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Livestock and human use of land: productivity trends and dietary choices as drivers of future land and carbon dynamics

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Abstract. Land use change has been the primary driving force of human alteration of terrestrial ecosystems. With 80% of agricultural land dedicated to livestock production, the sector is an important lever to attenuate land requirements for food production and carbon emissions from land use change. In this study, we quantify impacts of changing human diets and livestock productivity on land dynamics and depletion of carbon stored in vegetation, litter and soils. Across all investigated productivity pathways, lower consumption of livestock products can substantially reduce deforestation (47-55%) and cumulative carbon losses (34-57%). On the supply side, already minor productivity growth in extensive livestock production systems leads to substantial CO_2 emission abatement, but the emission saving potential of productivity gains in intensive systems is limited, mainly due to trade-offs with soil carbon stocks. If also accounting for uncertainties related to future trade restrictions, crop yields and pasture productivity, the range of projected carbon savings from changing diets increases to 23-78%. Highest abatement of carbon emissions (63-78%) can be achieved if reduced consumption of animal-based products is combined with sustained investments into productivity increases in plant production. Our analysis emphasizes the importance to integrate demand- and supply-side oriented mitigation strategies and to combine efforts in the crop and livestock sector to enable synergies for climate protection.

Keywords: livestock productivity; diets; land use; deforestation; carbon emissions; greenhouse gas mitigation

1. Introduction

Land transformation has been the primary driving force of human alteration of terrestrial ecosystems, strongly interacting with most other aspects of global environmental change (Lambin et al., 2001; Steffen et al., 2015; Vitousek et al., 1997). Carbon emissions from land use and land-cover change contribute 12.5% to anthropogenic carbon emissions (Houghton et al., 2012), thus representing the second-largest source after fossil fuel combustion (van der Werf et al., 2009). In view of the serious danger that climate change poses to ecosystems and human welfare (Smith et al., 2009), the capacity of land to sequester carbon is one of its crucial functions. Besides the protection and restoration of forests, recent efforts to foster climate action like the “4 per 1000 initiative” under the framework of the Lima-Paris Action Agenda emphasise the importance of soil carbon which is also stored in agricultural ecosystems.

The livestock sector is a key element of land related human interference with the Earth system, consuming 58% of the economically used plant biomass (12.1 Pg/yr) in contrast to 12% directly serving as food (Krausmann et al., 2008). Resulting overall land use of livestock production accounts for 80% of agricultural land (Steinfeld et al., 2006). Deforestation is the most critical aspect of land use change, with livestock playing a pivotal role through the establishment of new pastures or expansion of arable land to produce crops like soybeans in the wake of intensifying livestock feeding practices around the world (Herrero et al., 2009; Naylor et al., 2005). While cattle ranching is considered as the major proximate cause of forest clearing in the Legal Amazon, soy cultivation often expanded into areas previously used as pastures, thereby indirectly triggering forest-to-pasture conversion elsewhere (Barona et al., 2010). Moreover, soy production may have contributed to deforestation by other indirect pathways, such as boosting land prices and infrastructure development (Barona et al., 2010; Fearnside, 2001, 2005; Nepstad et al., 2006).

Accordingly, restraining land requirements is increasingly regarded as a decisive measure to alleviate detrimental impacts of livestock production on the environment (Smith et al., 2013; Steinfeld and Gerber, 2010; Wirsenius et al., 2010), either on the supply side by changes in livestock production systems or on the demand side by lower consumption of land-intensive livestock commodities. On the supply side, substantial differences in feed conversion efficiencies across regions and levels of intensification indicate a large potential to transform biomass flows within the global food system and attenuate pressures on natural resources (Bouwman et al., 2013; Havlík et al., 2014; Herrero et al., 2013b, 2015; Weindl et al., 2015; Wirsenius et al., 2010). Intensification of livestock production systems does not only considerably alter feed and overall resource use per animal product, but it also affects the composition of feed baskets, shifting the focus from residues, food waste and grazed biomass to higher quality and nutrient-rich feed. However, resulting increase in the importance of cropland at the expense of pastures could impede carbon sequestration, since grasslands have a high root turnover and build up substantial soil organic carbon stocks (Conant et al., 2001; Don et al., 2011).

In consequence, understanding the link between livestock, land and carbon requires a detailed representation of feeding regimes and a comprehensive coverage of different land use types and related carbon pools. While several studies highlight the importance of feeding efficiencies and shifts in livestock production systems to attenuate pressures on land and to reduce greenhouse gas (GHG) emissions (Cohn et al., 2014; Havlík et al., 2014; Herrero et al., 2013b; Valin et al., 2013), they consider aggregated carbon dioxide (CO_2) emissions without separating carbon pools and channels of land conversion or limit the scope to nitrous oxide (N_2O) and methane (CH_4) emissions. However, a dedicated coverage of soil carbon and non-forest land is essential for designing efficient climate protection schemes, since exclusion of non-forest carbon stocks from mitigation policies entails significant carbon leakage (Popp et al., 2014) and carbon stored in soils represents more than twice the amount found in the atmosphere (Smith, 2008).

This study aims at specifically addressing the impacts of future livestock production on the interplay between different managed and unmanaged land types and related trade-offs in terms of carbon losses from vegetation, litter and soils. Special attention is hereby given to sector-specific options to mitigate pressures on terrestrial ecosystems like changes in human diets and different livestock productivity pathways, either representing a catch-up of low productive systems to higher productivity levels, a stagnation of productivity in extensive systems or a moderate productivity reduction in intensive systems. For this aim, we apply a spatially explicit, global agro-economic model, where links between livestock, land and crop production are established through product-specific feed baskets that evolve with the productivity level, through manure provision, investments into research and development and trade flows.

2. Methods and data

2.1. Modelling framework

The Model of Agricultural Production and its Impact on the Environment (MAgPIE) is a global partial equilibrium agro-economic model that combines spatially explicit biophysical constraints with regional socioeconomic information for ten world regions (Table 1) to derive optimal resource allocation and agricultural production patterns (Bodirsky et al., 2014; Lotze-Campen et al., 2008; Popp et al., 2014, 2017; Stevanović et al., 2016). Possible future developments of the agricultural and land-use sectors are simulated in a recursive dynamic mode by minimizing a nonlinear global objective function defining global agricultural production costs.

Table 1. Socio-economic regions in MAgPIE.

Acronyms	MAgPIE regions
AFR	Sub-Sahara Africa
CPA	Centrally Planned Asia (incl. China)
EUR	Europe (incl. Turkey)
FSU	Former Soviet Union
LAM	Latin America
MEA	Middle East and North Africa
NAM	North America
PAO	Pacific OECD (Australia, Japan and New Zealand)
PAS	Pacific Asia
SAS	South Asia (incl. India)

Pasture productivity, crop yields under both rainfed and irrigated conditions, related irrigation water demand per crop, water availability for irrigation and carbon densities are simulated by the process-based, dynamic global vegetation and water balance model LPJmL (Lund-Potsdam-Jena model with managed Land) (Bondeau et al., 2007; Müller and Robertson, 2014) on 0.5 degree resolution and aggregated to 1000 clusters for this study (Dietrich et al., 2013). LPJmL simulates growth, production and phenology of 9 plant functional types (Sitch et al., 2003) and of 11 crop functional types as well as managed grassland (Bondeau et al., 2007). Water and carbon fluxes are directly connected to vegetation patterns and dynamics through the linkage of transpiration, photosynthesis and plant water stress.

Food demand projections are exogenously calculated based on an econometric regression model for national caloric intake per capita (Bodirsky et al., 2012, 2015; Valin et al., 2014). Regional feed demand depends on livestock production quantities and regional system-specific feed baskets that evolve with livestock productivity trajectories. Global demand for agricultural commodities is allocated to the supply regions via trade dynamics based on an exogenous rate of trade liberalization, defining the proportion of agricultural goods that are, on top of historical trade patterns, traded according to comparative advantages (Schmitz et al., 2012). Through investments in research and development, the model can endogenously increase crop yields and pasture productivity, with the costs of technological change depending on the current technology level (Dietrich et al., 2014). More information on the model version underlying this study can be found in the SI appendix.

2.2. Land use change

Competition for land is explicitly addressed for cropland, pasture, forest (including forestry), and other land (other natural vegetation such as savannahs and abandoned agricultural land). Forest areas designated for wood production (about 30% of the initial forest area) and pristine forests in protected areas (12.5% of global forests (FAO, 2010)) are excluded from conversion into agricultural land. The suitability of land for crop cultivation further constrains the conversion of natural vegetation or pastures to cropland and is primarily determined using crop yields from LPJmL. Additionally, cropping can only occur on land that is at least marginally suitable for rainfed crop production with regard to climate, topography and soil type according to the Global Agro-Ecological Assessment (GAEZ) methodology on land suitability (Fischer et al., 2002; Krause et al., 2013; van Velthuizen et al., 2007). In response to production costs (SI appendix A.1.5) and biophysical constraints, MAgPIE optimizes spatial distribution of crops and pasture within current agricultural land as well as the balance between land expansion, trade, and improvements in land productivity.

2.3. Carbon emissions

Carbon emissions in MAgPIE are computed as the change in terrestrial carbon stocks from land conversion processes between simulated land types. Spatially explicit carbon stocks for all land types and carbon pools (vegetation, litter and soils) are calculated by multiplying pool- and land-specific carbon densities with land area. Negative carbon emissions occur when cropland is set-aside from agricultural production and subsequent ecological succession restores natural vegetation carbon stocks (Humpenöder et al., 2014), thus turning land into a sink for atmospheric carbon. In case of regrowth, vegetation carbon density increases over time along sigmoid growth curves which are based on a Chapman-Richards volume growth model (Murray and von Gadow, 1993; von Gadow and Hui, 2001) and parameterized using vegetation carbon density of natural vegetation. Carbon densities for vegetation, litter and soil carbon pools of natural vegetation (Fig. 1) are provided by LPJmL.

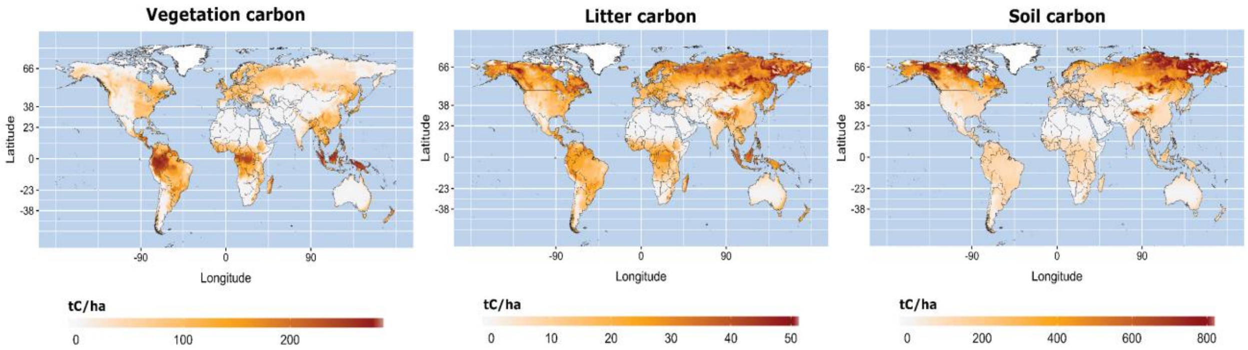

Fig. 1. Potential carbon densities for vegetation, litter and soil carbon pools in tC/ha calculated by LPJmL assuming that all terrestrial grid cells are covered with natural vegetation.

2.4. Livestock sector

Livestock products are supplied by five animal food systems (beef cattle, dairy cattle, pigs, broilers and laying hens). Feed conversion (total feed per product in dry matter) and feed baskets (demand for different feed types per product in dry matter) are derived by compiling system-specific feed energy balances (Wirsenius, 2000; Wirsenius et al., 2010), using feed energy requirements of all animals within the respective animal food system, i.e. reproducers, producers and replacement animals as estimated by Wirsenius (2000). These estimates are based on standardized bio-energetic equations and include energy requirements for maintenance, growth, lactation, reproduction and other basic biological functions of the animals. Non-linear regression models for feed conversion and feed composition (share of different feed groups in feed baskets) with livestock productivity (annual production per animal [ton/animal/year]) as predictor permit the construction of productivity dependent feed baskets. Incorporation of spatial heterogeneity and climatic conditions into weighted non-linear regression models for feed composition is facilitated by a proxy based on Koeppen-Geiger climate zones (Portland State University, 2015). More information on the livestock sector implementation can be found in the SI appendix A.2.

2.5. Scenario description

Socio-economic drivers are parametrized in line with the “Middle of the Road” scenario of the Shared Socioeconomic Pathways (SSPs) for climate change research (Kriegler et al., 2017; O’Neill et al., 2014; Popp et al., 2017). In this scenario (SSP2), gross domestic product and population trajectories reach global values of 230 trillion US Dollars (at 2005 prices and adjusted for purchasing power parity) and 9.1 billion people in 2050 (IIASA, 2013). Global trade barriers are relaxed by 5% per decade.

Table 2. Overview of scenario setting.

Scenario		Description
Dietary choices	SSP2	Food demand trajectories according to the SSP2 narrative with an average per capita food demand of 3051 kcal per day and 24% animal-based products in dietary calories in 2050
	DEMI	Gradual change towards a demitarian Western diet with a share of animal-based products in dietary calories of no more than 15% in 2050
Livestock productivity	BASELINE	Livestock productivity trajectories according to the SSP2 narrative with medium pace in productivity increases and a slight catch-up of low productive systems
	DIVERGENCE	Continuation of historically observed very divergent productivity trends with little improvements in low productive systems
	CATCH-UP	SSP2 + further closure of the productivity gap by 45% for ruminant systems and by 60% for monogastric systems until 2050
	MODERATION	SSP2 + productivity reductions in highly productive systems to the level of 75% relative to the productivity frontier

We investigate eight scenarios as combinations of two variants of future *dietary choices* and four variants of *livestock productivity* trends (Table 2). Supplementing the baseline diet scenario (SSP2), we define an alternative development of dietary patterns (SI appendix, Fig. S7), representing a gradual change of SSP2 diet projections to lower shares of animal-based calories in diets, with 15% as upper limit in 2050 for calories from livestock and fish (DEMI). With the share of animal-based calories being approximately half the currently observed level in OECD countries, the DEMI scenario builds upon the concept of a "demitarian" Western diet (Bodirsky et al., 2014; Stevanović et al., 2017; Sutton and Ayyappan, 2013).

The diet scenarios are combined with four alternative livestock productivity pathways (SI appendix, Fig. S8). Besides exploring impacts of productivity gains, we also explore how de-intensification strategies could affect land and carbon dynamics. The BASELINE scenario, following the SSP2 narrative, is characterized by a medium pace in productivity improvements, where low-productive regions catch up to a certain extent (Popp et al., 2017). With little improvements in some regions' low productive systems, the DIVERGENCE scenario represents the continuation of historically observed very divergent productivity developments and is constructed by following the extrapolation of historical trends between 1970 and 2010, if they are lower than SSP2 projections. The ambitious CATCH-UP scenario assumes a further closure of the productivity gap, defined by top-performing countries in 2010, by 45% for ruminant systems and by 60% for monogastric systems until 2050. The MODERATION scenario explores a variation of SSP2 livestock productivity trends at the opposite end of the range, the highly intensive systems. Until 2050, these systems are assumed to experience a reduction in livestock productivity to the level of 75% relative to the productivity frontier defined by top-performing countries in 2010.

To understand the role of trade and land productivity for land use change and related emissions, we conduct a sensitivity analysis applying three additional scenario settings: a) ***Restricted trade*** (relative to the default SSP2 setting) where we assume that interregional trade patterns, in terms of self-sufficiency ratios and relative shares of regional trade flows, are constant over time; b) ***Liberalized trade*** where global trade barriers are relaxed by 10% per decade (instead of 5% as in the SSP2 default setting), which is close to observed liberalization trends of the last decade; and c) ***Exogenous yield*** where all standard productivity and diet scenarios are calculated with exogenous trajectories of crop yields and pasture productivity, based on the endogenously calculated crop and pasture productivity trends from the SSP2 BASELINE simulation in the default model setting.

3. Results

3.1. Land dynamics

The potential of the livestock sector to substantially alter land use dynamics is clearly visible on the global scale (Fig. 2). The interaction between cropland and pasture dynamics plays an important role for deforestation and is strongly influenced by livestock productivity trajectories, but also subject to demand-side preferences. In the SSP2 BASELINE scenario, total agricultural land increases from 4630 Mha in 2010 to 4830 Mha in 2050 as a result of substantial cropland expansion (+370 Mha, +26%) that is partly compensated by a reduction in pasture area (-170 Mha, -5%). By 2050, forest losses amount to 150 Mha, while conversion of other natural vegetation represents a minor contribution to land use change (50 Mha). Across all diet and productivity scenarios, projected deforestation ranges between 70 and 360 Mha. Dietary changes towards less livestock products reduce pressures on land, translating into lower cropland expansion (23-39% less than under SSP2 diets) and avoided deforestation (47-55%).

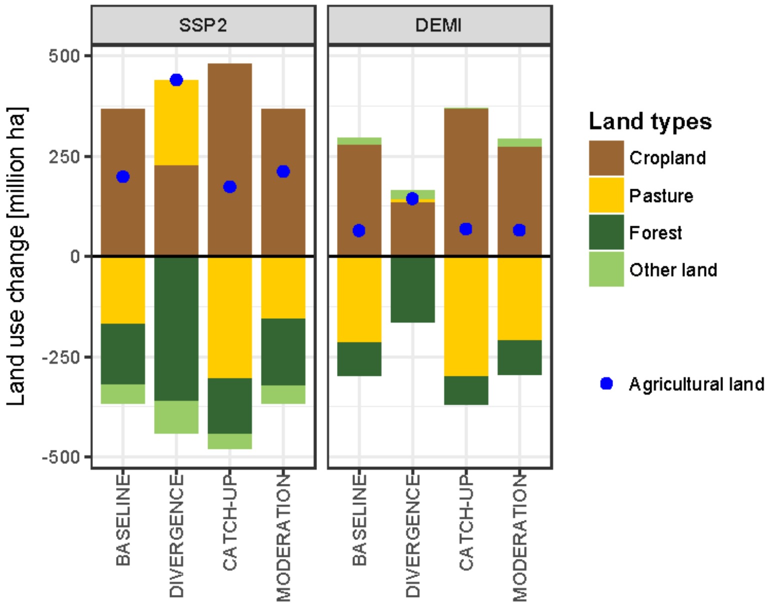

Fig. 2. Changes in global cropland, pasture, forest and other natural vegetation between 2010 and 2050 in Mha. Blue points indicate the net change in global agricultural land.

All scenarios involve expansion of cropland (10-35%) which increases with higher livestock productivity and decreases with lower consumption of livestock products. Implications for deforestation depend on the potential of pasture-to-cropland conversion to counterbalance increased land demand to grow crops. Reductions in pasture area in the wake of higher livestock productivity outpace related increases in cropland, thus entailing a land sparing effect. Only under stagnating low livestock productivity in some regions together with a growing demand for livestock products (SSP2 DIVERGENCE), we observe an increase in pasture area (+210 Mha) and consequently the highest estimate for deforestation. The MODERATION productivity scenarios entail very similar dynamics as the BASELINE scenarios, with slightly higher deforestation for SSP2 diets.

Global patterns of land use change are a congeries of diverse regional developments (Fig. 3). In Latin America, Sub-Saharan Africa and South Asia, land conversion processes across scenarios are strongly influenced by livestock productivity trends, resulting in a large regional spread of deforestation and loss of other natural ecosystems. In Centrally Planned Asia, Former Soviet Union, North America, Middle East and North Africa, land dynamics primarily react to dietary changes, ending forest conversion in North America and resulting in land abandonment and regrowth of natural vegetation in the Former Soviet Union. In the Middle East and North Africa, expansion of agricultural activities is heavily constrained by the scarcity of natural resources, with pasture being the only land resource available for cropland expansion. Establishment of new pastures, discernibly linked to loss of forests or other natural vegetation, is only simulated under the DIVERGENCE pathway with prevailing low productivity of regional livestock production. Regional patterns highlight the important role of developments in Sub-Saharan Africa and Latin America for further alteration of terrestrial ecosystems.

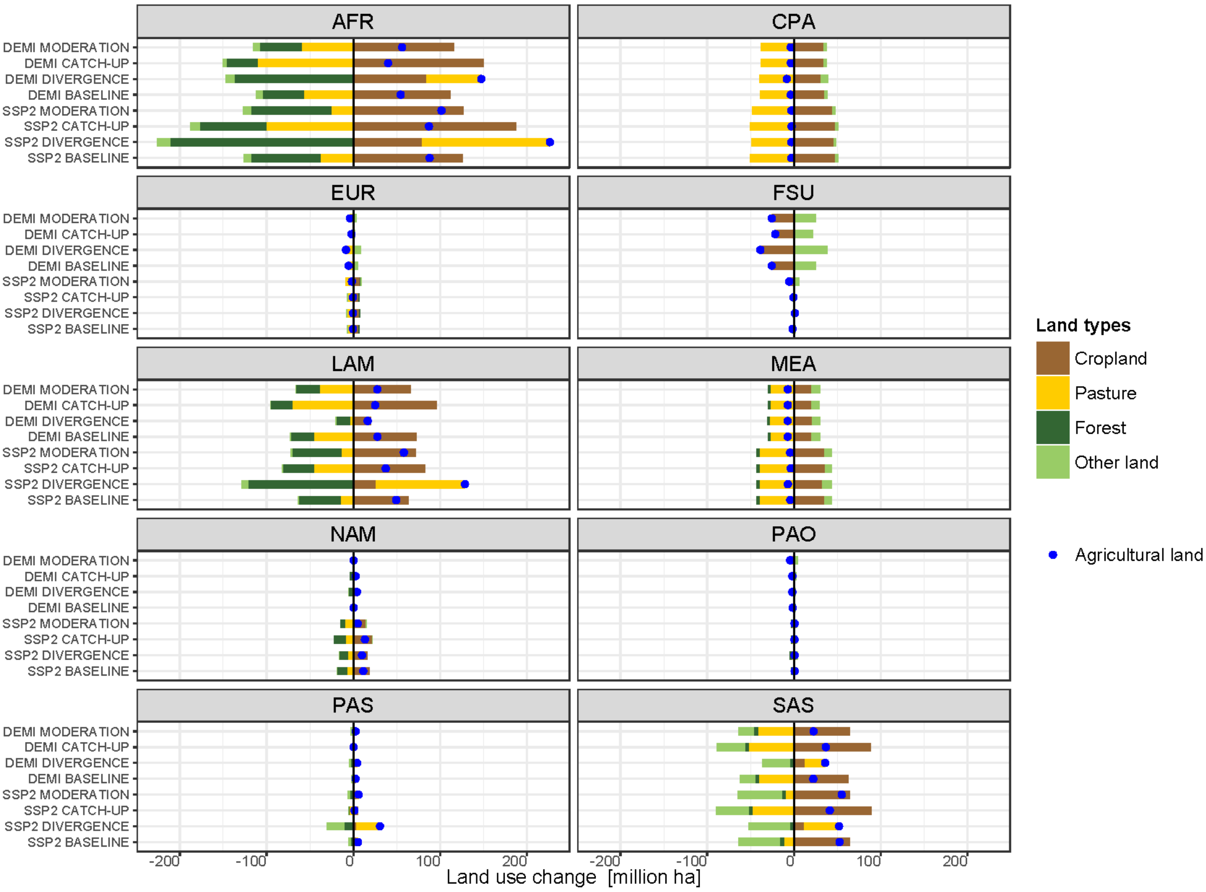

Fig. 3. Changes in regional cropland, pasture, forest and other natural vegetation between 2010 and 2050 in Mha. Blue points indicate changes in regional agricultural land defined as the sum of cropland and pasture. Results are depicted for the ten socio-economic regions in MAgPIE: AFR (Sub-Saharan Africa), CPA (Centrally Planned Asia), FSU (Former Soviet Union), EUR (Europe, including Turkey), LAM (Latin America), MEA (Middle East–North Africa), NAM (North America), PAO (Pacific OECD), PAS (Pacific Asia), and SAS (South Asia).

3.2. Carbon dynamics

Agricultural expansion and losses of natural ecosystems across all scenarios drive further depletion of terrestrial carbon stocks, but by different orders of magnitude (Fig. 4). Until 2050, cumulative carbon releases amount to 20-80 Gt C, which is equivalent to 74-295 Gt CO_2 emitted to the atmosphere (Table 3). As in the case of deforestation, the predominant role of Sub-Saharan Africa and Latin America is clearly visible in our results, contributing 74-93% to global carbon losses. If low historical productivity improvements are assumed to continue, both regions together are projected to double (DEMI) or triple (SSP2) their carbon emissions from land use change compared to BASELINE trends. Thus, already intermediate livestock productivity improvements, as assumed under the BASELINE pathways for these regions, lead to substantial abatement of carbon emissions. The role of different land types within overall land dynamics affects the extent at which the different above and belowground carbon pools contribute to net carbon losses, both at the regional and global scale. In the SSP2 BASELINE scenario, changes in vegetation carbon account for 51%, depletion of soil carbon for 39% and losses of carbon in litter for 10% of total releases (124 Gt C).

Table 3. Cumulative CO_2 emissions between 2010 and 2050 for all scenarios in Gt CO_2.

Diets	Productivity	Vegetation	Litter	Soil	All pools
SSP2	BASELINE	63	12	49	124
	DIVERGENCE	236	34	24	295
	CATCH-UP	47	10	68	125
	MODERATION	76	14	49	140
DEMI	BASELINE	27	5	43	75
	DIVERGENCE	97	13	17	127
	CATCH-UP	23	5	54	82
	MODERATION	27	5	42	74

CATCH-UP pathways entail very similar cumulative carbon losses compared to BASELINE productivity trends, with a higher contribution of soil carbon and a lower share of vegetation carbon. Although deforestation is slightly lower, considerable pasture-to-cropland conversion depletes carbon stored in soils and counteracts minor potential carbon savings from avoided deforestation. High deforestation, as triggered by the DIVERGENCE pathway in combination with SSP2 diets, results in high carbon emissions. However, total carbon releases and especially soil carbon losses would be even larger if we only considered loss of forest carbon stocks, as expanding pastures can also sequester significant amounts of carbon in soils. While in the SSP2 MODERATION scenario, deforestation and resulting carbon emissions are higher than in the BASELINE, no difference can be observed for reduced consumption of livestock products. In the DEMI scenarios, expansion of cropland is in general less linked to deforestation and relies stronger on conversion of pastures, resulting in a higher contribution of soil carbon to total carbon releases. Across all productivity pathways, dietary changes towards less livestock products can substantially reduce cumulative carbon losses (34-57%).

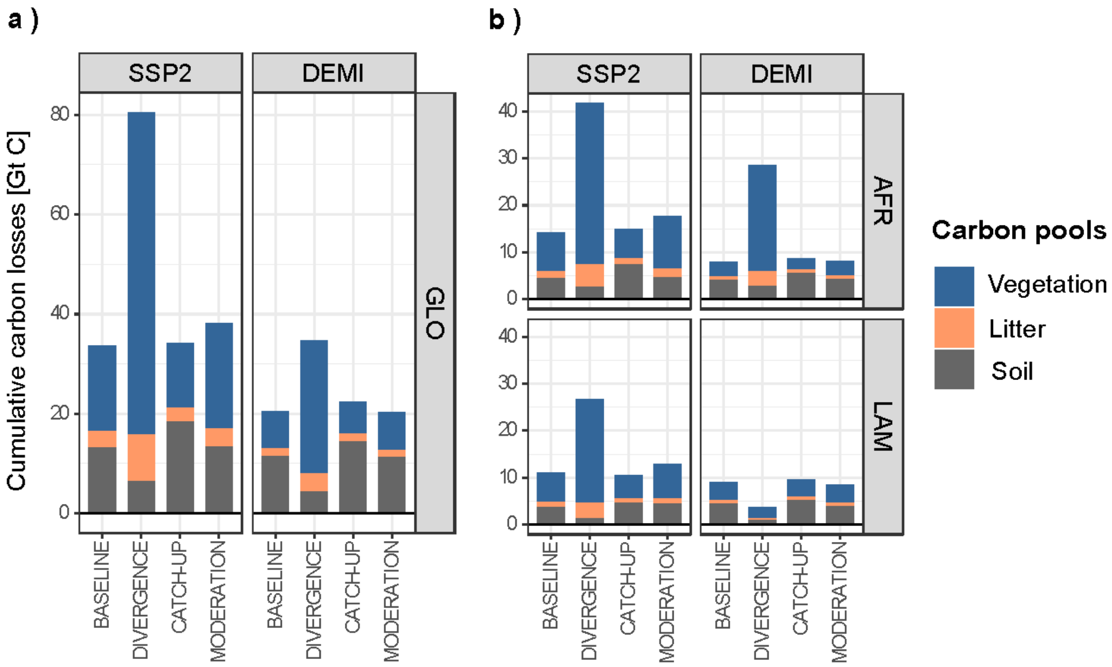

Fig. 4. Cumulative carbon losses between 2010 and 2050 in Gt C from vegetation, litter and soil carbon pools. The left panel (a) illustrates global values and the right panel (b) shows values for Sub-Saharan Africa (AFR) and Latin America (LAM).

3.3. Uncertainties in projected land and carbon dynamics

How demand- and supply-side scenarios alter land and carbon dynamics also depends on the role of intermediate processes such as reallocation of production through international trade and efforts to invest into yield improvements and pasture management (Fig. 5, Table 4). A *restricted trade* regime with self-sufficiency ratios and relative export flows fixed to 1995 levels constrains the possibility to balance heterogeneous demand trajectories and differences in land availability and productivity across regions through interregional reallocation of production. As a result, we observe more cropland expansion, deforestation and CO_2 emissions, although limited options to conciliate increasing food demand and available resources in some regions simultaneously lead to higher investments into yield increasing technological change. Due to the low flexibility in the system, the potential of dietary changes to attenuate land use change and related emissions (23-37% reduction in emitted CO_2) is low compared to other sensitivity settings.

In a *liberalized trade* setting, trade patterns endogenously respond to asymmetric regional developments and can compensate regional inefficiencies and imbalances between food demand and availability of natural resources. Production is allocated according to comparative advantages between regions, which could also favour locations where land is abundant and lead to lower incentives to invest into yield increases. Thus, impacts of trade liberalization on land and carbon dynamics are ambiguous and depend on overall development pathways of agriculture. In the case of the SSP2 BASELINE and MODERATION scenarios, trade liberalization entails higher forest losses and CO_2 emissions, while production costs and investments into research and development are lower. In the case of diverging livestock productivity trends, however, a reallocation of trade flows and production can exploit the large heterogeneity of regional livestock productivities and feed efficiencies, resulting in avoided deforestation and mitigation of CO_2 emissions.

Comparison of scenarios assuming *exogenous yield trajectories* with default simulations highlights the buffering effect of yield increasing innovation and management. Efforts to invest into land productivity depend on land scarcity and are driven by demand- and supply-side pressures on the agricultural system. Scenarios with exogenous yield trajectories exclude this dampening effect, thus leading to stronger signals of changes in productivity pathways and dietary choices. Assuming persistent efforts to increase land productivity independent from demand trajectories, the land sparing effect of a reduced consumption of livestock products is more pronounced, with a decline in deforestation by 64-72% and emissions abatement by 63-78%.

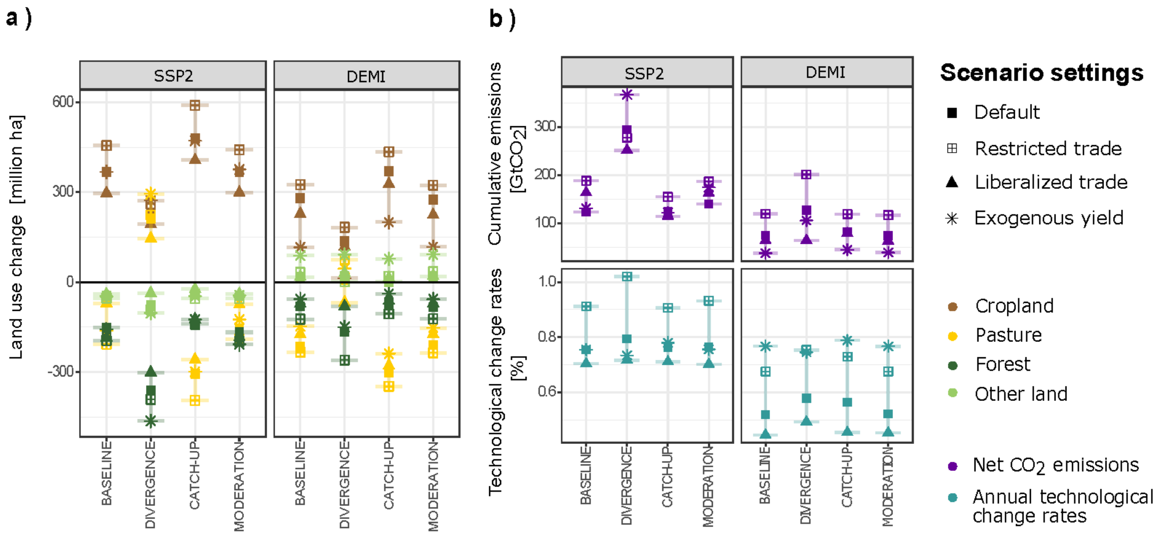

Fig. 5. Sensitivity analysis exploring the influence of international trade and yield trajectories on land use change and related emissions between 2010 and 2050. Panel a) illustrates changes in regional cropland, pasture, forest and other natural vegetation in Mha. Panel b) shows cumulative CO_2 emissions from changes in vegetation, litter and soil carbon stocks in Gt CO_2 and average annual technological change rates (%) between 2010 and 2050.

Table 4. Impacts of dietary changes on deforestation and cumulative CO_2 emissions between 2010 and 2050 for all productivity scenarios in the default and additional model settings of the sensitivity analysis (changes in CO_2 emissions (%) for DEMI diet scenarios relative to SSP2 diet scenarios).

		BASELINE	DIVERGENCE	CATCH-UP	MODERATION
Deforestation	*Default*	-47%	-55%	-49%	-50%
	Restricted trade	-37%	-34%	-25%	-38%
	Liberalized trade	-61%	-73%	-50%	-62%
	Exogenous yield	-64%	-68%	-69%	-72%
CO_2 emissions	*Default*	-39%	-57%	-34%	-47%
	Restricted trade	-36%	-28%	-23%	-37%
	Liberalized trade	-61%	-74%	-31%	-62%
	Exogenous yield	-71%	-71%	-63%	-78%

4. Discussion

Recent work suggests that emission and land saving potentials of livestock system intensification by far outpace contributions from the crop sector (Cohn et al., 2014; Havlík et al., 2013, 2014; Valin et al., 2013). Moreover, there is evidence that shifts in dietary patterns have a similar potential to abate GHG emissions as an agricultural GHG tax policy, but without possible negative effects on food prices (Stevanović et al., 2017). Building upon these insights, we further disentangle impacts of livestock productivity growth and dietary changes on land and carbon dynamics, focusing on the interplay between different land types and related trade-offs in terms of carbon losses from vegetation, litter and soils.

4.1. Data uncertainty and assumptions in livestock modelling

Estimation of feed baskets for different animal food systems is based on feed energy balances, following the approach of Wirsenius et al. (2010), where we use the net energy (NE) system for cattle and the metabolizable energy (ME) system for monogastrics. Hereby, the assumed homogenous energy densities within the different feed commodities are a potential source of inaccuracy, especially in the case of grasses and forage crops that are characterized by large variations in nutrient content. Digestible energy (DE) of harvested grass does not only depend on species composition and climate, but also on management factors such as fertilizer input and stage of maturity (Stergiadis et al., 2015). Moreover, the non-linear empirical equations used to calculate NE contents from DE contents of different feed commodities are based on experimental diets with relatively high digestibility (NRC, 1996; Wirsenius, 2000), which introduces an additional potential source of inaccuracy if applied to extensive cattle systems relying on native pastures and crop residues.

Establishment of feed energy balances also necessitates information on feed energy supply. While for food crops and food industry byproducts, feed use of the whole livestock sector at country-scale is derived from FAOSTAT (2013), we use estimates from the literature to determine feed use of crop residues and food waste (Bodirsky et al., 2012; Eggleston et al., 2006; Lal, 2005; Wirsenius, 2000). Grazed biomass is calculated as the residuum required for balancing ruminant feed demand with supply and therefore the most uncertain component within feed rations. In addition, quantification of pasture area is prone to uncertainty, as conceptual assumptions of classifying pastures and rangelands are diverse (Erb et al., 2007; Ramankutty et al., 2008; Sayre et al., 2017). Multiplying pasture area with pasture productivity from LPJmL at high spatial resolution, we obtain potential supply of grass biomass which in most regions exceeds demand.

At initialization of the simulation period, potential supply of grass biomass is calibrated to regional grass demand, where the calibration factors reflect regional grazing intensities. While we assume that pasture management proportionally improves with productivity gains in the crop sector leading to higher grazing intensities, we do not account for related changes in nutritional quality of grasses and for the complex responses of net primary productivity and soil carbon sequestration to management and grazing at different stocking rates (Asner et al., 2004; Lambin et al., 2001; Rolinski et al., 2017). In South Asia, the high calibration factor points to a mismatch between feed energy requirements and availability of considered feed categories, similar to observations by Singh (1997) and Wirsenius (2000). In this region, a heterogeneous array of not considered feed source such as browse, biomass from weeding and grazing in forests and other non-agricultural land is likely to substantially contribute to feed availability (Wirsenius, 2000).

For projecting future feed demand under different productivity pathways, we derive relationships between feed baskets and livestock productivity. Results indicate that productivity gains lead to better feed efficiencies together with a shift from low-cost and low-energy feed, sourced from pastures or available as by-products from the agricultural supply chain, to cropland feed with higher nutrient densities, similar to findings obtained by Herrero et al. (2013b) and Wirsenius (2000). However, larger dispersion in the model for feed composition compared to feed conversion highlights the need for a more in-depth analysis of other potentially relevant factors such as availability of pasture compared to cropland feed, agro-ecological and climatic conditions that favour selected feed items, innovation and management that improve the quality of non-cropland or by-product feed components, and socio-economic as well as cultural determinants.

4.2. Implications of productivity improvements

Our model simulations indicate that livestock productivity gains drive cropland expansion, whose consequences regarding deforestation depend on the relative reduction in pasture and the suitability of these areas for cropping. Assuming no rebound effect of productivity increases on food demand, already minor productivity gains in extensive livestock systems are identified as an effective lever to avoid deforestation (50-58% reduction in BASELINE scenarios compared to DIVERGENCE pathways) and abate carbon emissions (41-58% reduction), since decreases in pasture area occur faster than expansion of cropland. Trade-offs with soil carbon losses equivalent of 25 Gt CO_2 are more than compensated by substantially lower emissions from vegetation carbon stored in native forests.

However, if further proceeding to high productivity levels, trade-offs with ecosystem services on managed land are more pronounced since large-scale pasture-to-cropland conversion impair carbon sequestration in agricultural soils and biodiversity (Alkemade et al., 2013). Our simulations reveal that strong increases in livestock productivity involve substantial depletion of soil carbon stocks, which can lead to a net increase of carbon emissions, although feed demand and deforestation are slightly lower under CATCH-UP pathways compared to BASELINE scenarios. Thus, a metric assessing the sustainability of livestock production that is solely oriented on feed or resource use efficiency may reach its limits in the case of significant conversion of pastures to cropland triggered by high livestock productivity gains.

4.3. Context, barriers and potential limits of livestock system intensification

A transition towards more intensive livestock systems is already occurring in many parts of the world in the wake of socio-economic changes such as increased population densities and rangeland fragmentation (Herrero et al., 2009; Hobbs et al., 2008). Yet, there is concern that especially poor and vulnerable farmers and pastoralists might not be able to keep pace with these rapid change processes and the combined challenge of satisfying the growing demand for food without using more resources and impeding climate mitigation in the agricultural sector (Garnett et al., 2013; Herrero et al., 2009). While in developing countries large farms might achieve innovation and technological change relying on the private sector, institutional mechanisms and public investments need to be designed to especially reach smallholder farmers and herders, providing access to formal and informal markets, extension services and innovation platforms as well as fostering efficient value chain and infrastructure development (Herrero et al., 2013a; McDermott et al., 2010).

Moreover, livestock production does not only take place under changing socio-economic conditions, but also in the context of a changing climate that is likely to negatively affect yields of major feed crops such as maize as well as rangeland productivity (Müller and

Robertson, 2014; Nelson et al., 2010; Weindl et al., 2015). Shifts in livestock production systems are an important lever to alter biomass flows and counterbalance detrimental impacts of climate change on the natural resource base. A transition towards more efficient mixed crop-livestock system can simultaneously reduce adaptation costs and deforestation, thereby responding to both mitigation and adaptation imperatives (Weindl et al., 2015).

While increasing productivity of extensive systems in developing regions is perceived as beneficial both with regard to environmental and social considerations (Herrero et al., 2009; Steinfeld et al., 2006), there is an increasing concern about the downsides of large intensive operations (Franzluebbers et al., 2014; Lemaire et al., 2014). Pollution of terrestrial and aquatic ecosystems through excessive nitrogen and pesticides, decreasing soil fertility, conflicts with animal welfare, breeding of antibiotic-resistant pathogens, and the exploitation of non-renewable resources question the long-term sustainability of modern livestock industries (Carvalho et al., 2010; Franzluebbers, 2007; Herrero et al., 2010; Russelle et al., 2007). Analysing land and carbon effects of a moderate de-intensification of highly productive systems, we observe only small and ambiguous impacts on the system, starting with a slight growth in total feed demand and minor reduction in cropland feed, which translate into a small increase in deforestation and carbon emissions in the case of SSP2 diets and into almost identical land and carbon outcomes (compared to BASELINE) in the case of DEMI diet trajectories. Thus, potentially beneficial effects of moderate productivity decreases in intensive livestock systems on pollution and other aspects of the broader sustainability context are not jeopardized by impacts on land use and carbon losses, especially under reduced consumption of livestock products.

4.4. Implications of food consumption patterns

Positive effects of changing diets for climate protection are well documented (Aiking et al., 2006; Bajželj et al., 2014; Popp et al., 2010; Stehfest et al., 2009; Stevanović et al., 2017). While supply-side climate policies have repercussions on food prices in developing regions (Havlík et al., 2014; Stevanović et al., 2017), demand-side oriented strategies aim at a reduction of animal-based food in affluent societies. Besides synergies in the area of public health, a shift in consumption patterns has various co-benefits, like ecosystem recovery through abandonment of land and mitigation of nitrogen pollution (Bodirsky et al., 2014; Springmann et al., 2016; Stehfest et al., 2009). Our estimates of the annual carbon mitigation potential until 2050 are in the range of 1.1-4.2 Gt CO_2/yr for our default model setting, which is lower than 5.6 Gt CO_2eq/yr and 5.9 Gt CO2eq/yr suggested by Stevanović et al. (2017) and Bajželj et al. (2014). While both studies use trajectories of dietary changes comparable to our DEMI diet scenario, they additionally assume a 50% food waste reduction and also account for non-CO_2 emissions which are projected to represent the major contribution of agricultural emissions over the 21st century. The spread of our estimates, which amounts to 0.9-6.5 Gt CO_2/yr if including results of the sensitivity analysis, indicates a strong dependence of climate benefits of changing consumer preferences on future productivity pathways in the livestock and crop sector, as well as on trade regulations.

4.5. Economic processes and complex interactions in the agricultural system

Our results show that the theoretical potential of flexible trade flows to exploit regional differences in feed conversion efficiency through interregional reallocation of production only unfolds in scenarios that assume prevailing large geographical disparities of livestock production. Comparative advantages of some regions characterised by high resource availability can dampen efforts to invest into land productivity, with detrimental consequences for deforestation and carbon emissions, similar to dynamics attested by Schmitz et al. (2012). However, Havlík et al. (2014) suggest that intra- and interregional relocation of livestock production could contribute 49% of total emission abatement if incentivized by a global carbon price. In case that relative trade flows are fixed to 1995 levels, the inflexibility of the system generally leads to higher carbon emissions and constrains the potential of dietary changes to attenuate CO_2 emissions in our scenarios.

In our study, highest carbon savings from changing diets (63-78%) can be achieved if relaxed pressures on land have no negative repercussions on pasture management and productivity growth in the crop sector, emphasizing the importance to combine efforts in the crop and livestock sector to enable synergies for climate protection, in line with findings obtained by Valin et al. (2013). Moreover, our two-dimensional scenario matrix reveals that the spread of cumulative carbon emissions (between 2010 and 2050) associated with the explored productivity pathways is high for SSP2 diets (125-295 Gt CO_2), while dietary changes towards less livestock products smooth differences (74-127 Gt CO_2). Thus, a reorientation of consumer preferences would allow for a larger option space to develop regional livestock systems, progressing from a “land and carbon-only” approach to a broader sustainability metric that also considers animal well-being, livelihoods, water resources, biodiversity and pollution through various organic and inorganic substances.

5. Conclusion

If the growing demand for livestock products in developing countries is to be met without improvements in historically observed low livestock productivities in some regions, substantial increases in feed demand would imply massive forest and carbon losses. However, already intermediate livestock productivity gains can halt the expansion of pastures into pristine ecosystems and substantially reduce net land requirements for agricultural production, with significant benefits for climate change mitigation. In contrast, ambitious productivity increases that still slightly improve feed and land use efficiency involve trade-offs with carbon sequestration in agricultural soils, thereby possibly increasing net carbon emissions. At the same time, moderate de-intensification of highly intensive systems has negligible impacts on land and carbon losses, thus not jeopardizing potentially beneficial effects on pollution, animal welfare and other aspects of the broader sustainability context.

On the demand side, reducing the consumption of livestock products to 15% animal-based calories in diets until 2050 can significantly abate carbon emissions from land use change by up to 78%. However, the carbon saving potential of changing diets depends not only on livestock productivity pathways, but also on productivity trends in the crop sector, pasture management and on other boundary conditions of agricultural production such as trade regimes. Thus, preference-based strategies aiming at behavioural change have to go hand in hand with supply-side oriented schemes to increase the resource efficiency of livestock production as well as with dedicated forest and climate protection policies, which counteract resource inefficiencies in global trade patterns, prevent interregional leakage and incentivize efforts to invest in the sustainable intensification of the whole agricultural and food system.

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