Science of the Total Environment 536 (2015) 419–431

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Biodiversity conservation: The key is reducing meat consumption

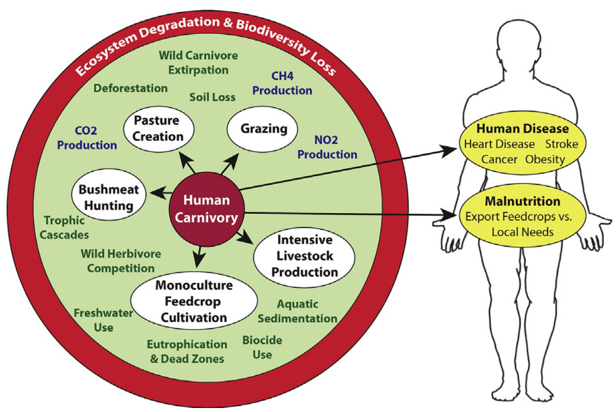
Brian Machovina [a,b,*], Kenneth J. Feeley [a,b], William J. Ripple [c]

[a] Florida International University, Miami, FL 33199, USA
[b] Fairchild Tropical Botanic Garden, Coral Gables FL 33156, USA
[c] Department of Forest Ecosystems and Society, Oregon State University, Corvallis, OR 97331, USA

HIGHLIGHTS

- Patterns of meat consumption in tropical Americas, Africa, and Asia are examined.
- Rates of meat production of tropical megadiverse countries are increasing.
- Some countries may require 30–50% increases in land for meat production in 2050.
- Livestock consumption in China and bushmeat in Africa are of special concern.
- Solutions include reduction, replacement, and reintegration of livestock production.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 25 March 2015
Received in revised form 30 June 2015
Accepted 5 July 2015
Available online xxxx

Keywords:
Biodiversity loss
Livestock
Meat consumption
Climate change
Permaculture

ABSTRACT

The consumption of animal-sourced food products by humans is one of the most powerful negative forces affecting the conservation of terrestrial ecosystems and biological diversity. Livestock production is the single largest driver of habitat loss, and both livestock and feedstock production are increasing in developing tropical countries where the majority of biological diversity resides. Bushmeat consumption in Africa and southeastern Asia, as well as the high growth-rate of per capita livestock consumption in China are of special concern. The projected land base required by 2050 to support livestock production in several megadiverse countries exceeds 30–50% of their current agricultural areas. Livestock production is also a leading cause of climate change, soil loss, water and nutrient pollution, and decreases of apex predators and wild herbivores, compounding pressures on ecosystems and biodiversity. It is possible to greatly reduce the impacts of animal product consumption by humans on natural ecosystems and biodiversity while meeting nutritional needs of people, including the projected 2–3 billion people to be added to human population. We suggest that impacts can be remediated through several solutions: (1) reducing demand for animal-based food products and increasing proportions of plant-based foods in diets, the latter ideally to a global average of 90% of food consumed; (2) replacing ecologically-inefficient ruminants (e.g. cattle, goats, sheep) and bushmeat with monogastrics (e.g. poultry, pigs), integrated aquaculture, and other more-efficient protein sources; and (3) reintegrating livestock production away from single-product, intensive, fossil-fuel based systems into diverse, coupled systems designed more closely around the

* Corresponding author.
E-mail address: brianmachovina@gmail.com (B. Machovina).

http://dx.doi.org/10.1016/j.scitotenv.2015.07.022

structure and functions of ecosystems that conserve energy and nutrients. Such efforts would also impart positive impacts on human health through reduction of diseases of nutritional extravagance.

Contents

1. Introduction . . . 420
2. Patterns of biodiversity loss driven by meat consumption in the tropics . . . 420
2.1. Trends and projections . . . 420
2.2. Increasing meat production in biodiverse countries . . . 421
2.3. The importance of China . . . 422
3. Livestock-driven climate change . . . 424
3.1. Effects on biodiversity . . . 424
3.2. Contribution of livestock to greenhouse gases . . . 424
3.3. Important role of ruminants . . . 424
4. Human health . . . 424
5. Solutions . . . 425
5.1. Reduce . . . 425
5.2. Replace . . . 426
5.3. Reintegrate . . . 427
6. Conclusions . . . 428
Appendix A. Supplementary data . . . 428
References . . . 428

1. Introduction

Livestock production is the predominant driver of natural habitat loss worldwide. Over the 300 years ending in 1990, the extent of global cropland area increased more than five-fold and pasture areas increased more than six-fold, the latter encompassing an area 3.5 times larger than the United States (Goldewijk, 2001). A direct cost of land being converted to food production was the loss of nearly one-half of all natural grasslands and the loss of nearly one-third of all natural forests worldwide (Goldewijk, 2001). Although much of habitat lost to agriculture in the 1800s was temperate forests and grasslands, the second half of the 1900s saw rapid agricultural expansion in tropical countries, predominantly at the expense of biodiverse tropical forests (Gibbs et al., 2010). Agricultural expansion is, by far, the leading cause of tropical deforestation (Geist and Lambin, 2002). Although some agricultural expansion is driven by farmers growing crops for direct human consumption, livestock production, including feed production, accounts for approximately three-quarters of all agricultural land and nearly one-third of the ice-free land surface of the planet, making it the single largest anthropogenic land use type (Steinfeld et al., 2006a). Livestock comprise one-fifth of the total terrestrial biomass, and consume over half of directly-used human-appropriated biomass (Krausmann et al., 2008) and one-third of global cereal production (Foley et al., 2011; Alexandratos and Bruinsma, 2012). Though difficult to quantify, animal product consumption by humans (human carnivory) is likely the leading cause of modern species extinctions, since it is not only the major driver of deforestation but also a principle driver of land degradation, pollution, climate change, overfishing, sedimentation of coastal areas, facilitation of invasions by alien species, (Steinfeld et al., 2006a) and loss of wild carnivores (Ripple et al., 2014a) and wild herbivores (Ripple et al., 2015). Global trade is an underlying and powerful driver of threats to biodiversity (Lenzen et al., 2012), and international trade of feedcrops and animal products is growing rapidly (Keyzer et al., 2005b; Godfray et al., 2010). Current global rates of extinction are about 1000 times the estimated background rate of extinction, (Pimm et al., 2014) and the number of species in decline are much higher in the tropics — even after accounting for the greater species diversity of the tropics (Dirzo et al., 2014). Here we present an overview of the connection between animal product consumption and current and likely future patterns of ecosystem degradation and biodiversity loss, the important influence of China in this relationship, the interwoven role of climate change, as well as the direct linkages with human health. In addition, we propose solutions for potentially reducing the negative effects of animal product consumption on ecosystems, biodiversity, and human health.

2. Patterns of biodiversity loss driven by meat consumption in the tropics

2.1. Trends and projections

Animal product consumption is ubiquitous, but consumption levels, types and levels of livestock production, and future projected growth vary among Earth's tropical regions. The Amazon is the planet's largest continuous tropical forest and is a primary example of biodiversity loss being driven by livestock production. Never before has so much old-growth and primary forest been converted to human land uses so quickly as in the Amazon region (Walker et al., 2009). Over three-quarters of all deforested lands in the region have been converted to livestock pasture and feedcrop production for domestic and international markets (Nepstad et al., 2006; Nepstad et al., 2008; Walker et al., 2009). Rising worldwide demands for meat, feedcrops, and biofuel are driving rapid agro-industrial expansion into Amazon forest regions (Nepstad et al., 2008). Although there have been some recent brief periods (2006–2010) when deforestation rates slowed in the Amazon as feedcrop (soy) production expanded more into pasture (Macedo et al., 2012), or were offset by clearing of native vegetation in the adjacent Cerrado region (Gibbs et al., 2015), rates have recently increased. The deforestation accumulated during the period from August 2014 to April 2015, corresponding to the first nine months of the calendar for measuring deforestation, reached 1898 km^2, a 187% increase in deforestation in relation to the previous period (August 2013 to April 2014) when it reached 662 km^2 (Fonseca et al., 2015). Feedcrop production as well as pasture is projected to continue expanding in the Amazon (Masuda and Goldsmith, 2009). Eventually, cleared land that is suitable for feedstock soy production will become scarce and remaining forests outside of protected areas in the Brazilian Amazon will be at risk of conversion to soy (Nepstad et al., 2014). The woodland–savannah ecosystem of the Cerrado bordering the south-southeastern region of the Amazon is another expansive and diverse tropical habitat. More than half of the Cerrado's original expanse has already been converted to agriculture (Bianchi and Haig, 2013), primarily for the production of beef and soy. At the current rate of loss, the entire 2,000,000 km^2 of the Cerrado ecosystem (21% of Brazil's territory) could be altered in less than two decades (Steinfeld et al., 2006a). As another neotropical example, nearly half of Costa Rica's formerly highly-diverse tropical forests are now cleared and dedicated to livestock production (Morales-Hidalgo, 2006). In fact, livestock grazing in pastures is the top land use in Costa Rica, covering four times more land than is under protected status — this in a country often considered a model for biodiversity protection (Boza, 1993). The conversion of forests to pasture in other Central American and Latin American nations has been similarly extensive (Szott et al., 2000).

In some other tropical areas there is little evidence of the livestock industry as a major factor in deforestation. For example, in Africa, timber harvesting and fire appear to be the two main processes leading to deforestation, with instances of farms replacing forest predominantly due to small-scale cropping (Steinfeld et al., 2006a). However, a rise in feedstock production is projected for Africa as international agricultural companies are acquiring or leasing land in Africa to grow feedstocks for export markets (Rulli et al., 2013), modeled after the industrial development of the Brazilian Cerrado region (Clements and Fernandes, 2013). Hunting of wildlife as a direct meat source is often considered to be a more immediate and significant threat to the conservation of biological diversity in tropical forests than deforestation (Wilkie et al., 2005). The multibillion-dollar trade in bushmeat, especially critical in Africa and southeastern Asia, is among the most immediate threats to the persistence of tropical vertebrates (Brashares et al., 2004), which also causes many cascading trophic effects (Dirzo, 2013; Ripple et al., 2014a). Hunting, habitat modification, and denial of access to water and other resources by humans, in combination with competition and disease transfer with livestock are driving critical decreases of wild ungulates in Africa and southeastern Asia (Daszak et al., 2000; Prins, 2000; Ripple et al., 2015).

Agricultural production in tropical Asia, which has transformed natural habitats for thousands of years, is based primarily around the intensive production of rice and wheat and other secondary crops. Multipurpose livestock are integrated with many crops in small-scale, farming systems which characterize historical agriculture systems in Asia. This integration intensifies total output, and the closed nature of these mixed farming systems makes them less damaging to the environment. However, in many Asian countries all of the available arable land is nearly completely utilized. In Southeast Asia, shifting cultivation is widely practiced and is associated with deforestation and erosion (Devendra and Thomas, 2002a). Under growing demand by urbanizing populations, livestock production is rapidly changing in Asia, with both an increase of production and a shift away from mixed farming systems to intensive production systems located proximate to urban markets. This drives negative environmental consequences of increased monoculture feedstock demands at local and international scales as well as increased pollution of surface water, ground water and soils by nutrients, organic matter, and heavy metals (Rae and Hertel, 2000).

2.2. Increasing meat production in biodiverse countries

Because of its devastating effects on natural habitats and species, land-use change is projected to continue having the largest global impact on biodiversity, especially in tropical forests (Sala et al., 2000) where societies are increasing animal product and feedcrop production. The health of many of the world's poorest people living in developing countries would be improved if they could include more essential fatty acids, minerals, vitamins and protein in their diets, which could be achieved by both animal and plant-based sources (Young and Pellett, 1994; Sanders, 1999; Tilman and Clark, 2014). The rapid expansion of livestock production in developing countries has been referred to as the "livestock revolution" (Delgado, 2003). As incomes in many developing countries have grown in recent decades, per capita consumption levels of animal products have also increased (Steinfeld et al., 2006b), including strong growth in the tropics (Figs. 1 & 2) (Tropics, 2014). Half of global meat production now takes place in developing countries (Green et al., 2005), where annual per capita consumption of meat more than doubled from 11 kg to 25 kg from 1973 to 1997 (Delgado, 2003; Steinfeld et al., 2006a). With continued economic growth, per capita meat consumption in some developing countries can be expected to quickly approach levels found in high-income industrialized countries of between 80 kg and 130 kg yr^{-1}. (Steinfeld et al., 2006b).

Animal products currently constitute a median of approximately 21% of the weight of food in global human diets — a 24% increase since the 1960s. However, great disparity exists among developed and developing countries. Many developed countries have consistently maintained high animal product consumption rates constituting 40% or more of diets by mass. This is contrasted with the majority of sub-Saharan countries and most of Southeast Asia which have had a consistent pattern of low animal product consumption rates (<10%). Of concern are the historically-low, but increasing animal consumption rates found in several countries throughout Asia, Africa, and South America — most notably China which quadrupled its animal product consumption from 5% to 20% of diets since the 1960s (Bonhommeau et al., 2013). Increasing per capita consumption of animal products combined with rapidly growing populations in most developing countries will be a potent force driving habitat and biodiversity loss. Much of the future population growth will occur in biodiverse tropical nations. Today the tropics contain about 40% of the global human population, but house over half of all children under five. Within 40 years, it is expected that more than half the world's population will be in the tropics, containing over two-thirds of its young children, and adding 3 billion people by the end of the century (Tropics, 2014).

Across global ecosystems, twenty-five biodiversity hotspots have been identified (Myers et al., 2000) that collectively contain as endemics approximately 44% of the world's plants and 35% of terrestrial vertebrates in an area that formerly covered only about 12% of the land surface of the planet. Due to human activities, the total extent of these hotspots has been reduced by nearly 90% of the original size — meaning that this wealth of biodiversity is now restricted to only <2% of Earth's land surface (Myers et al., 2000). Among the top five hotspots for endemic diversity, the Caribbean retains only 11.3% of its primary vegetation, Madagascar 9.9%, Sundaland 7.8% and Brazil's Atlantic Forest 7.5%. When analyzed by political boundaries, 17 megadiverse countries have been identified which collectively harbor the majority of the Earth's species (Mittermeier et al., 1997). Fifteen of the megadiverse countries are developing countries located in the tropics. Extrapolating rates of production of cattle, pigs, and chickens from 1985–2013 in these countries (FAO, 2014) and the land area required to produce them (Röös et al., 2013) indicate that the developing tropical megadiverse countries could need to expand their agricultural land base by an estimated 3,000,000 km^2 over the next 35 years to meet projected increases in meat production (Fig. 3). Eleven of the tropical megadiverse countries have rates of increasing per capita meat (beef, pork, chicken) production (Fig. S1), and, by 2050, several of them (Ecuador, Brazil and China) are on trajectory to require new areas of land for meat-production that are >30% expansions of their total current agricultural areas. The additional land required is equivalent to approximately 10%, 10%, and 18% of the total country areas, and 26%, 24%, and 111% of size of the total protected areas in Ecuador, Brazil and China, respectively. In the Philippines, the area of land required for future meat-production is projected to exceed 50% of the country's total current agricultural lands, and is equivalent to approximately 20% of the total country's area and 73% of the size of its protected areas. To help meet these meat production expansion needs, developing countries are

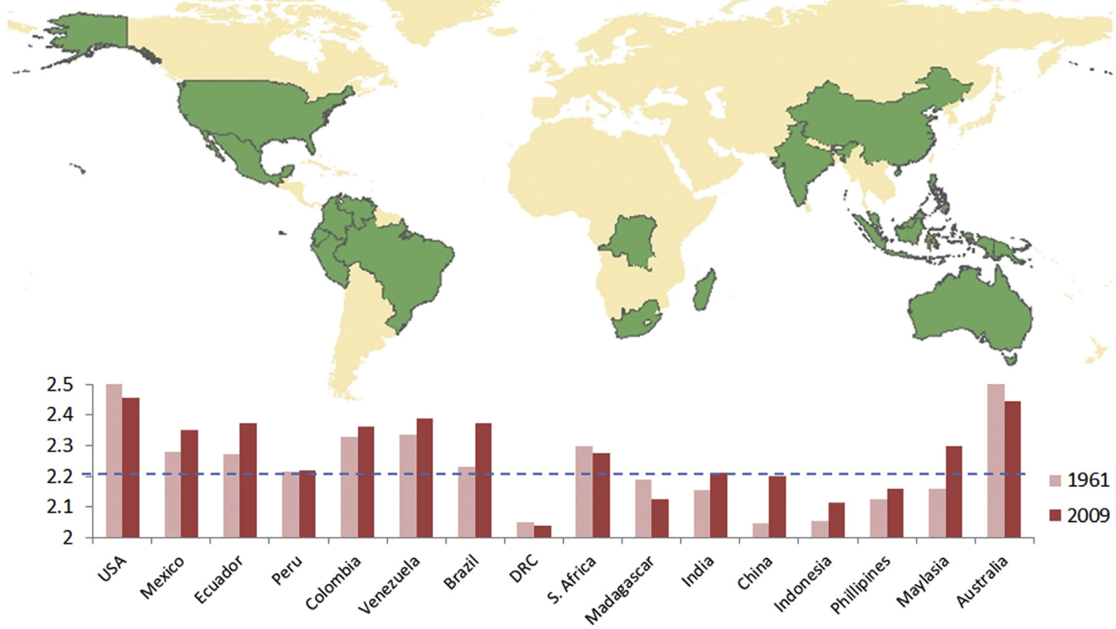


Fig. 1. Human Trophic Level (HTL) of megadiverse countries based on consumption of livestock products in 1961 and 2009 (Bonhommeau et al., 2013). An HTL of 2 indicates 0% of a nation's diet is composed of animal products whereas an HTL of 2.5 indicates 50% of a nation's diet composed of animal products. The blue line indicates the global median value of 2.21. Eleven of the 16 megadiverse countries represented here have increased HTLs from 1961 to 2009. (data not available for Papua New Guinea, which is ranked among the 17 megadiverse countries) (Myers et al., 2000). Consumption of bushmeat, especially important in Africa and southeastern Asia, were not included in analysis.

both acquiring land in other countries as well as selling or leasing land within their borders to fulfill other nation's food demands (Rulli et al., 2013).

The global increase in livestock production is destroying natural habitats and driving the loss of species at multiple trophic levels with cascading effects on biodiversity and ecosystem function. In a recent analysis of threats to the world's largest terrestrial carnivores (Ripple et al., 2014a), 94% were found to be negatively affected by either habitat loss and/or persecution due to conflict with humans. Being the largest cause of global habitat loss, livestock are likely the most significant cause of the decline of large carnivores (Machovina and Feeley, 2014c). Persecution of carnivores via shooting, trapping or poisoning is commonly a result of interactions with livestock. The loss of top predators can cause many negative trophic cascading effects within ecosystems (Ripple et al., 2014a). Large wild herbivores are generally facing dramatic population declines and range contractions, such that ~60% are threatened with extinction, with major threats including hunting, land-use change, and resource depression by livestock (Ripple et al., 2015). Grazing livestock can also cause more direct effects on entire ecosystems, such as riparian systems. For example, heavy grazing in riparian zones can lead to vegetation loss, soil erosion and reductions of fish and wildlife (Beschta et al., 2013; Batchelor et al., 2015). The conversion of forests into pasture and the industrial production of feedcrops also cause extensive soil erosion and downstream sedimentation of high diversity coastal habitats like coral reefs (Rogers, 1990). Manure effluent and extensive over-use of fertilizers for feedstock production, especially corn (West et al., 2014), also pollute many waterways and are significant contributors to the more than 400 dead zones that exist at river mouths worldwide (Diaz and Rosenberg, 2008).

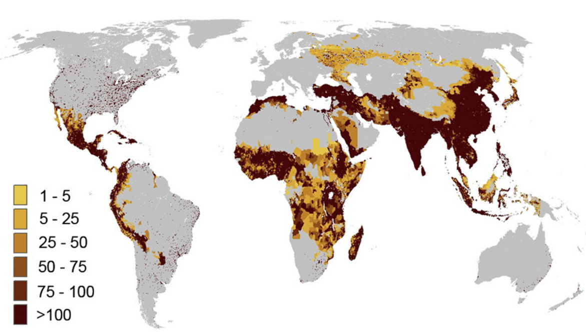


Fig. 2. Map showing projected global increases of demand for meat (beef, pig, chicken) from 2000–2030. Legend indicates kg/km^2 demand increase (FAO, 2011). Developing countries of Latin America, Africa, and Asia exhibit the highest levels of demand increase. Data for Europe were not available.

2.3. The importance of China

Because of changing dietary habits and increasing population densities, China will have especially profound future effects on biodiversity far beyond its own borders. From 2000–2030, China will likely add over 250 million new households, more than the total number of households in the entire Western Hemisphere in 2000 (Liu and Diamond, 2005). Currently 20% of China's food consumption by mass is animal product-based, approximating the global median, but consumption of animal products is on trajectory to reach 30% in 20 years (Keyzer et al., 2005a; Bonhommeau et al., 2013; FAO, 2014). Already over the past 20 years, animal products have increased from 10% to 20% of Chinese diets, and were only 5% in 1960. Between 1978 and 2002, China's per capita consumption of meat, milk and eggs increased four-, four- and eight-fold, respectively (Liu and Diamond, 2005). Production within the nation has increased enormously over the past 50 years, with most growth occurring since the 1980s (Fig. S2) (FAO, 2014). If China attains dietary habits similar to that of the United States during the next 35 years, each of its projected 1.5 billion inhabitants would increase their consumption of meat and other animal-products by an average of 138% (Liu and Diamond, 2005; Bonhommeau et al., 2013). India, the world's second most populous country, has also shown rising animal product consumption with increasing affluence, but its rates of increase have been lower than China, rising from approximately 15% of

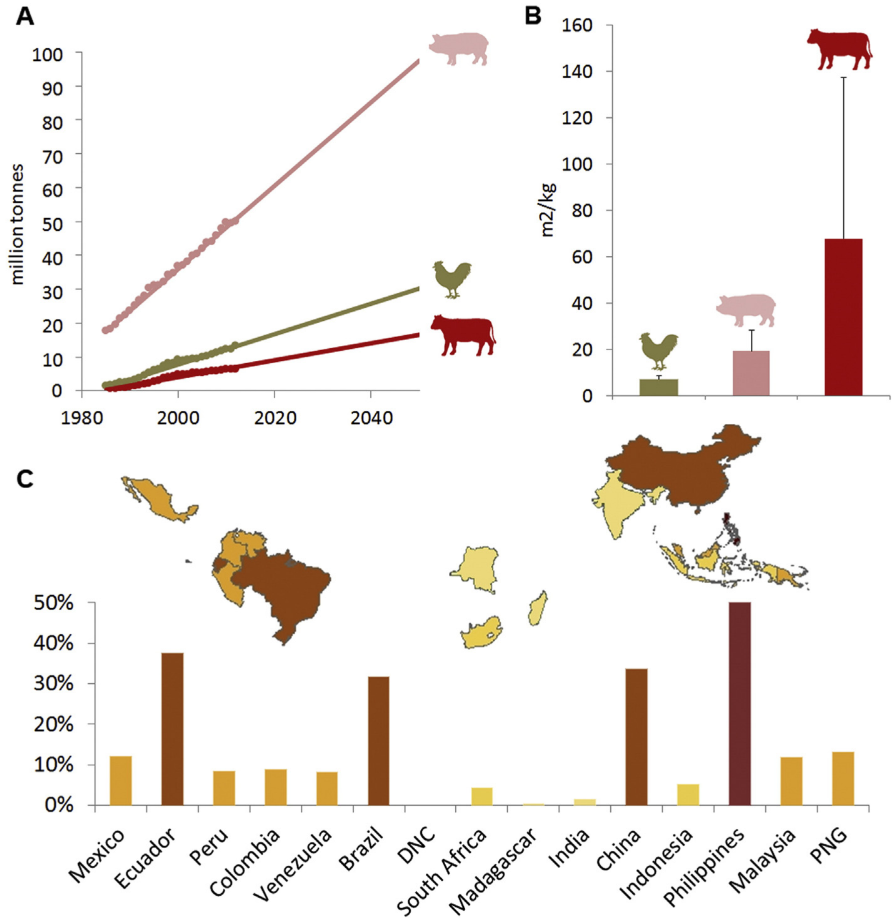


Fig. 3. Projected increases in area required to produce meat in developing megadiverse (DMD) countries by 2050. (a) Extrapolating recent (1985–2012) production data for beef, chicken, and pork (FAO, 2014) in each DMD country to 2050 (data for China shown) multiplied by (b) mean area required to produce livestock biomass (Röös et al., 2013) provides (c) an estimate of area in each country required to produce livestock in 2050 as a percentage increase beyond total current agricultural area (2012) (FAO, 2014). Agricultural area expansion needs can be met by internal expansion or by agricultural expansion in other countries and importation of feedcrops and/or meat products. This analysis addresses only beef, chicken, and pork. It does not include eggs, other meat sources, or dairy, which would increase area projections.

diets by mass in the 1960s to 21% in the late 2000s (Bonhommeau et al., 2013).

Despite rising animal product demand, the extent of agricultural land in China has been decreasing under pressures of urbanization and land appropriation for mining, forestry and aquaculture. Furthermore, grasslands have been severely degraded by overgrazing and other pressures, with 90% of China's grasslands now considered degraded. Production rates of grasslands have decreased approximately 40% since the 1950s (Liu and Diamond, 2005). Consequently, China's increasing appetite for animal products will need to reach far beyond its own borders to meet its needs, importing both meat products as well as feedstocks to produce meats locally (Rae and Hertel, 2000). Much of the livestock production in China is fueled by soy-protein feedstock produced in the Amazon, with annual imports of soy from Brazil growing from zero in 1996 to approximately 7,000,000 tons only 10 years later. In 2003 China imported 21,000,000 tons of soybeans, 10% of world production and 83% more than it imported in 2002, with 29% of this soy coming from Brazil (Nepstad et al., 2006). In the 10 years from 2002 to 2012 this increased nearly 3× to reach 60,000,000 tons (Fig. S3) (FAO, 2014). Approximately 4,000,000 ha of Brazilian cropland is utilized for exports of soybean to China for livestock feed (MacDonald et al., 2015).

Sources of crops and ruminant products for global trade are dominated by 20 major countries, including 6 developing megadiverse countries, which account for more than 70% of global trade in these products. Projected increased demand for animal products in developing megadiverse countries, like China, could potentially be met by increasing supplies from other regions with lower biodiversity. However, the effects of animal product production beyond potential biodiversity loss (soil loss, biocide use, etc.) are important even in lower biodiversity areas. In addition, current trends, including the large supply of soy to China from the Brazilian Amazon, indicate an expansion of sourcing of agricultural products from tropical developing countries. Land grabbing, the transfer of the right to own or use land from local communities to foreign investors through large-scale land acquisitions, mainly for agriculture, has increased dramatically since 2005. The increase began initially in response to the 2007–2008 global increase in food prices and growing food demand (especially in China and India). In 2010 the World Bank estimated that about 45,000,000 ha had been acquired by foreign investors since 2008 (Rulli et al., 2013). Grabbed areas are often in developing tropical countries with sufficient freshwater resources and can constitute a large fraction of a country's area (e.g. up to 19.6% in Uruguay, 17.2% in the Philippines, or 6.9% in Sierra Leone). Other tropical developing countries such as Liberia, Gabon, Papua New Guinea, Sierra Leone, and Mozambique have high grabbed-to-cultivated area ratios, indicating that the grabbed land may not have been cultivated before the acquisition but was developed through deforestation or land-use change (Hansen et al., 2010; Rulli et al., 2013).

Given current trends, the extent of land area converted to agriculture to meet growing global food demands is predicted to increase by approximately 18% from 2000 to 2050. This equates to a loss of 1,000,000,000 ha of natural habitats — an area larger than the USA

(Tilman et al., 2001). The globalization of food trade, production of foreign fodder sources, and standardization of food products is driving the replacement of wild and biodiversity-rich agriculture lands with extensive monoculture landscapes. Diversity found within traditional mix-cultured systems is threatened by this industrialization, including decreases in bees, butterflies, and plants (Idel, 2013). In addition, the biodiversity found within crops of traditional farming systems is decreasing as industrial agriculture expands (Altieri and Merrick, 1987), driven by global demands for uniform products that ship and store well.

3. Livestock-driven climate change

3.1. Effects on biodiversity

Over the past 30 years, climate change has produced numerous shifts in the distributions and abundances of species, and its effects are projected to increase dramatically in the future (Walther et al., 2002), leading to potential declines or extinctions of many species (Carpenter et al., 2008; Keith et al., 2008; Pimm et al., 2014). One assessment of extinction risks for sample regions that cover 20% of the Earth's terrestrial surface indicated that 15–37% of species will be 'committed to extinction' by 2050 under mid-range climate-warming scenarios (Thomas et al., 2004). Effects on marine ecosystems already include decreased ocean productivity, altered food web dynamics, reduced abundances of habitat-forming species, shifting species distributions, and a greater incidence of diseases (Hoegh-Guldberg and Bruno, 2010). Shifts in climate may also cause changes in crop yields (Rosenzweig et al., 2014) that could induce pressures to shift agricultural zones, exacerbating negative effects on undeveloped or protected areas, with effects especially pronounced within developing countries.

3.2. Contribution of livestock to greenhouse gases

Given the potential widespread and profound effects of climate change, addressing the contribution of livestock-produced greenhouse gases is a valuable component of biodiversity conservation. Livestock are an important contributor to global warming through the production of greenhouse gases (carbon dioxide, methane, and nitrous oxide). Worldwide, the livestock sector is responsible for approximately 14.5% of all anthropogenic greenhouse gas emissions, approximately equivalent to all the direct emissions from transportation (Gerber et al., 2013; Ripple et al., 2014b). Land-use change (deforestation & feedcrop expansion) dominates CO_2 production from livestock with an estimated 2,400,000,000 tons of CO_2 released annually (Steinfeld et al., 2006a). Releases of methane from enteric fermentation are equivalent to 2,200,000,000 tons of CO_2. The use of nitrogen fertilizers in feed and manure production contributes 75–80% of annual agricultural emissions of N_2O, equivalent to 2,200,000,000 tons of CO_2. Some data suggest that N_2O is the largest livestock-driven climate change threat, primarily resulting from the production of manure and the intensive over-use of fertilizers for the production of animal feed (Idel, 2013). Indeed the amount of nitrogen released by livestock via manure is estimated to exceed the global use of nitrogen fertilizers (Bouwman et al., 2009).

Land-use change involves not only the release of carbon with the conversion of forests and other habitats into grazing pastures, but also the conversion of natural grasslands into intensive feedcrop agriculture, which is an ongoing trend in developing countries as intensive, industrial livestock production is increasing (Bruinsma, 2003; Thornton, 2010). Grasslands are one of the most extensive vegetation types, covering 15,000,000 km^2 in the tropics (as much as tropical forests) and another 9,000,000 km^2 in temperate regions (Scurlock and Hall, 1998) for a total of nearly 40% of the world's land surface excluding Greenland and Antarctica (White et al., 2000). Grasslands are an important organic carbon store, with tropical woodland and savannahs alone holding approximately 10% of the world's soil carbon (Post et al., 1982; Cao and Woodward, 1998). When grasslands are tilled for agriculture, large amounts of CO_2 are released (Scurlock and Hall, 1998). In a meta-analysis of carbon fluxes (Guo and Gifford, 2002), it was found that shifts from pasture to crops always reduce soil carbon stocks by 50% or more, and in high rainfall environments the resultant soil carbon losses can exceed 75%. Reverting croplands to grasslands reverses this process, eventually creating a carbon sink that can persist for up to many decades (McLauchlan et al., 2006). In the western hemisphere, over 70% of all grasslands have already been converted to croplands. In Asia and Africa over 19% of grasslands have been converted to crops and in Oceania over 37% of grasslands have been converted to crops (White et al., 2000). Conversion of the world's remaining grasslands to agro-industrial croplands is likely to continue and potentially accelerate under ongoing international land grabbing and intensification of livestock production (Rulli et al., 2013).

3.3. Important role of ruminants

There are a reported 3.6 billion domestic ruminants on Earth in 2011 (1.4 billon cattle, 1.1 billion sheep, 0.9 billion goats and 0.2 billon buffalo), and on average, 25 million domestic ruminants have been added to the planet each year over the past 50 years (Ripple et al., 2014b). By 2050, the global cattle population may increase by more than a billion animals, and the global goat and sheep population by over 700 million animals (Hubert et al., 2010). Globally, mixed crop–livestock systems produce 69% of the milk (407,000,000 million tons) and 61% of the meat (43,000,000 tons) from ruminants. In both developed and developing countries, mixed crop–livestock systems are the most important production systems in terms of ruminant production (Herrero et al., 2013). Distribution of ruminants across the earth overlaps extensively with areas that harbor high levels of biodiversity (Fig. 4). Of the considerable amount of greenhouse gases emitted by the livestock sector, estimated at 14.5% of anthropogenic greenhouse gas, CO_2 from land-use change, methane production, and N_2O production from ruminants are much higher than monogastrics (Fig. 5) (Gerber et al., 2013; Ripple et al., 2014b). Ruminants consume the bulk of feedcrops (3,700,000,000 tons compared with 1,000,000,000 tons by pigs and poultry) (Herrero et al., 2013). In addition to requiring the greatest area per kilogram of meat (or protein) produced of all types of livestock and globally occupying more area than any other land use, enteric fermentation from ruminant production alone is the largest source of anthropogenic methane emissions (Ripple et al., 2014b). Beef production also requires 6 times more reactive nitrogen to produce than dairy, poultry, pork, and eggs (Eshel et al., 2014).

4. Human health

In addition to ecological and biodiversity-related effects, increased animal product consumption also directly affects human health (Tilman and Clark, 2014). For example, heart disease, the leading cause of human death, is strongly associated with the consumption of animal products, and can be largely prevented or reversed by switching to plant-based diets (Campbell et al., 1998; Ornish et al., 1998; Campbell and Campbell, 2007). Increased animal product consumption is closely tied to many 'diseases of nutritional extravagance' such as obesity and associated higher rates of heart disease, cancer, and diabetes, among other ailments (Menotti et al., 1999; Lock et al., 2010; Popkin et al., 2012; Pan et al., 2013). Under conditions of food abundance, diets based largely on plant foods are associated with health and longevity and shifts toward diets richer in animal products often leads to less-healthy populations (Nestle, 1999). Studies have suggested that even small intakes of foods of animal origin are associated with significant plasma cholesterol concentrations, which are associated with substantial increases in chronic degenerative disease mortality rates (Campbell and Junshi, 1994). This has been evident with recent trends in China. Diets of Chinese people that are higher in animal products

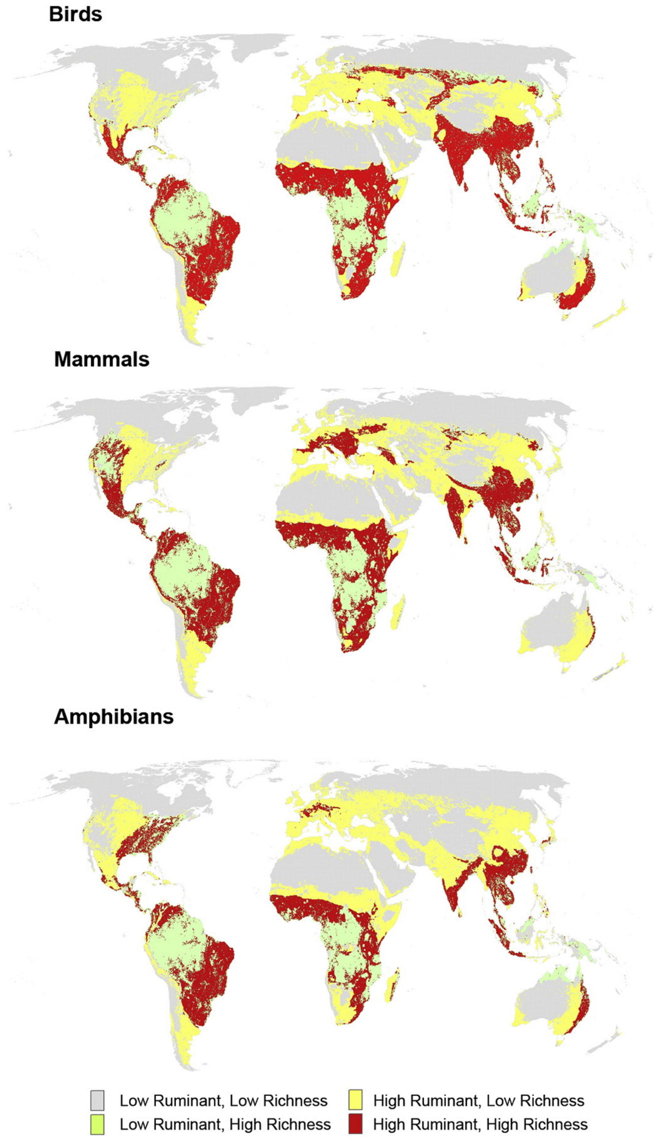


Fig. 4. Maps indicating density (high or low) of ruminants (cattle, goats, sheep) (Wint and Robinson, 2007) and species richness (high or low) of birds, mammals, and amphibians (Pimm et al., 2014). Classification as 'high' indicate values above the mean value for all areas and 'low' indicate values below the mean value. Mean density value for ruminants = 5/km^2. Mean species richness values (spp/100 km^2) are: birds = 192, mammals = 56, amphibians = 16.

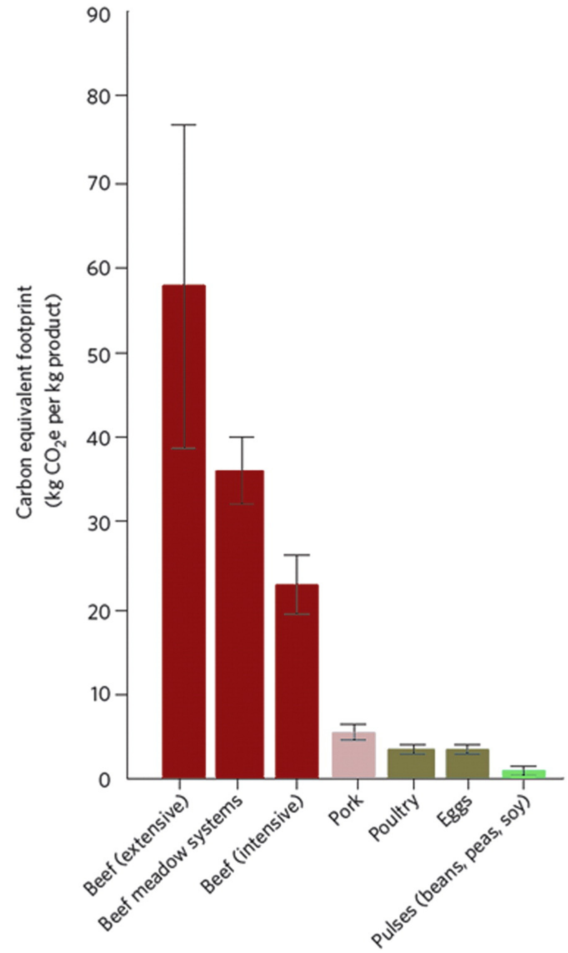


Fig. 5. Average carbon equivalent footprint of meats and pulses per kilogram of product from a global meta-analysis of life-cycle assessment studies (adapted from Ripple et al., 2014b). Extensive beef involves cattle grazing across large pastoral systems, whereas intensive beef typically involves feedlots. Error bars represent standard errors.

are associated with increases in many diseases (Shu et al., 1993; Campbell and Junshi, 1994; Campbell et al., 1998; Campbell and Campbell, 2007; Popkin et al., 2012). Vegetarian, and especially vegan, diets can sometimes be deficient in B vitamins (McDougall, 2002), but this deficiency can be addressed through small amounts of animal products (especially fish) in the diet, dietary diversity, or supplements (Davis and Kris-Etherton, 2003).

5. Solutions

Given that roughly 7.0 gigatons (Gt) of plant biomass is required to produce the 0.26 Gt of meat in our modern global agricultural systems (Smith et al., 2013), even a small increase in the consumption of animal-based foods will drive a large increase in habitat conversion and greenhouse gas emissions. We propose three solutions to help improve human nutritional health, decrease the land demands of agriculture, and protect plant and animal biodiversity: (1) reduce animal product consumption, (2) replace meat, and especially meat from ruminant sources, with more efficient protein sources, and (3) reintegrate livestock into diverse agroecological production systems.

5.1. Reduce

Reducing demand for livestock products, or other demand-side mitigation measures, such as reduced waste, offer a much greater potential for meeting the challenges of both food security and greenhouse gas mitigation than supply side measures that allow the production of more agricultural product per unit of input, although both supply and demand-side measures should be implemented (Smith et al., 2013). Eliminating the loss of energy available in plants via livestock production and instead growing crops only for direct human consumption is estimated to increase the number of food calories available for human consumption by as much as 70%. This could feed an additional 4 billion people, exceeding the projected 2–3 billion people to be added through future population growth (Cassidy et al., 2013). Substituting soy for meat as a source of protein for humans would reduce total biomass appropriation in 2050 by 94% below 2000 baseline levels (Pelletier and Tyedmers, 2010). Soy and other legumes are excellent sources of protein, and plant-based protein sources can meet complete amino acid dietary requirements (McDougall, 2002). When compared to an equivalent mass of common raw cuts of meats, soybeans contain on average twice the protein of beef, pork or chicken, and 10× more protein than whole milk (U.S. Department of Agriculture, 2013). When comparing the area needed to produce 1 kg of protein from soybeans (12 m^2) to the average land area required to produce common cuts of meat, chicken requires 3× more area (39 m^2), pork 9× more area (107 m^2), and beef 32× more area (377 m^2) (Röös et al., 2013a, 2013b; U.S. Department of Agriculture, 2013).

A large amount of food, including animal products, is wasted worldwide. In the United States, 30% of all food, worth more than US $48 billion is thrown away each year (Nellemann, 2009). Reducing this waste, especially related to animal products, would impart large environmental benefits. Wasting 1 kg of feedlot-raised boneless beef is estimated to have ~24 times the effect on available calories as wasting 1 kg of wheat (~98,000 kcal versus ~3800 to 4125 kcal), because of the inefficiencies of caloric and protein conversion from plant to animal flesh (West et al., 2014). Waste varies greatly between countries, especially developing and developed. For example, food loss in India for vegetables and pork is <3 kcal per person day^{-1}, and this is dramatically higher at 290 kcal per person day^{-1} for beef in the United States. This equates to approximately 7 to 8 times more land required to support this waste in the United States than in India. The elimination of waste of major plant-based foods and meats in China, India and the United States is estimated to be able to feed over 400 million people per year (West et al., 2014). Traditional plant based diets combine legumes and grains (i.e. rice and soybeans in Asia, rice and black beans in Latin America) to achieve a complete and well-balanced source of amino acids for meeting human physiological requirements (Young and Pellett, 1994). Although veganism is growing in popularity, completely eliminating animal based products from global diets is too simplistic, not practical (Idel, 2013), nor makes the best use of many land types. It is estimated that grazing on pasture unsuitable for cropping, and which did not cause deforestation, contributes approximately 14% of total global livestock feed measured in carbon mass (Bajželj et al., 2014). In small-scale farms, especially in poor cultures with marginal lands unsuitable for many agricultural crops, livestock are a valuable resource that converts low protein grass and other plants into more concentrated protein in a self-transportable format. For economically disadvantaged peoples, livestock can also provide draft power and a vital form of insurance during hard times (Laurance et al., 2014). However, low-cost, locally-available, and environmentally-sensitive practices and technologies can improve production (Pretty et al., 2003) of plant-based food sources and provide necessary caloric, protein, and nutrient levels (Young and Pellett, 1994; Campbell and Campbell, 2007) accentuated by small amounts of animal products. One of the largest surveys of sustainable agricultural practices and technologies in developing countries examined 45 projects in Latin America, 63 in Asia and 100 in Africa, in which 9 million farmers have adopted more sustainable practices and technologies on 29,000,000 million ha (Pretty et al., 2003). Beneficial practices and technologies that were shown to increase average per project per hectare food production by 93% include increased water use efficiency, improvements to soil health and fertility, and pest control with minimal or zero-pesticide use.

Based on a balance between the need to increase nutritional health (Campbell and Campbell, 2007), availability of calories with the need to decrease the land demands and ecological footprint of agriculture (Foley et al., 2011), and the desire for people to eat meat, we argue that people should strive toward a goal of significantly reducing the contribution of animal products in the human diet, ideally to a global average of 10% or less of calories (Machovina and Feeley, 2014b; Machovina and Feeley, 2014c). This is roughly equivalent to limiting average daily consumption of animal products to approximately 100 g (a portion of meat approximately the size of a deck of playing cards or smaller). Others have proposed 90 g per day as a working global target (McMichael et al., 2007), shared more evenly among nations which currently range 10-fold in meat consumption, with not more than 50 g per day coming from ruminants (McMichael et al., 2007). These scenarios, combined with further crop improvements, could enable the future global population to be fed on extant agricultural lands, potentially enable restoration of habitats (Machovina and Feeley, 2014a; Machovina and Feeley, 2014c), while still enabling people to eat some meat. Reaching these goals and reducing the overall global animal product consumption to ~10% will require significant decreases in per capita meat consumption by developed countries and little or no increase in most developing countries (Bonhommeau et al., 2013).

Success has previously been achieved in changing some dietary habits that are deleterious to the environment. A notable example is the recent campaign against consumption of shark fin soup in China. A large scale media campaign featuring Chinese National Basketball Association star Yao Ming in television, bus stop and billboard advertisements, and social media campaigns was disseminated widely throughout China in 2006 and again in 2009. Messages focused on the declining numbers of sharks and their important role in the ecosystem, the cruelty involved in the practice of finning, and the presence of mercury in shark fin soup. Survey's found that 83% of people exposed to the campaigns had stopped or reduced consumption (Fabinyi, 2012). In 2012, the Chinese government pledged to ban shark fin soup from official banquets within three years. Conservation organization WildAid claims that there was a 50–70% reduction in shark fin consumption over a two year period during the campaign (Denyer, 2013). However, the connection between livestock consumption and ecological damage is less direct than shark-fin consumption. As with shark fin soup in China, animal product consumption is ingrained into many societies. High levels of livestock consumption are a traditional part of many diets or a sign of affluence in many countries. Meat is often believed (incorrectly) to be a physiologically necessary or superior form of protein. Many cultures also consider livestock ownership to be a sign of higher status (Laurance et al., 2014). In addition, government financial incentives often support livestock production and animal product consumption over plant-based foods (Geist and Lambin, 2002; Steinfeld et al., 2006a; Nepstad et al., 2014).

Clearly many challenges exist to reducing animal product consumption and increasing plant-based food consumption, but awareness is increasing. Fueled by rapid urbanization, increases in animal-product consumption and lifestyle choices, chronic diseases have emerged as a critical public health issue in China, as they have in many other developing countries. The Chinese government has set a goal of promoting public health and making health care accessible and affordable for all Chinese citizens by year 2020 via the "Healthy China 2020" program. One important element of the program is to reduce chronic diseases by promoting healthy eating and active lifestyles (Hu et al., 2011). These and other efforts to reduce animal product consumption on national and international levels will require significant political, financial, and cultural support.

5.2. Replace

Within the context of reducing the amount of animal products consumed globally, additional benefits would come from replacing ecologically damaging and inefficient animal protein sources such as bushmeat and ruminants with more sustainable sources. Less than 5% of the protein and under 2% of the calories consumed by humans world-wide come from beef, compared to about 6% from pork, 6% from seafood, 9% poultry and eggs, and 10% from milk (Boucher et al., 2012). However, the ecological footprint of beef is much higher than other meats. The type of livestock consumed has a strong influence on the area required for its production, and hence direct and indirect effects on biodiversity. Land-use rates vary by country (Elferink and Nonhebel, 2007; de Ruiter et al., 2014) but feedstock-raised beef generally requires 2–3 times more area per kilogram produced than pork or chicken, and much greater area per unit of beef production is required on tropical pasture — up to 100 times greater than feedstock-raised animals (Cowan, 1986). A recent analysis indicated that ruminants (primarily cattle) yield about 0.14 billion tons annually (measured as dry biomass) which is about the same as monogastric animal (mostly pigs and chickens). However, the ruminants require at least 20× more area to produce a ton of meat than chickens and pigs (28 ha vs. 1.4 ha). If cattle are raised only on feedcrops, the area of land required decreases to 2.8 ha/ton but is still twice the area required for pigs or chickens (Smith et al., 2013). Although requiring larger amounts of land for meat production, grazing ruminants can be a valuable food resource on natural pastures that are not able to be cropped if stocking and grazing patterns are managed sustainably (Bajželj et al., 2014).

Within a greater context of reducing the proportion of animal products in diets to 10% of calories, efforts to increase the proportion of chicken or pork while reducing beef consumption will magnify benefits to ecosystems and biodiversity. In addition to the less land required to produce meat, monogastrics produce a fraction of the methane as ruminants. Methane is the most abundant non-CO_2 greenhouse gas and because it has a much shorter atmospheric lifetime (~9 years) than CO_2 it holds the potential for more rapid reductions in radiative forcing. Decreases in worldwide ruminant populations and their emissions could potentially be accomplished quickly and relatively inexpensively through meat-source replacement (Ripple et al., 2014b). A shift of preference for meat products is already occurring in many locations and should be further expanded. In developed countries, total livestock production increased by 22% between 1980 and 2004, but ruminant meat production declined by 7% while that of poultry and pigs increased by 42%. As a result, the share of production of poultry and pigs has gone up from 59 to 69% of total meat production. Poultry is the meat commodity with the highest growth rates across the world. Per capita retail beef demand in the United States declined by nearly 50% from 1980 to 1998, offset largely by increased chicken consumption (FAO, 2014), and attributed to changing consumer preferences (health, food safety, inconsistent quality), changing demographics, and relative meat prices (Marsh, 2003). Another potential part of a strategy of replacement is the growing investment in research and development of meat replacement products (in vitro cultured meat and plant-based meat alternative products) that strive to replicate the gustatory experience of meat (Sadler, 2004; Bhat and Fayaz, 2011).

Providing economical alternative protein sources, either plant-based or low-footprint animal product (chicken, aquaculture fish, or insect) to developing countries can also help relieve pressures on hunting of wildlife as a protein source. In one study in Ghana, fish supplies, which could vary 24% between consecutive years, were negatively correlated with biomass of terrestrial mammals, indicating a transfer of harvest pressure and consumption between these resources. Developing cheap protein alternatives to bushmeat as well as improving fisheries management to avert extinctions of tropical wildlife is critical (Brashares et al., 2004). However, unsustainable consumption of wildlife also remains a problem even in many relatively prosperous countries with sufficient protein supplies as consumption of bushmeat in many locations is considered a delicacy or a sign of affluence (Bennett, 2013). This is similar to the historical and cultural perceptions around shark-fin soup in China which, as discussed above, has been addressed with considerable success through public awareness campaigns.

5.3. Reintegrate

A major ongoing trend in livestock production is the intensification of production systems through industrial-scale feedcrop production and confined livestock production in high capacity facilities. Centralized agriculture feeding operations (CAFOS) in industrialized countries are the source of much of the world's poultry and pig meat production, and such systems are being established in developing countries, particularly in Asia, to meet increasing demand (Thornton, 2010) with at least 75% of total production growth to 2030 projected to occur in confined systems (Bruinsma, 2003). Traditional fibrous feedcrops are in relative decline, and protein-rich feeds together with nutritional additives that enhance feed conversion are on the rise (Steinfeld et al., 2006b). As global livestock production grows and intensifies, it depends less on locally-available feed resources but increasingly on feed concentrates that are traded domestically and internationally. In 2004, a total of 690,000,000 tons of cereals were fed to livestock (34% of the global cereal harvest) and another 18,000,000 tons of oilseeds (mainly soy). In addition, 295,000,000 tons of protein-rich processing by-products were used as feed (mainly bran, oilcakes and fish meal) (Steinfeld et al., 2006b).

Intensification of livestock operations is being supported by intensification of crop production systems. From 1980 to 2004, the total global supply of cereals increased by 46% while the area dedicated to cereal production shrank by 5.2% (Steinfeld et al., 2006a). In some areas the intensification of global livestock production combined with yield increases have reduced some pressure to expand livestock industries into natural areas. For example, from 2006 to 2010, deforestation in the Amazon frontier state of Mato Grosso decreased to 30% of its average from 1996 to 2005, and 78% of production increases in soy were due to expansion (22% to yield increases), with 91% on previously-cleared land (Macedo et al., 2012). However, deforestation rates in the Brazilian Amazon have recently increased (Fonseca et al., 2015).

Transitions away from extensive to more intensive and efficient livestock production systems present an attractive mitigation opportunity for reducing CH_4 and N_2O emissions per unit of livestock product, while at the same time increasing productivity (Havlík et al., 2014). Although the land footprint of intensive feedcrop-produced beef can be as low as one-tenth the area required by pasture-raised beef (Smith et al., 2013), or even 100 times less than some low-productivity tropical pasture beef (Cowan, 1986), many negative tradeoffs result from intensive agriculture since it is highly dependent on non-renewable fossil fuel energy to produce fertilizers and biocides, as well as operate machinery, exacerbating climate change. Increased nutrient pollution from farms and confined operations, methane, N_2O and ammonia production, soil erosion, and biocide, hormone and pharmaceutical contamination are all results of livestock industry intensification (Steinfeld et al., 2006a). As point-source pollution sources, some opportunities exist to capture and utilize outputs such methane from CAFOS (Massé et al., 2011) or treat nutrient-rich livestock wastewater with constructed wetlands (Knight et al., 2000). However, CAFOS are now a major source of atmospheric methane and ammonia releases, (Golston et al., 2014), nutrient and microbial pollution to aquatic ecosystems (Mallin and Cahoon, 2003), and health problems among local residents (Juska, 2010).

Within the context of reducing animal product consumption (ideally to 10% of diets), and replacing much of the high environmental-footprint ruminant production with monogastric or other low-impact protein production, intensification is an additional, but not optimal solution. Intensification is an ongoing, powerful trend undergoing high global growth that makes it challenging to shift to other potential systems that may have lower environmental impacts, but alternative solutions exist. With the release of highly-productive arable lands that would occur with reduction of meat consumption and replacement of ruminants, an opportunity exists to reintegrate livestock production into agricultural systems that are designed around the structure and processes of natural ecosystems. Much of Asia's traditional agricultural systems have operated in this fashion for thousands of years (Devendra and Thomas, 2002a, b), and this agricultural philosophy is the basis of modern permaculture (Mollison and Holmgren, 1979; Mollison, 1988) and agroecology (Hathaway, 2015). Ecologically-based agricultural systems have been developed by an estimated 75% of the 1.5 billion smallholders, family farmers and indigenous people on 350 million small farms which comprise at least 50% of the global agricultural output for domestic consumption (Altieri and Nicholls, 2012).

In contrast to modern intensive livestock production, within a permaculture or agroecological system, livestock are integrated into a designed and diverse agricultural production system that strives to maximize production of foods from solar (not fossil fuel) energy, conserve nutrients and water, and produce little waste. Livestock are integrated as herbivores or omnivores would be in a natural ecosystem, consuming a variety of feeds, and producing nutrient-rich waste that is returned into the system. Grazing ruminants are valuable resources on natural pastures that are not able to be cropped and can be a valuable part of a production system. However, continuous grazing systems and 'improved' pastures, which as opposed to semi-natural pastures, are sown and require artificial inputs, can have many negative consequences (Bajželj et al., 2014). Exclusion of livestock from riparian zones (Batchelor et al., 2015) and rotational grazing that better emulates the natural migration feeding patterns of wild herbivores can increase plant biodiversity (Stinner et al., 1997), build soils, sequester carbon, increase soil nitrogen (Ciesiolka et al., 2008), increase soil water content (Weber and Gokhale, 2011), and overall potentially increase productivity and sustainability (Jacobo et al., 2006). In addition to providing food for humans, livestock provide many services within the system. For example, in addition to being fed grains, chickens can be utilized in movable zones to prepare fields for planting. This "chicken tractor" produces eggs and meat, turns the surface of the soil, removes insects and other pests, and deposits nutrients. Though many permaculture and agroecological technologies are typically used on smallholder systems, ecological designs can be scaled up to operate in larger commercial systems. Chickens and turkeys have been integrated into large areas of pasture. After cattle have finished grazing and been moved to another location, the birds are directed into the grazed pasture to feed on insects uncovered by grazing and attracted to the manure (Strom, 2013). Permaculture systems are designed to best fit into local ecological limitations and opportunities, and appropriate products can be produced to supply market demands.

The closed-system, diverse, coupled designs of permaculture systems are reflected in traditional integrated agriculture-aquaculture (IAA) systems of Asia (Prein, 2002), which supply diets traditionally based primarily on consumption of fruits, vegetables, and whole grains with small amounts of animal products (Campbell and Campbell, 2007). These systems are based on multiple synergies in which outputs from sub-systems in an integrated farming system become inputs to other sub-systems instead of being wasted. The flow and reuse of energy and nutrients between enterprises produces higher efficiency outputs while reducing external energy or nutrient inputs. Many types of IAA systems exist such as the rice-aquaculture systems from which fish, freshwater prawns and crabs, snails, mussels and frogs are harvested, and which may be fertilized with agricultural, livestock, or human waste. For example, in the Mekong Delta of Vietnam, fruit orchards are built upon berms dug from adjacent canals that provide fish habitat and connect to nearby rice fields. Fish and freshwater prawns can move between the sub-systems and benefit from the decomposing rice straw as well as fruit and insects dropping into the water. Due to energetic efficiencies of fish metabolism and the use of energy and nutrient inputs that are often wasted or not utilized in modern high production livestock systems, IAA systems can have very high productivities. The area required to produce 1 kg of fish is as small as 1 m^2 to 2 m^2 (Prein, 2002), which is much less than area required to produce beef (68 m^2), pork (19 m^2), chicken (7 m^2) (Röös et al., 2013), or even soybeans (4 m^2) (Masuda and Goldsmith, 2009). Aquaculture, which has high energetic efficiencies, provides over 40% of global aquatic animal food for human consumption (Bostock et al., 2010), but many aquaculture practices are not optimal and would be greatly improved with a reduction of wild fish inputs in feed and adoption more ecologically sound management practices (Naylor et al., 2000). Integrated multi-trophic aquaculture (IMTA), in which the by-products (wastes) from one species are recycled to become inputs (fertilizers, food and energy) for another, are more ecologically efficient and less polluting (Ridler et al., 2007; Barrington et al., 2009). Agroecological systems can be designed to produce a variety of products that are desired by local societies or potentially traded on international markets.

Shifting to the kind of integrated polyculture system usually employed in agroecology can increase yields by an average of 20 to 60% over monocrop systems, because polycultures reduce of losses due to weeds, insects, and diseases, and make a more efficient use of the available resources of water, light, and nutrients. Overall, ecologically integrated farms are more productive than large farms if total output is considered rather than yield from a single crop. In addition, these systems provide a much greater level of resiliency to climatic perturbations (Altieri et al., 2012). However, expanding or scaling up permaculture or agroecological systems has been difficult for a number of reasons, including a lack of access to local-regional markets, lack of land tenure, and limited to no government support such as credit, seeds or dissemination of agroecological technologies by extension agents. An underlying and powerful obstacle to the spread of permaculture and agroecological technologies has been the economic and institutional interests backing conventional agroindustrial approaches, while research and development for agroecology and sustainable approaches has in most countries been largely ignored or ostracized (Altieri, 2002). It may be more practical to transistion smallscale farms in developing countries (where biodiversity is highest) to permaculture and agroecological methods, as many of these farms are still labor-intensive and because these methods often build on existing traditional farming methods and knowledge (Hathaway, 2015).

The major wildlife crisis in much of Africa and southeastern Asia, bushmeat hunting, can potentially be addressed in a sustainable manner via community-based wildlife management (CWM) through a bottom-up, participatory approach, whereby a maximum number of community members stand to benefit from a sustainable management and utilization of wildlife. This feedback loop provides a value-driven reintegration of local communities into the surrounding forest environment to harvest a protein source with long-term benefits. In addition, game ranching in fenced areas or mini-livestock breeding with indigenous species (bush rodents, guinea-pigs, frogs, giant snails, manure worms, insects and many other small species) can provide protein sources that relieve pressure on bushmeat, are low-cost, and more closely integrated into local ecosystems than industrialized livestock production (Van Vliet, 2011). Furthermore, a high priority is for programs that emphasize maintaining traditional protein-rich plant-based foods that have been historically consumed in these regions.

6. Conclusions

Given the large ecological footprint of livestock production, humans' negative impact on biodiversity can be significantly reduced by: (1) reducing demand for animal-based food products and increasing proportions of plant-based foods in diets; (2) replacing ecologically-inefficient ruminants and bushmeat with monogastrics, aquaculture, or other more-efficient protein sources; and (3) reintegrating livestock production away from single-product, intensive, fossil-fuel based systems into diverse, coupled systems designed more closely around the structure and functions of ecosystems that conserve energy and nutrients. Applying ecologically-integrated structures and functions to plant and livestock production systems to support a future with lower animal-product food demands would drastically reduce habitat and biodiversity loss, fossil fuel energy use, greenhouse gas emissions, and pollution while providing highly nutritious diets that greatly improve global human health.

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.scitotenv.2015.07.022.

References

Alexandratos, N., Bruinsma, J., 2012. World agriculture towards 2030/2050: the 2012 revision. FAO, Rome.

Altieri, M.A., 2002. Agroecology: the science of natural resource management for poor farmers in marginal environments. Agric. Ecol. Environ. 93, 1–24.

Altieri, M.A., Funes-Monzote, F.R., Petersen, P., 2012. Agroecologically efficient agricultural systems for smallholder farmers: contributions to food sovereignty. Agron. Sustain. Dev. 32, 1–13.

Altieri, M.A., Merrick, L., 1987. In situ conservation of crop genetic resources through maintenance of traditional farming systems. Econ. Bot. 41, 86–96.

Altieri, M.A., Nicholls, C., 2012. Agroecology scaling up for food sovereignty and resiliency. Sustainable agriculture reviews. Springer, pp. 1–29.

Bajželj, 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. Nat. Clim. Chang. 4, 924–929.

Barrington, K., Chopin, T., Robinson, S., 2009. Integrated multi-trophic aquaculture (IMTA) in marine temperate waters. Integrated mariculture: a global review. FAO Fisheries and Aquaculture Technical Paper 529, pp. 7–46.

Batchelor, J.L., Ripple, W.J., Wilson, T.M., Painter, L.E., 2015. Restoration of riparian areas following the removal of cattle in the Northwestern Great Basin. Environ. Manag. 55, 930–942.

Bennett, E.L., 2013. Hunting for sustainability in tropical forests. Columbia University Press.

Beschta, R.L., Donahue, D.L., DellaSala, D.A., Rhodes, J.J., Karr, J.R., O'Brien, M.H., Fleischner, T.L., Williams, C.D., 2013. Adapting to climate change on western public lands: addressing the ecological effects of domestic, wild, and feral ungulates. Environ. Manag. 51, 474–491.

Bhat, Z.F., Fayaz, H., 2011. Prospectus of cultured meat—advancing meat alternatives. J. Food Sci. Technol. 48, 125–140.

Bianchi, C.A., Haig, S.M., 2013. Deforestation trends of tropical dry forests in central Brazil. Biotropica 45, 395–400.

Bonhommeau, S., Dubroca, L., Le Pape, O., Barde, J., Kaplan, D.M., Chassot, E., Nieblas, A.-E., 2013. Eating up the world's food web and the human trophic level. Proc. Natl. Acad. Sci. 110, 20617–20620.

Bostock, J., McAndrew, B., Richards, R., Jauncey, K., Telfer, T., Lorenzen, K., Little, D., Ross, L., Handisyde, N., Gatward, I., 2010. Aquaculture: global status and trends. Philos. Trans. R. Soc., B 365, 2897–2912.

Boucher, D.H., Pipa, E., Goodman, L., May-Tobin, C., Mulik, K., Roquemore, S., 2012. Grade A choice? Solutions for deforestation-free meat. Union of Concerned Scientists, Cambridge, Massachussetts.

Bouwman, A., Beusen, A., Billen, G., 2009. Human alteration of the global nitrogen and phosphorus soil balances for the period 1970–2050. Glob. Biogeochem. Cycles 23.

Boza, M.A., 1993. Conservation in action: past, present, and future of the national park system of Costa Rica. Conserv. Biol. 7, 239–247.

Brashares, J.S., Arcese, P., Sam, M.K., Coppolillo, P.B., Sinclair, A.R., Balmford, A., 2004. Bushmeat hunting, wildlife declines, and fish supply in West Africa. Science 306, 1180–1183.

Bruinsma, J., 2003. World agriculture: towards 2015/2030. An FAO perspective. Earthscan Publications Ltd.

Campbell, T.C., Campbell, T.M., 2007. The China study: the most comprehensive study of nutrition ever conducted and the startling implications for diet, weight loss and long-term health. Wakefield Press.

Campbell, T.C., Junshi, C., 1994. Diet and chronic degenerative diseases: perspectives from China. Am. J. Clin. Nutr. 59, 1153S–1161S.

Campbell, T.C., Parpia, B., Chen, J., 1998. Diet, lifestyle, and the etiology of coronary artery disease: the Cornell China Study. Am. J. Cardiol. 82, 18–21.

Cao, M., Woodward, F.I., 1998. Net primary and ecosystem production and carbon stocks of terrestrial ecosystems and their responses to climate change. Glob. Chang. Biol. 4, 185–198.

Carpenter, K.E., Abrar, M., Aeby, G., Aronson, R.B., Banks, S., Bruckner, A., Chiriboga, A., Cortés, J., Delbeek, J.C., DeVantier, L., 2008. One-third of reef-building corals face elevated extinction risk from climate change and local impacts. Science 321, 560–563.

Cassidy, E., West, P.C., Gerber, J.S., Foley, J.A., 2013. Redefining agricultural yields: from tonnes to people nourished per hectare. Environ. Res. Lett. 8, 8.

Ciesiolka, C.A.A., Ghadiri, H., Sanjari, G., Yu, B., 2008. Comparing the effects of continuous and time-controlled grazing systems on soil characteristics in Southeast Queensland. Aust. J. Soil Res. 46, 348 +.

Clements, E.A., Fernandes, B.M., 2013. Land grabbing, agribusiness and the peasantry in Brazil and Mozambique. Agrar. S. Eur. J. Polit. Econ. 2, 41–69.

Cowan, R.S., 1986. Beef and dairy production in the wet tropics. Pasture Management for the Wet Tropics of South East Asia Course Manual. 6th FAO Regional Training course, pp. 193–197.

Daszak, P., Cunningham, A.A., Hyatt, A.D., 2000. Emerging infectious diseases of wildlife — threats to biodiversity and human health. Science 287, 443–449.

Davis, B.C., Kris-Etherton, P.M., 2003. Achieving optimal essential fatty acid status in vegetarians: current knowledge and practical implications. Am. J. Clin. Nutr. 78, 640S–646S.

de Ruiter, H., Kastner, T., Nonhebel, S., 2014. European dietary patterns and their associated land use: variation between and within countries. Food Policy 44, 158–166.

Delgado, C.L., 2003. Rising consumption of meat and milk in developing countries has created a new food revolution. J. Nutr. 133, 3907S–3910S.

Denyer, S., 2013. In China, victory for wildlife conservation as citizens persuaded to give up shark fin soup. Washington Post.

Devendra, C., Thomas, D., 2002a. Crop–animal systems in Asia: importance of livestock and characterisation of agro-ecological zones. Agric. Syst. 71, 5–15.

Devendra, C., Thomas, D., 2002b. Smallholder farming systems in Asia. Agric. Syst. 71, 17–25.

Diaz, R.J., Rosenberg, R., 2008. Spreading dead zones and consequences for marine ecosystems. Science 321, 926–929.

Dirzo, R., 2013. Defaunation, alteration of trophic cascades and extinction of ecological processes: consequences for ecosystems and humans. New Frontiers in Tropical Biology: The Next 50 Years (A Joint Meeting of ATBC and OTS). Atbc.

Dirzo, R., Young, H.S., Galetti, M., Ceballos, G., Isaac, N.J.B., Collen, B., 2014. Defaunation in the anthropocene. Science 345, 401–406.

Elferink, E.V., Nonhebel, S., 2007. Variations in land requirements for meat production. J. Clean. Prod. 15, 1778–1786.

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.

Fabinyi, M., 2012. Historical, cultural and social perspectives on luxury seafood consumption in China. Environ. Conserv. 39, 83–92.

FAO, 2014. FAOSTAT. FAO, Rome, Italy.

Foley, J.A., Ramankutty, N., Brauman, K.A., Cassidy, E.S., Gerber, J.S., Johnston, M., Mueller, N.D., O/'Connell, C., Ray, D.K., West, P.C., Balzer, C., Bennett, E.M., Carpenter, S.R., Hill, J., Monfreda, C., Polasky, S., Rockstrom, J., Sheehan, J., Siebert, S., Tilman, D., Zaks, D.P.M., 2011. Solutions for a cultivated planet. Nature 478, 337–342.

Fonseca, A., Souza, C.J., Verissimo, A., 2015. Deforestation report for the Brazilian Amazon (April 2015) SAD. Imazon/SAD.

Geist, H.J., Lambin, E.F., 2002. Proximate causes and underlying driving forces of tropical deforestation tropical forests are disappearing as the result of many pressures, both local and regional, acting in various combinations in different geographical locations. Bioscience 52, 143–150.

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

Gibbs, H.K., Rausch, L., Munger, J., Schelly, I., Morton, D.C., Noojipady, P., Soares-Filho, B., Barreto, P., Micol, L., Walker, N.F., 2015. Brazil's soy moratorium. Science 347, 377–378.

Gibbs, H.K., Ruesch, A.S., Achard, F., Clayton, M.K., Holmgren, P., Ramankutty, N., Foley, J.A., 2010. Tropical forests were the primary sources of new agricultural land in the 1980s and 1990s. Proc. Natl. Acad. Sci. 107, 16732–16737.

Godfray, H.C.J., Beddington, J.R., Crute, I.R., Haddad, L., Lawrence, D., Muir, J.F., Pretty, J., Robinson, S., Thomas, S.M., Toulmin, C., 2010. Food security: the challenge of feeding 9 billion people. Science 327, 812–818.

Goldewijk, K.K., 2001. Estimating global land use change over the past 300 years: the HYDE database. Glob. Biogeochem. Cycles 15, 417–433.

Golston, L., Pan, D., Stanton, L., Tao, L., Sun, K., Zondlo, M., 2014. Ammonia and methane emissions from cattle and dairy feedlots in Colorado. AGU Fall Meeting Abstracts, p. 07.

Green, R.E., Cornell, S.J., Scharlemann, J.P.W., Balmford, A., 2005. Farming and the fate of wild nature. Science 307, 550–555.

Guo, L.B., Gifford, R., 2002. Soil carbon stocks and land use change: a meta analysis. Glob. Chang. Biol. 8, 345–360.

Hansen, M.C., Stehman, S.V., Potapov, P.V., 2010. Quantification of global gross forest cover loss. Proc. Natl. Acad. Sci. 107, 8650–8655.

Hathaway, M.D., 2015. Agroecology and permaculture: addressing key ecological problems by rethinking and redesigning agricultural systems. J. Environ. Stud. Sci. 1–12.

Havlík, P., Valin, H., Herrero, M., Obersteiner, M., Schmid, E., Rufino, M.C., Mosnier, A., Thornton, P.K., Böttcher, H., Conant, R.T., 2014. Climate change mitigation through livestock system transitions. Proc. Natl. Acad. Sci. 201308044.

Herrero, M., Havlík, P., Valin, H., Notenbaert, A., Rufino, M.C., Thornton, P.K., Blümmel, M., Weiss, F., Grace, D., Obersteiner, M., 2013. Biomass use, production, feed efficiencies, and greenhouse gas emissions from global livestock systems. Proc. Natl. Acad. Sci. 110, 20888–20893.

Hoegh-Guldberg, O., Bruno, J.F., 2010. The impact of climate change on the world's marine ecosystems. Science 328, 1523–1528.

Hu, F.B., Liu, Y., Willett, W.C., 2011. Preventing chronic diseases by promoting healthy diet and lifestyle: public policy implications for China. Obes. Rev. 12, 552–559.

Hubert, B., Rosegrant, M., van Boekel, M.A., Ortiz, R., 2010. The future of food: scenarios for 2050. Crop Sci. 50, S-33–S-50.

Idel, A., September 2013. Livestock production and food security in a context of climate change and environmental and health challenges, in Trade and Environment Review 2013. U.N. Conference on Trade and Development, Geneva, Switzerland, pp. 138–153.

Jacobo, E.J., Rodríguez, A.M., Bartoloni, N., Deregibus, V.A., 2006. Rotational grazing effects on rangeland vegetation at a farm scale. Rangel. Ecol. Manag. 59, 249–257.

Juska, A., 2010. "Profits to the Danes, for us — Hog stench?" The campaign against Danish swine CAFOs in rural Lithuania. J. Rural. Stud. 26, 250–259.

Keith, D.A., Akçakaya, H.R., Thuiller, W., Midgley, G.F., Pearson, R.G., Phillips, S.J., Regan, H.M., Araújo, M.B., Rebelo, T.G., 2008. Predicting extinction risks under climate change: coupling stochastic population models with dynamic bioclimatic habitat models. Biol. Lett. 4, 560–563.

Keyzer, M.A., Merbis, M., Pavel, I., Van Wesenbeeck, C., 2005a. Diet shifts towards meat and the effects on cereal use: can we feed the animals in 2030? Ecol. Econ. 55, 187–202.

Keyzer, M.A., Merbis, M.D., Pavel, I.F.P.W., van Wesenbeeck, C.F.A., 2005b. Diet shifts towards meat and the effects on cereal use: can we feed the animals in 2030? Ecol. Econ. 55, 187–202.

Knight, R.L., Payne, V.W., Borer, R.E., Clarke, R.A., Pries, J.H., 2000. Constructed wetlands for livestock wastewater management. Ecol. Eng. 15, 41–55.

Krausmann, F., Erb, K.-H., Gingrich, S., Lauk, C., Haberl, H., 2008. Global patterns of socioeconomic biomass flows in the year 2000: a comprehensive assessment of supply, consumption and constraints. Ecol. Econ. 65, 471–487.

Laurance, W.F., Sayer, J., Cassman, K.G., 2014. The impact of meat consumption on the tropics: reply to Machovina and Feeley. Trends Ecol. Evol.

Lenzen, M., Moran, D., Kanemoto, K., Foran, B., Lobefaro, L., Geschke, A., 2012. International trade drives biodiversity threats in developing nations. Nature 486, 109–112.

Liu, J., Diamond, J., 2005. China's environment in a globalizing world. Nature 435, 1179–1186.

Lock, K., Smith, R.D., Dangour, A.D., Keogh-Brown, M., Pigatto, G., Hawkes, C., Fisberg, R.M., Chalabi, Z., 2010. Health, agricultural, and economic effects of adoption of healthy diet recommendations. Lancet 376, 1699–1709.

MacDonald, G.K., Brauman, K.A., Sun, S., Carlson, K.M., Cassidy, E.S., Gerber, J.S., West, P.C., 2015. Rethinking agricultural trade relationships in an era of globalization. Bioscience 65, 275–289.

Macedo, M.N., DeFries, R.S., Morton, D.C., Stickler, C.M., Galford, G.L., Shimabukuro, Y.E., 2012. Decoupling of deforestation and soy production in the southern Amazon during the late 2000s. Proc. Natl. Acad. Sci. 109, 1341–1346.

Machovina, B., Feeley, K.J., 2014a. Livestock: limit red meat consumption. Nature 508 (186-186).

Machovina, B., Feeley, K.J., 2014b. Meat consumption as a key impact on tropical nature: a response to Laurance et al. Trends Ecol. Evol. 29, 430.

Machovina, B., Feeley, K.J., 2014c. Taking a bite out of biodiversity. Science 343, 838.

Mallin, M.A., Cahoon, L.B., 2003. Industrialized animal production—a major source of nutrient and microbial pollution to aquatic ecosystems. Popul. Environ. 24, 369–385.

Marsh, J.M., 2003. Impacts of declining U.S. retail beef demand on farm-level beef prices and production. Am. J. Agric. Econ. 85, 902–913.

Massé, D., Talbot, G., Gilbert, Y., 2011. On farm biogas production: a method to reduce GHG emissions and develop more sustainable livestock operations. Anim. Feed Sci. Technol. 166, 436–445.

Masuda, T., Goldsmith, D., 2009. World soybean production: area harvested, yield, and long-term projections. International Food and Agribusiness Management Review 12.

McDougall, J., 2002. Plant foods have a complete amino acid composition. Circulation 105 (e197-e197).

McLauchlan, K.K., Hobbie, S.E., Post, W.M., 2006. Conversion from agriculture to grassland builds soil organic matter on decadal timescales. Ecol. Appl. 16, 143–153.

McMichael, A.J., Powles, J.W., Butler, C.D., Uauy, R., 2007. Food, livestock production, energy, climate change, and health. Lancet 370, 1253–1263.

Menotti, A., Kromhout, D., Blackburn, H., Fidanza, F., Buzina, R., Nissinen, A., 1999. Food intake patterns and 25-year mortality from coronary heart disease: cross-cultural correlations in the Seven Countries Study. Eur. J. Epidemiol. 15, 507–515.

Mittermeier, R.A., Gil, P.R., Mittermeir, C.G., 1997. Megadiversity. Earth's biologically wealthiest nations, CEMEX, Mexico City, Mexico.

Mollison, B., 1988. Permaculture: a designer's manual. Permaculture: a designer's manual.

Mollison, B.C., Holmgren, D., 1979. Permaculture. Transworld Publishers.

Morales-Hidalgo, D., 2006. Tree cover assessment: with special focus on the relative position issue. Case Studies in Open Areas in Costa Rica. Cuvillier Verlag.

Myers, N., Mittermeier, R.A., Mittermeier, C.G., da Fonseca, G.A.B., Kent, J., 2000. Biodiversity hotspots for conservation priorities. Nature 403, 853–858.

Naylor, R.L., Goldburg, R.J., Primavera, J.H., Kautsky, N., Beveridge, M.C., Clay, J., Folke, C., Lubchenco, J., Mooney, H., Troell, M., 2000. Effect of aquaculture on world fish supplies. Nature 405, 1017–1024.

Nellemann, C., 2009. The environmental food crisis: the environment's role in averting future food crises: a UNEP rapid response assessment. UNEP/Earthprint.

Nepstad, D., McGrath, D., Stickler, C., Alencar, A., Azevedo, A., Swette, B., Bezerra, T., DiGiano, M., Shimada, J., Seroa da Motta, R., Armijo, E., Castello, L., Brando, P., Hansen, M.C., McGrath-Horn, M., Carvalho, O., Hess, L., 2014. Slowing Amazon deforestation through public policy and interventions in beef and soy supply chains. Science 344, 1118–1123.

Nepstad, D.C., Stickler, C.M., Almeida, O.T., 2006. Globalization of the Amazon soy and beef industries: opportunities for conservation. Conserv. Biol. 20, 1595–1603.

Nepstad, D.C., Stickler, C.M., Filho, B.S.-., Merry, F., 2008. Interactions among Amazon land use, forests and climate: prospects for a near-term forest tipping point. Philos. Trans. R. Soc., B 363, 1737–1746.

Nestle, M., 1999. Animal v. plant foods in human diets and health: is the historical record unequivocal? Proc. Nutr. Soc. 58, 211–218.

Ornish, D., Scherwitz, L.W., Billings, J.H., et al., 1998. INtensive lifestyle changes for reversal of coronary heart disease. JAMA 280, 2001–2007.

Pan, A., Sun, Q., Bernstein, A.M., Manson, J.E., Willett, W.C., Hu, F.B., 2013. Changes in red meat consumption and subsequent risk of type 2 diabetes mellitus: three cohorts of US men and women. JAMA Intern. Med. 173, 1328–1335.

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

Pimm, S.L., Jenkins, C.N., Abell, R., Brooks, T.M., Gittleman, J.L., Joppa, L.N., Raven, P.H., Roberts, C.M., Sexton, J.O., 2014. The biodiversity of species and their rates of extinction, distribution, and protection. Science 344.

Popkin, B.M., Adair, L.S., Ng, S.W., 2012. Global nutrition transition and the pandemic of obesity in developing countries. Nutr. Rev. 70, 3–21.

Post, W.M., Emanuel, W.R., Zinke, P.J., Stangenberger, A.G., 1982. Soil carbon pools and world life zones.

Prein, M., 2002. Integration of aquaculture into crop–animal systems in Asia. Agric. Syst. 71, 127–146.

Pretty, J.N., Morison, J.I., Hine, R.E., 2003. Reducing food poverty by increasing agricultural sustainability in developing countries. Agric. Ecol. Environ. 95, 217–234.

Prins, H.H., 2000. Competition between wildlife and livestock in Africa. Wildlife conservation by sustainable use. Springer, pp. 51–80.

Rae, A.N., Hertel, T.W., 2000. Future developments in global livestock and grains markets: the impacts of livestock productivity convergence in Asia-Pacific. Aust. J. Agric. Resour. Econ. 44, 393–422.

Ridler, N., Wowchuk, M., Robinson, B., Barrington, K., Chopin, T., Robinson, S., Page, F., Reid, G., Szemerda, M., Sewuster, J., 2007. Integrated Multi — Trophic Aquaculture (IMTA): a potential strategic choice for farmers. Aquac. Econ. Manag. 11, 99–110.

Ripple, W.J., Estes, J.A., Beschta, R.L., Wilmers, C.C., Ritchie, E.G., Hebblewhite, M., Berger, J., Elmhagen, B., Letnic, M., Nelson, M.P., Schmitz, O.J., Smith, D.W., Wallach, A.D., Wirsing, A.J., 2014a. Status and ecological effects of the world's largest carnivores. Science 343.

Ripple, W.J., Newsome, T.M., Wolf, C., Dirzo, R., Everatt, K.T., Galetti, M., Hayward, M.W., Kerley, G.I., Levi, T., Lindsey, P.A., 2015. Collapse of the world's largest herbivores. Sci. Adv. 1, e1400103.

Ripple, W.J., Smith, P., Haberl, H., Montzka, S.A., McAlpine, C., Boucher, D.H., 2014b. Ruminants, climate change and climate policy. Nat. Clim. Chang. 4, 2–5.

Rogers, C.S., 1990. Responses of coral reefs and reef organisms to sedimentation. Mar. Ecol. Prog. Ser. 62, 185–202 (Oldendorf).

Röös, E., Sundberg, C., Tidåker, P., Strid, I., Hansson, P.-A., 2013. Can carbon footprint serve as an indicator of the environmental impact of meat production? Ecol. Indic. 24, 573–581.

Rosenzweig, C., Elliott, J., Deryng, D., Ruane, A.C., Müller, C., Arneth, A., Boote, K.J., Folberth, C., Glotter, M., Khabarov, N., 2014. Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison. Proc. Natl. Acad. Sci. 111, 3268–3273.

Rulli, M.C., Saviori, A., D'Odorico, P., 2013. Global land and water grabbing. Proc. Natl. Acad. Sci. 110, 892–897.

Sadler, M.J., 2004. Meat alternatives—market developments and health benefits. Trends Food Sci. Technol. 15, 250–260.

Sala, O.E., Stuart Chapin III, F., Armesto, J.J., Berlow, E., Bloomfield, J., Dirzo, R., Huber-Sanwald, E., Huenneke, L.F., Jackson, R.B., Kinzig, A., Leemans, R., Lodge, D.M., Mooney, H.A., Oesterheld,, M.n., Poff, N.L., Sykes, M.T., Walker, B.H., Walker, M., Wall, D.H., 2000. Global biodiversity scenarios for the year 2100. Science 287, 1770–1774.

Sanders, T., 1999. The nutritional adequacy of plant-based diets. Proc. Nutr. Soc. 58, 265–269.

Scurlock, J.M.O., Hall, D.O., 1998. The global carbon sink: a grassland perspective. Glob. Chang. Biol. 4, 229–233.

Shu, X.O., Zheng, W., Potischman, N., Brinton, L.A., Hatch, M.C., Gao, Y.-T., Fraumeni, J.F., 1993. A population-based case–control study of dietary factors and endometrial cancer in Shanghai, People's Republic of China. Am. J. Epidemiol. 137, 155–165.

Smith, P., Haberl, H., Popp, A., Erb, K.H., Lauk, C., Harper, R., Tubiello, F.N., Siqueira Pinto, A., Jafari, M., Sohi, S., 2013. How much land-based greenhouse gas mitigation can be achieved without compromising food security and environmental goals? Glob. Chang. Biol. 19, 2285–2302.

Steinfeld, H., Gerber, P., Wassenaar, T.D., Castel, V., Haan, C.d., 2006a. Livestock's long shadow: environmental issues and options. Food and Agriculture Organization of the United Nations, Rome.

Steinfeld, H., Wassenaar, T., Jutzi, S., 2006b. Livestock production systems in developing countries: status, drivers, trends. Rev. Sci. Tech. Off. Int. Epiz. 25, 505–516.

Stinner, D.H., Stinner, B.R., Martsolf, E., 1997. Biodiversity as an organizing principle in agroecosystem management: case studies of holistic resource management practitioners in the USA. Agric. Ecol. Environ. 62, 199–213.

Strom, S., 2013. An accidental cattle ranch points the way in sustainable farming. New York Times.

Szott, L., Ibrahim, M., Beer, J., 2000. The hamburger connection hangover: cattle, pasture land degradation and alternative land use in Central America. Bib. Orton IICA/CATIE.

Thomas, C.D., Cameron, A., Green, R.E., Bakkenes, M., Beaumont, L.J., Collingham, Y.C., Erasmus, B.F., De Siqueira, M.F., Grainger, A., Hannah, L., 2004. Extinction risk from climate change. Nature 427, 145–148.

Thornton, P.K., 2010. Livestock production: recent trends, future prospects. Philosophical Transactions of the Royal Society B: Biological Sciences 365, 2853–2867.

Tilman, D., Clark, M., 2014. Global diets link environmental sustainability and human health. Nature advance online publication.

Tilman, D., Fargione, J., Wolff, B., D'Antonio, C., Dobson, A., Howarth, R., Schindler, D., Schlesinger, W.H., Simberloff, D., Swackhamer, D., 2001. Forecasting agriculturally driven global environmental change. Science 292, 281–284.

Tropics, S.o.t., 2014. State of the tropics 2014 report. Cairns, Australia.

U.S. Department of Agriculture, A.R.S., 2013. USDA National Nutrient Database for Standard Reference, Release 26. Nutrient Data Laboratory Home Page.

Van Vliet, N., 2011. Livelihood alternatives for the unsustainable use of bushmeat. Report prepared for the CBD Bushmeat Liaison Group. Technical Series.

Walker, R., Browder, J., Arima, E., Simmons, C., Pereira, R., Caldas, M., Shirota, R., Zen, S.d., 2009. Ranching and the new global range: Amazônia in the 21st century. Geoforum 40, 732–745.

Walther, G.-R., Post, E., Convey, P., Menzel, A., Parmesan, C., Beebee, T.J., Fromentin, J.-M., Hoegh-Guldberg, O., Bairlein, F., 2002. Ecological responses to recent climate change. Nature 416, 389–395.

Weber, K.T., Gokhale, B.S., 2011. Effect of grazing on soil–water content in semiarid rangelands of southeast Idaho. J. Arid Environ. 75, 464–470.

West, P.C., Gerber, J.S., Engstrom, P.M., Mueller, N.D., Brauman, K.A., Carlson, K.M., Cassidy, E.S., Johnston, M., MacDonald, G.K., Ray, D.K., Siebert, S., 2014. Leverage points for improving global food security and the environment. Science 345, 325–328.

White, R.P., Murray, S., Rohweder, M., Prince, S.D., Thompson, K.M., 2000. Grassland ecosystems. World Resources Institute Washington, DC, USA.

Wilkie, D.S., Starkey, M., Abernethy, K., Effa, E.N., Telfer, P., Godoy, R., 2005. Role of prices and wealth in consumer demand for bushmeat in Gabon, Central Africa. Conserv. Biol. 19, 268–274.

Young, V.R., Pellett, P.L., 1994. Plant proteins in relation to human protein and amino acid nutrition. Am. J. Clin. Nutr. 59, 1203S–1212S.

Literature cited

FAO, 2011. Mapping supply and demand for animal-source foods to 2030. In: Robinson, T.P., Pozzi, F. (Eds.), Animal Production and Health Working Paper 2. FAO, Rome.

Röös, E., Sundberg, C., Tidåker, P., Strid, I., Hansson, P.-A., 2013b. Can carbon footprint serve as an indicator of the environmental impact of meat production? Ecol. Indic. 24, 573–581.

Wint, W., Robinson, T., 2007. Gridded livestock of the world 2007. pp. 50–59 (Aportes (Costa Rica), (Jun 2004)).