products considered, i.e. imitation meat and insects, both come with consumer perception barriers, a shift towards poultry meat, eggs and milk was also found to offer land use and associated environmental benefits, of only slightly smaller magnitudes. Reductions in consumer waste have potentially important but smaller impacts on resource requirement than the other scenarios considered. We conclude that a diet which reduces agricultural land requirements may best be achieved through a combination of approaches, including both waste reduction, shifts towards more efficient conventional animal products (e.g. chicken and eggs), and greater use of alternatives such as insect and imitation meat. A more balanced approach than those in the stylised scenarios considered here would also require less extreme shifts in diets and therefore need less dramatic changes in consumer consumption habits. This work focuses principally on the land requirements, although out of scope here, a similar consistent greenhouse gas lifecycle analysis across all options is warranted, as well as consideration of consequences for biodiversity, water requirements and other ecosystem services. Further research is also required into the technologies and production systems for the large scale production of insects, including what feeds are most appropriate and the potential use of food waste and by-products, and to better understand how consumer behaviour and preferences can be influenced towards a healthier and more sustainable diet.

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