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Livestock in a changing climate: production system transitions as an adaptation strategy for agriculture

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Abstract

Livestock farming is the world's largest land use sector and utilizes around 60% of the global biomass harvest. Over the coming decades, climate change will affect the natural resource base of livestock production, especially the productivity of rangeland and feed crops. Based on a comprehensive impact modeling chain, we assess implications of different climate projections for agricultural production costs and land use change and explore the effectiveness of livestock system transitions as an adaptation strategy. Simulated climate impacts on crop yields and rangeland productivity generate adaptation costs amounting to 3% of total agricultural production costs in 2045 (i.e. 145 billion US$). Shifts in livestock production towards mixed crop-livestock systems represent a resource- and cost-efficient adaptation option, reducing agricultural adaptation costs to 0.3% of total production costs and simultaneously abating deforestation by about 76 million ha globally. The relatively positive climate impacts on grass yields compared with crop yields favor grazing systems inter alia in South Asia and North America. Incomplete transitions in production systems already have a strong adaptive and cost reducing effect: a 50% shift to mixed systems lowers agricultural adaptation costs to 0.8%. General responses of production costs to system transitions are robust across different global climate and crop models as well as regarding assumptions on CO_2 fertilization, but simulated values show a large variation. In the face of these uncertainties, public policy support for transforming livestock production systems provides an important lever to improve agricultural resource management and lower adaptation costs, possibly even contributing to emission reduction.

1. Introduction

Livestock production constitutes a significant interference with many Earth system processes. In the courses of providing on average 17% of food calories and more than a third of protein to human diets (Herrero *et al* 2009), livestock is consuming almost 60% of the global biomass harvest (Krausmann *et al* 2008), using around 30% of agricultural water withdrawals (Peden *et al* 2007, Mekonnen and Hoekstra 2010), and dominating the agricultural nitrogen cycle (Bodirsky *et al* 2012, 2014, Bouwman *et al* 2013). Moreover, the livestock sector is held responsible for about 12%–18% of all anthropogenic greenhouse gas (GHG) emissions (Steinfeld *et al* 2006, Westhoek *et al* 2011). While being associated with many critical environmental impacts, livestock reduces vulnerability to environmental risks for 600 million poor smallholder farmers (Steinfeld *et al* 2006, Thornton and Herrero 2010) and provides livelihoods as well as many other services beyond food production such as traction and nutrients (Steinfeld *et al* 2006, Herrero *et al* 2009). Especially for many poor and undernourished people in the developing world, livestock products are crucial for protein supply.

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Livestock is thus intertwined with many aspects of the challenge to sustainably feed a growing world population and achieve a balance between livelihoods, food security and the environment (Herrero and Thornton 2013). Being the world's largest user of land and biomass and at the same time an important risk management strategy for vulnerable communities (Herrero *et al* 2009), livestock is at the center of the discourse on climate change and agriculture. Recent work reveals large potentials to abate GHG emissions in the livestock sector, amongst others by reducing livestock product consumption (Stehfest *et al* 2009, Popp *et al* 2010), shifts in production systems and improved management (Thornton and Herrero 2010, Havlík *et al* 2013, 2014, Smith *et al* 2013, Valin *et al* 2013, Cohn *et al* 2014). However, impacts of climate change on the livestock sector have hitherto been analyzed in a comparably integrated approach only by Havlík *et al* (2015). As most studies on climate change impacts and agriculture so far have focussed on the crop sector (Schlenker and Lobell 2010, Müller *et al* 2011, Leclère *et al* 2014, Nelson *et al* 2014a), there are still large gaps in knowledge of how climate change could affect livestock production and how a transformation of livestock production systems (LPS) could contribute to a climate-smart agriculture.

There are several ways in which livestock production will be influenced by a changing climate, such as changes in the productivity of rangelands and yields of feed crops (Thornton and Gerber 2010, Ghahramani and Moore 2013). Moreover, heat stress directly impairs production (meat, milk and egg yield and quality) and reproductive performance as well as animal health and welfare (Thornton *et al* 2009, Nardone *et al* 2010, Gaughan 2012, Lara and Rostagno 2013). One key entry point into the complex livestock-climate-nexus is the substantial heterogeneity of feed conversion efficiencies (product output per feed input) across different LPS. Not only is the overall resource use intensity affected by shifts in LPS, but also the feed basket composition, i.e. concentrates from cropland, roughage from rangelands or crop residues as by-products (Herrero *et al* 2013). Both mechanisms can absorb detrimental impacts of climate change on the natural resources base, where the latter can exploit the potentially diverging impacts of climate change on different crops as well as on cropland and pasture productivity. At the same time, structural changes like a transition from grazing to mixed crop-livestock systems may also positively affect the resource footprint of livestock, deforestation rates and GHG emissions (Herrero *et al* 2010b, 2013, Havlík *et al* 2014).

In this study, we quantify the impacts of a changing climate on the agricultural sector and explore the adaptive potential of LPS transitions, based on a comprehensive impact modeling chain. Hereby, we analyze direct climate impacts on cropland and pasture productivity as well as secondary impacts such as changes in land-use dynamics (i.e. deforestation) and agricultural production costs. By contrasting effects of different LPS transition pathways, we provide insights into how related changes in feed conversion efficiencies and feed baskets may buffer or amplify secondary climate impacts in the light of the changing availability of natural resources and identify regionally specific adaptation strategies in the livestock sector.

2. Methods and data

2.1. Modeling framework

We assess the biophysical response of agricultural crops and rangelands to a changing climate at a spatial resolution of 0.5 × 0.5 geographic degrees, using the Lund-Potsdam-Jena dynamic global vegetation model with managed Land (LPJmL) (Bondeau *et al* 2007, Rost *et al* 2008, Waha *et al* 2012, Müller and Robertson 2014). LPJmL simulates growth, production and phenology of 9 plant functional types (representing natural vegetation at the level of biomes (Sitch *et al* 2003)) and of 12 crop functional types (SI appendix, tables S3(a)–(f)) as well as managed grass, ensuring global balances of carbon and water fluxes and explicitly accounting for the photosynthesis pathway (C3 versus C4 plants). The photosynthetic processes are modeled according to Farquhar *et al* (1980) and Collatz *et al* (1992). Yield simulations are based on various process-based implementations as described in more detail by Bondeau *et al* (2007) and Waha *et al* (2012). Harvesting of crops occurs on completion of the phenological cycle (maturity), while grassland is harvested at least once a year (up to several times a year) as soon as the phenological leaf development is completed and a minimum above-ground biomass threshold of 100 gC/m^2 has been reached (see SI appendix for more details). The LPJmL model represents both C3 and C4 grasses, with distinct photosynthetic pathways (Sitch *et al* 2003). Up to annual mean temperatures of 15.5 °C, C3 grasses establish, at or above 15.5 °C C4 grasses establish, which also allows for mixed composition.

The impacts of climate change and shifts in LPS on agricultural land use and production costs are explored with the Model of Agricultural Production and its Impact on the Environment (MAgPIE) (Lotze-Campen *et al* 2008, Bodirsky *et al* 2012, 2014, Popp *et al* 2014, 2010), a spatially explicit global land-use allocation model. By minimizing a nonlinear global cost function for each time step, the model fulfils demand for food, feed and material for 10 world regions (table 1, figure S2). The model represents key human-environment interactions in the agricultural sector by combining socio-economic regional information with spatially explicit data on biophysical constraints provided by LPJmL (i.e. pasture productivity, crop yields under rainfed and irrigated conditions,

Table 1. Socio-economic regions in MAgPIE.

Regional 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)

related irrigation water demand per crop, water availability) and land availability (Krause *et al* 2013). Region-specific costs associated with different farming activities are derived from the GTAP database (Narayanan and Walmsley 2008). In view of the involved production costs and resource availability, MAgPIE optimizes land use patterns and simulates major dynamics of the agricultural sector like land use change (including deforestation, abandonment of agricultural land and conversion between cropland and pastures), investments into research and development (R&D) and associated yield increases, interregional trade flows, and irrigation (see SI appendix for more details).

Livestock products are represented by six categories: beef, sheep and goat meat, pork, chicken, eggs, and milk. These commodities are produced in eight different LPS according to the updated International Livestock Research Institute/FAO classification (Robinson *et al* 2011, Herrero *et al* 2013): three rangeland-based systems (LG), and three mixed crop-livestock systems (MX), which are the aggregate of the mixed rainfed systems (MR) and mixed irrigated systems (MI) of the original FAO nomenclature, an industrial system, and a smallholder system. LG and MX systems are further differentiated by agroecological zones (arid and semiarid; humid and semihumid; tropical highlands and temperate). Pork, chicken, and eggs are only produced in industrial and smallholder systems, whereas ruminant meat and milk are mainly produced in rangeland-based and mixed systems. The parameterization of the different LPS, especially total feed efficiencies and the composition of feed baskets, relies on the dataset presented by Herrero *et al* (2013) and is consistent with FAO statistics regarding livestock production, animal numbers, and livestock productivity.

2.2. Scenario definition

The analysis presented here is based on the reference scenario of the International Assessment of Agricultural Science and Technology for Development (IAASTD) (McIntyre *et al* 2009) which was developed applying several models like the IMPACT agriculture-economy model (Rosegrant *et al* 2002) and the Integrated Model to Assess the Global Environment (IMAGE) (Bouwman *et al* 2006). The underlying climate patterns of the IAASTD scenario (SI appendix, figure S1) define our central climate scenario which is provided by the IMAGE group (van Vuuren *et al* 2007). Acknowledging the uncertainty involved in simulating future climate conditions, we test the sensitivity of our results to other climate projections for the A2 SRES scenario, based on 5 different general circulation models (GCMs) (i.e. CCSM3 (Collins *et al* 2006), ECHAM5 (Jungclaus *et al* 2006), ECHO-G (Min *et al* 2005), GFDL (Delworth *et al* 2006), and HadCM3 (Cox *et al* 1999); see SI appendix for more details).

Moreover, we address another important aspect of uncertainty: the effectiveness of CO_2 fertilization, i.e. the potential of atmospheric CO_2 to stimulate net photosynthesis in C3 plants by increasing the CO_2 concentration gradient between air and the leaf interior, and improved water use efficiency of all crops and grasses due to stomatal closure. Whether and how CO_2 fertilization is accounted for in global gridded crop models (GGCMs) substantially influences simulated climate impacts on agriculture (Rosenzweig *et al* 2013). Thus, we perform a sensitivity analysis by simulating yield responses over time both with the full CO_2 effect as implemented in LPJmL (i.e. direct CO_2 fertilization, indirect CO_2 fertilization via reduced stomatal conductance, no down-regulation or feedbacks via nutrient dynamics, no effects on pests and diseases) and with static atmospheric CO_2 concentrations of the year 2000 (370 ppm) for all scenarios and climate projections. Due to large variations of simulated climate impacts on crop yields among GGCMs (Asseng *et al* 2013, Rosenzweig *et al* 2013, Müller and Robertson 2014), we also test the sensitivity of our results to the choice of crop growth model by using alternative crop yield simulations derived by EPIC (Williams 1995, Izaurralde *et al* 2006) and pDSSAT (Jones *et al* 2003).

Throughout the paper, the base year 2005 and the final year 2045 of the simulation period represent 10-year averages, in terms of climate and yield changes as well as all other outputs.

To explore impacts of climate change on agriculture and the adaptive potential of two different LPS transitions, we conduct a scenario analysis with MAgPIE (see table 2 for an overview of the scenario setting). In all scenarios, regional food and material demand as well as international trade in agricultural commodities is harmonized with the reference case of the IAASTD (McIntyre *et al* 2009) (SI appendix, table S1). In the baseline, climate conditions are kept constant at 2005 levels and the regional composition of LPS is parametrized over time following projected rates of growth in different LPS 2000–2030 according to Herrero *et al* (2010a) which are also based on

Table 2. Overview of the scenario setting.

Scenario	Description
Baseline	World population increases to 8.9 billion people and average per capita food demand to 3 447 kcal per day in 2045, consistent with the reference case of the IAASTD (McIntyre *et al* 2009). The regional composition of LPS changes gradually over time according to Herrero *et al* (2010a). Climate conditions are kept constant at 2005 levels.
Climate_impact	In addition to 'Baseline' conditions, climate effects on yields, based on the IAASTD climate scenario (van Vuuren *et al* 2007), are taken into account. Global mean temperature increases by 1.1 °C from 2005 to 2045.
Shift_to_rangeland	In addition to 'Climate_impact' conditions, production of ruminant meat and milk is gradually shifted towards rangeland-based systems, with full convergence until 2045.
Shift_to_mixed	In addition to 'Climate_impact' conditions, production of ruminant meat and milk is gradually shifted towards mixed systems, with full convergence until 2045.

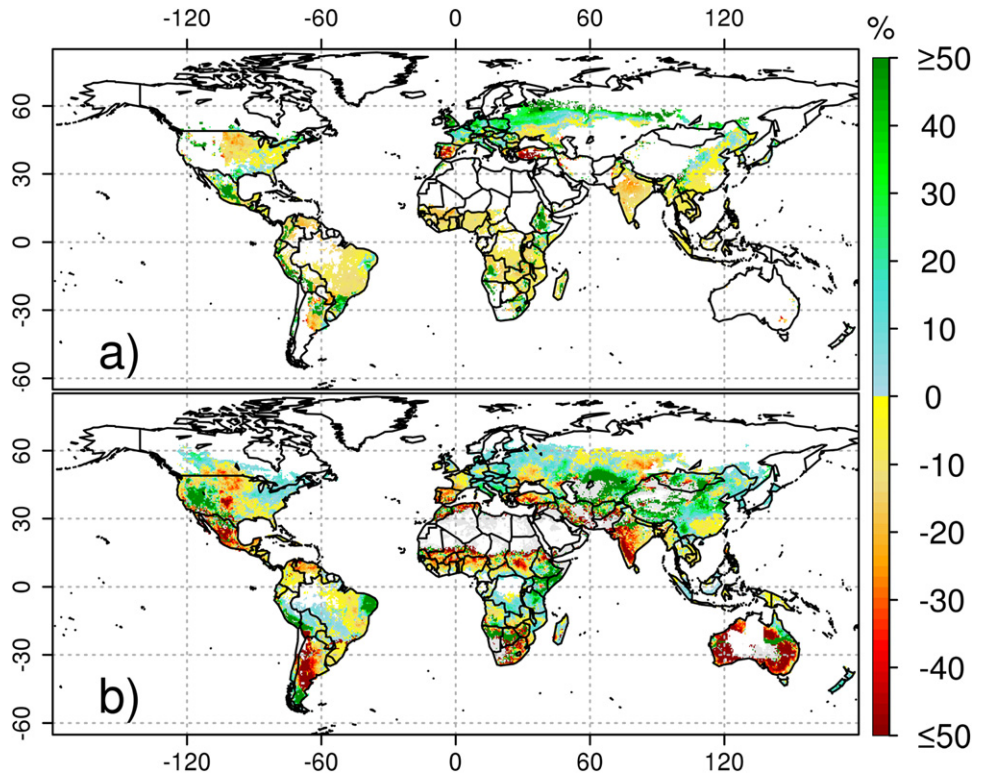

Figure 1. Climate impacts on maize yields (a) and rangeland productivity (b) by 2045 for the IAASTD climate scenario (percent change from 2005, simulated with the LPJmL model, no CO_2 effect; for maize: no adaptation in cropping period or varieties, area-weighted mean of rain-fed and irrigated; for rangeland: no nutrient limitations, adaptive harvest cycles). Results with full CO_2 effect are given in figure S7 (SI appendix).

the reference scenario of the IAASTD. Adaptation costs are calculated as the difference in total agricultural production costs between the baseline run and scenarios accounting for climate change impacts. These costs reflect the sum of additional expenses needed to counterbalance the changes in land productivity, i.e. higher investments into R&D and land conversion, and increasing factor inputs. The LPS transition scenarios described below focus on shifts in ruminant meat and milk production, since ruminants account for the largest share in agricultural land use and are crucial for land use changes between cropland and rangeland. We design stylized LPS transition scenarios with full system convergence until 2045 to unravel their complete potential to alter agricultural land use and production costs, especially in comparison to climate change impacts.

3. Results

3.1. Climate impacts on crop and rangeland productivity

According to the IAASTD climate scenario, large parts of SAS, AFR, NAM and FSU become warmer by 1.8 °C or more (SI appendix, figure S1). Precipitation declines by 25%–50% in parts of MEA, AFR, SAS, PAO, and LAM. Many other regions, especially in the Northern Hemisphere, experience an increase in precipitation. Under constant CO_2 levels, yields of

maize, one of the most important feed crops, tend to increase in most temperate zones, owing to alleviated temperature limitations (figure 1(a)). However, declining yields are simulated in parts of NAM, FSU, and CPA, where precipitation also decreases. In most tropical zones, maize yields are negatively affected, reflecting faster phenological development (White *et al* 2011) and lower precipitation during the growing period. Rising yields can be observed in some parts of AFR and LAM. The strongest average regional decreases occur in SAS (−9%) and in PAS (−7%) (SI appendix, table S3(a)). Under elevated atmospheric CO_2 concentrations, negative effects on maize yields occur in few aggregated regions, namely PAS and SAS (SI appendix, figure S7(a) and table S3(a)).

Grass yields decrease by 2% at the global area-weighted average for simulations assuming constant CO_2 levels. The strongest negative effects are visible in PAO (mainly Australia) and in MEA (−11% and −28% respectively), while grass yields rise in FSU and CPA. Figure 1(b) shows strong negative sub-regional effects (e.g. Sahel) as well as strong positive ones (e.g. East Africa) in all ten world regions, mainly reflecting changes in precipitation patterns. Under elevated CO_2 levels, the productivity of grassland rises by 14% at the global scale, while the regional signals range from 1% in PAS to 42% in FSU. Sub-regional patterns emphasize the beneficial effect of CO_2 fertilization on grassland productivity in moisture-limited areas (SI appendix, figure S7(b)).

We assess the sensitivity of our simulations to other climate projections for the SRES A2 emission scenario (Nakicenovic and Swart 2000), derived by 5 different GCMs (SI appendix, tables S3(b)–S3(f)). Resulting differences in yield projections mainly reflect differences between GCMs regarding simulated precipitation patterns (SI appendix, figures S9–S13). For maize, there is relatively good agreement across the GCMs in most regions, except in NAM, EUR and parts of FSU. For grass, projected yield impacts coincide only in MEA, PAS, and parts of AFR. In all other regions, strong differences can be observed between the GCMs. With full CO_2 fertilization, the differences across GCMs are much less pronounced.

3.2. Changes in cropland, rangeland, and intact forest

In the baseline, global cropland increases by 165 million ha between 2005 and 2045 (figure 2(a)). Cropland expansion is even larger in the 'climate_impact' scenario (197 and 213 million ha under constant and elevated CO_2 levels respectively) and the 'shift_to_mixed' scenario (222 and 207 million ha), while being smaller in the 'shift_to_rangeland' scenario (127 and 122 million ha). For all scenarios based on the IAASTD climate projection (independent to assumptions regarding CO_2 fertilization), changes in cropland area agree in sign in all regions except in MEA, being positive for most regions and negative for CPA and SAS. Regional cropland mostly increases at the expense of rangeland. In contrast, both cropland and rangeland are expanded into forest in LAM and PAS (figure 2(c)), where vast areas of potentially productive land are currently under intact forest (see SI appendix for definition).

Results for the LPS transition scenarios reflect differences in feed conversion efficiencies and the relative shares of concentrates and roughage within feed baskets. In the 'shift_to_rangeland' scenario, changes in cropland areas are smaller than in the 'climate_impact' scenario in most regions (−70 and −91 million ha globally under constant and elevated CO_2 levels respectively), except in NAM, EUR, and PAO. In NAM, feed conversion efficiencies are higher in rangeland-based systems than in mixed systems (SI appendix, figures S5–S6) (Herrero *et al* 2013). Hence, rangeland can be converted into cropland and R&D investments can be reduced (SI appendix, figure S15). In contrast, additional 169 million ha (252 million ha with CO_2 effect) are converted from intact forests into rangeland in LAM, due to much lower feeding efficiencies in rangeland-based systems (figure 2(c)). In the 'shift_to_mixed' scenario, more cropland is used in most regions apart from e.g. PAS and SAS, while rangeland is reduced by 90 million ha (21 million ha under elevated CO_2 levels). Deforestation in LAM is strongly reduced, compared to both the baseline and 'climate_impact' scenario and irrespective of assumptions concerning CO_2 fertilization. Required technological change rates are lower in most regions and deforestation is abated by about 76 million ha globally (27 million ha with CO_2 effect).

Results are sensitive to the choice of climate projection and assumptions about CO_2 fertilization, where cropland simulations in AFR, FSU and LAM show a particularly wide range of uncertainty. Moreover, sign and magnitude of secondary climate impacts on rangeland and intact forest are strongly influenced by underlying climate projections and the effectiveness of CO_2 fertilization. Overall dynamics of the LPS transition scenarios (relative to the respective 'climate_impact' simulations) are in most cases unaffected by the uncertainty in climate change impacts on agriculture (figure 2), but the magnitude of effects depends on assumptions regarding CO_2 fertilization. Including the full CO_2 effect leads in most regions to a further decrease in rangeland and expansion of cropland, compared to the baseline. In LAM, however, expansion of both cropland and rangeland is reduced, also slowing down deforestation.

3.3. Changes in global and regional agricultural production costs

In the 'climate_impact' scenario, global agricultural production costs increase by about 3% relative to the baseline in 2045 due to negative climate impacts

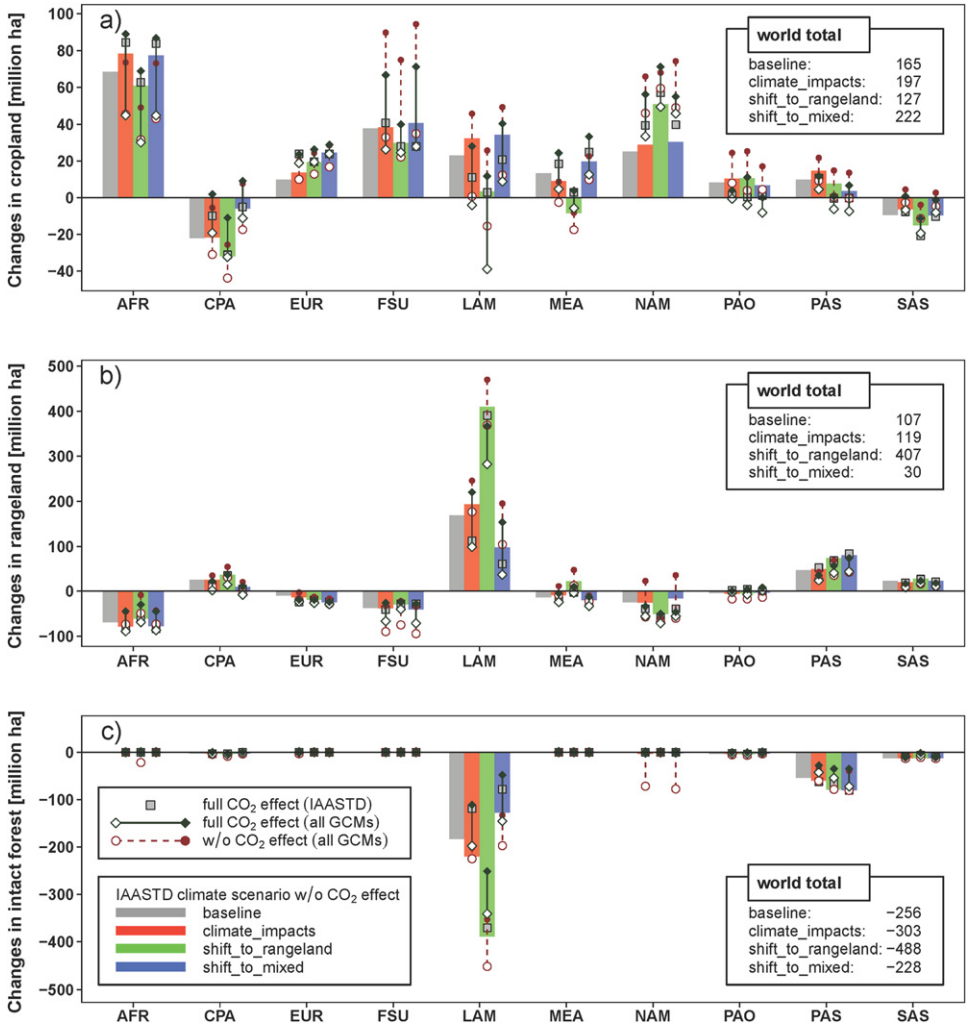

Figure 2. Changes in (a) cropland, (b) rangeland, and (c) intact forest by region (colored bars show differences between 2045 and 2005 in million ha for the IAASTD climate scenario; error bars show minimum and maximum change from sensitivity analysis with five additional climate model inputs (dark red dashed lines with circles indicating minimum (hollow) and maximum (solid) values for scenarios without CO_2 effect and dark green solid lines with diamonds for scenarios with full CO_2 effect); gray squares show results for the IAASTD climate scenario with full CO_2 effect).

(figure 3), which is equivalent to 145 billion US$. In MEA, agricultural production costs rise by about 16%, in SAS by 9%, in LAM by 5%, and in AFR by 2%. In CPA, by contrast, production costs drop due to climate impacts by about 3%. In the 'shift_to_rangeland' scenario, global agricultural production costs increase much more, by about 14%, while a transition towards mixed systems almost completely offsets detrimental climate impacts. In all regions except PAS, at least one of the considered shifts in LPS is not only suited to counterbalance the additional production costs caused by climate change, but also to reduce costs beyond the baseline level. In PAS however, where smallholder systems with relatively high feed conversion efficiencies dominate ruminant livestock production, both LPS transition scenarios covered here are detrimental compared to the reference setting.

Regional results are sensitive to uncertainties in climate projections. Even the sign of change in regional production costs may differ between different GCM inputs (figure 3). However, global production costs are less sensitive, as counteracting regional signals partly cancel each other out. Moreover, the observation that shifts in LPS offer the potential to alleviate climate change related costs in all regions (except PAS), is valid for all considered climate projections. We have also tested the sensitivity of agricultural production costs to CO_2 fertilization (figure 3, table S4) as well as to incomplete (i.e. 50%) LPS transitions, up to the year 2045 (table 3). The uncertainty in the effectiveness of CO_2 fertilization on agricultural yields heavily impacts on global and regional production costs. In most regions, the full CO_2 effect turns cost increases into cost decreases. Substantial cost increases in LAM and MEA in the 'shift_to_rangeland' scenario are considerably reduced. Incomplete transitions in LPS already have a relatively strong adaptive and cost reducing effect: a 50% shift to mixed systems lowers global adaptation costs from 3% of total agricultural production costs to 0.8%. Especially in more severely

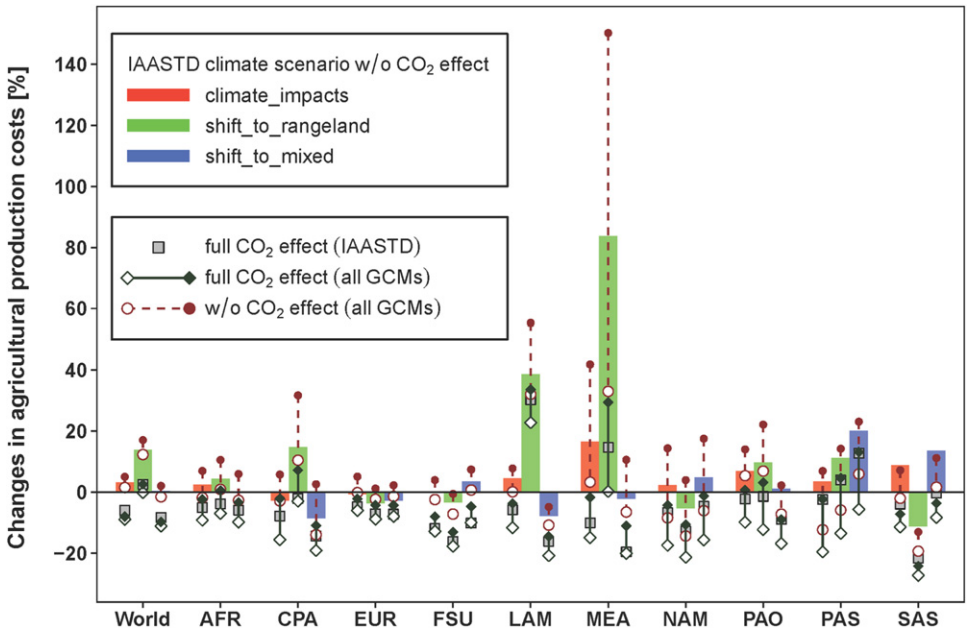

Figure 3. Changes in total agricultural production costs by region (colored bars show percent change to baseline in 2045 for the IAASTD climate scenario; error bars show minimum and maximum change from sensitivity analysis with five additional climate model inputs (dark red dashed lines with circles indicating minimum (hollow) and maximum (solid) values for scenarios without CO_2 effect and dark green solid lines with diamonds for scenarios with full CO_2 effect); gray squares show results for the IAASTD climate scenario with full CO_2 effect).

affected regions like MEA, SAS and LAM (16%, 9%, and 5% increase in production costs), incomplete transitions in LPS substantially buffer detrimental impacts of climate change on agriculture: resulting changes in production costs relative to the baseline amount to 3% in MEA, −3% in SAS and −1% in LAM.

Acknowledging the uncertainty related to the choice of crop growth model, we compare agricultural adaptation costs based on the LPJmL-MAgPIE modeling suite to MAgPIE simulations which use crop yield simulations from EPIC and pDSSAT under evolving climate conditions according to the SRES A2 socio-economic scenario (SI appendix, table S4). Similar to uncertainties related to climate projections, variations across different GGCMs are more distinct at the regional than at the global level (SI appendix, figure S16). Especially in FSU, LAM, NAM and PAO, differences related to crop growth models dominate overall uncertainty in results, but general responses with regard to LPS transitions are robust, i.e. declining production costs associated with a shift towards rangeland based livestock production in FSU and NAM as well as with a shift towards mixed systems in LAM (and also in PAO for all but one simulation based on pDSSAT). Similar patterns and magnitude of effects across different GCMs and GGCMs are simulated for CPA, EUR and SAS. In MEA, general patterns with respect to LPS scenarios are preserved, but the magnitude of climate change impacts is generally lower for EPIC and both pDSSAT scenarios compared to LPJmL simulations. In AFR, production costs respond differently to LPS transitions under EPIC and pDSSAT crop yield projections, suggesting that also rangeland based LPS could buffer detrimental impacts on crop production. Results based on the two models simulating crop yields both with and without CO_2 effect (LPJmL and pDSSAT) show a good concordance with regard to overall adaptation costs at the global level excluding CO_2 fertilization (3% and 5% respectively) as well to the beneficial effects of elevated CO_2 concentrations (−6% and −3%).

4. Discussion and conclusion

A growing body of literature is exploring climate impacts on livestock (Seo and Mendelsohn 2008, Thornton *et al* 2009, Nardone *et al* 2010, Thornton and Gerber 2010, Gaughan 2012, Ghahramani and Moore 2013, Godber and Wall 2014) and rangeland productivity (Hopkins and Del Prado 2007, Tubiello *et al* 2007b, Morgan *et al* 2008). However, global assessments of climate change impacts on agriculture and possible adaptation options still largely disregard the livestock sector (Leclère *et al* 2014, Nelson *et al* 2014a, 2014b), thus neglecting its pivotal and potentially adaptive role within the whole agricultural system—with the noticeable exception of Havlík *et al* (2015). We add to the literature an integrated, process-based analysis of biophysical climate impacts and livestock-specific adaptation options, and a first quantification of how transitions in LPS can reduce regional and global agricultural adaptation costs. Our study's

Table 3. Impact of full convergence of LPS (100) versus half convergence of LPS (50) on agricultural production costs for the IAASTD climate scenario (changes in agricultural production costs (%) in 2045 relative to the reference scenario in 2045; no CO_2 effect, see table 1 for regional acronyms).

Scenarios		World	AFR	CPA	EUR	FSU	LAM	MEA	NAM	PAO	PAS	SAS
Shift_to_rangeland	100	13.8	4.3	14.7	−3.7	−3.4	38.6	83.7	−5.3	9.6	11.2	−11.2
	50	7.7	2.3	3.4	−1.7	−3.5	25.0	41.9	−1.8	6.5	7.1	−2.6
Shift_to_mixed	100	0.3	0.2	−8.5	−2.7	3.4	−7.8	−2.2	4.8	1.1	20.0	13.5
	50	0.8	0.1	−7.4	−2.3	1.7	−1.2	2.7	3.7	4.6	12.1	11.3

entry point into the complex livestock-climate-nexus is the importance of strategic feed sourcing in the light of the changing availability of resources due to climate change.

Based on a comprehensive impact modeling chain, we trace implications of different climate projections through the agricultural systems, starting with impacts on crop yields and rangeland productivity. Simulations indicate significant negative impacts on crop yields in several regions, i.e. AFR, NAM and SAS. Strongest positive climate impacts on livestock feed production occur in CPA, where most crops as well as rangeland experience an increase in productivity. The LPJmL model is capable of reproducing national yields as reported by the FAO (Fader *et al* 2010) and simulated climate impacts on agricultural productivity are well within the range of other estimates (Müller *et al* 2011, Müller and Robertson 2014). For wheat, our results (−6.9% to −3.8%) compare well with the study by Nelson *et al* (2010) which projects changes in rainfed wheat yields from −10% to −4%. For maize, we estimate average global yield changes of −9.3% to +3.5%, while their results indicate a reduction from −12% to −2%.

A major uncertainty is the effectiveness of CO_2 fertilization, i.e. the stimulation of photosynthesis in C3 crops (e.g. wheat, rice, soy) and C3 grasses, and reduced water requirements of all crops and grasses. A strong positive effect of elevated CO_2 levels is simulated for rangeland productivity (+14% compared to −2.3% with constant CO_2 levels). In ecosystem-based experiments, grassland production increased on average by +17% due to the stimulatory effect of double ambient CO_2, with higher responses in moisture-limited and warm-season grassland systems (Campbell and Stafford Smith 2000). The size of the CO_2 fertilization effect on crop yields attainable in the field is still subject to debate (Long *et al* 2006, Tubiello *et al* 2007a, Ziska and Bunce 2007), owing to many complex and interrelated plant processes and depending on water and nutrient availability. Experiments across plant types, climatic zones, and production systems illustrate the large variability of plant physiological and growth responses to elevated CO_2 (Wang *et al* 2012).

Results derived within the Inter-Sectoral Impacts Model Intercomparison Project (ISI-MIP) highlight both the importance and uncertainty of CO_2 fertilization for simulating climate impacts on agriculture and the critical role of model parametrization to understand differences in simulated responses to elevated CO_2 (Rosenzweig *et al* 2013). Moreover, studies based on ensemble crop modeling demonstrated the large uncertainty stemming from different modeling approaches and the representation and parametrization of important bio-chemical processes (Asseng *et al* 2013, Rosenzweig *et al* 2013, Bassu *et al* 2014). Crop yield projections under evolving climate conditions simulated by LPJmL (one of the GGCMs included in ISI-MIP) lie well within the range of ensemble uncertainty. The CO_2 effect as implemented in LPJmL is relatively strong, but within a plausible physiological range.

But even results without CO_2 fertilization could be too optimistic: LPJmL currently does not account for various co-limitations (e.g. nutrient limitations, imperfect management, pests and diseases) and extreme events like prolonged droughts or heavy rainstorms. Even though aggregate climate impacts are relatively small by 2045, extreme events could have severe impacts even earlier (Diffenbaugh and Scherer 2011). Moreover, we do neither account for shifts in livestock disease distribution and severity due to climate change (Thornton and Gerber 2010, Perry *et al* 2013, Godber and Wall 2014) nor for direct impacts of rising temperatures and extreme weather events on animals, impairing production (meat, milk and egg yield and quality) and reproductive performance as well as animal health and welfare (Thornton *et al* 2009, Nardone *et al* 2010, Lara and Rostagno 2013).

To reveal the full adaptive potential being inherent in the heterogeneity of regional feeding efficiencies and feed basket compositions across systems, we apply LPS transition scenarios with full system convergence until 2045. In all regions except PAS (and also PAO for one simulation based on pDSSAT), at least one LPS scenario offers the potential to alleviate climate change related costs, independent of the choice of climate or crop model, and thus represents a cost-effective and low-risk adaptation option. Responses of production costs with regard to LPS transitions are generally robust across different GGCMs used in this study, except in AFR where simulations based on EPIC and pDSSAT indicate that also rangeland based livestock production could buffer detrimental climate impacts on agriculture.

In many regions (i.e. CPA, LAM, MEA and PAO), mixed livestock systems are more efficient than rangeland-based systems in converting feed to food, while providing a range of additional benefits (Herrero *et al* 2009). Globally, shifts in LPS towards mixed crop-livestock systems can reduce agricultural adaptation costs from 3% to 0.3% of total production costs and simultaneously reduce tropical deforestation by about 76 million ha. Moreover, an integration of livestock and crop production is likely to be more resilient to climate extremes due to greater system and income diversity. A transition from agro-pastoral to mixed systems is already occurring for various reasons. In regions with strong population growth, farm sizes tend to decrease, and, without sufficient fallow periods or appropriate crop rotations, soil fertility and eventually farm productivity decline over time. Here, the role of livestock for provision of manure, nutrient recycling and additional farm income is essential. Rising opportunity costs of labor also prompt systems to evolve towards higher value products and stronger integration of agricultural activities (Herrero *et al* 2014). A better integration of crop and livestock production is an important target for sustainable intensification and growth with few externalities and many co-benefits (Russelle *et al* 2007, Herrero *et al* 2009, 2010b).

Our results indicate that in some regions, grazing systems are well suited to buffer negative climate impacts, e.g. in EUR, FSU, NAM and especially in SAS. Here, further increases in production of concentrate feeds, especially with increasing levels of irrigation, will be challenging in view of declining groundwater tables and soil fertility as well as biodiversity losses (Herrero *et al* 2010a, 2009). Thus, a shift towards rangeland based systems is clearly favored in SAS, leading to a cost reduction of 11.2% compared with the baseline, while substantial cost increases of 13.5% go along with a transformation to mixed livestock systems. Projecting autonomous shifts in LPS in response to climate change impacts on feed crops and rangeland, Havlík *et al* (2015) also show that the relatively more optimistic impacts of climate change on grass yields compared with crop yields favor grazing systems in some regions, inter alia in SAS.

Globally, more than 1 billion ha of rangeland are biophysically suitable for cropping, especially in AFR, FSU and NAM (Erb *et al* 2007, van Velthuizen *et al* 2007). In our scenarios, between 61 and 78 million ha of rangeland in AFR are converted into cropland by 2045. This is well below the potential of about 400 million ha, estimated by the World Bank (Morris *et al* 2009). Rangeland-based systems also entail various co-benefits. In areas where rain-fed cropping becomes economically infeasible due to rising temperatures or declining precipitation, rangeland-based production could be a more drought-resilient option for sustaining agricultural production and rural income (Jones and Thornton 2009). However, this requires appropriate livestock densities and timing over the year to avoid rangeland degradation. Well-managed rangelands may also support high levels of biodiversity and can sequester substantial quantities of carbon (Conant and Paustian 2002, Alkemade *et al* 2013, Soussana and Lemaire 2014).

Due to strong interdependencies between climate change adaptation and mitigation in agriculture and especially in the livestock sector, potential adaptation measures have to be assessed with regard to associated GHG emissions. The 'shift_to_rangeland' scenario in our analysis incurs, due to lower average feed-use efficiency, a strong increase in tropical deforestation with potentially high additional CO_2 emissions. This finding is consistent with results reported by Havlík *et al* (2014). In the 'shift_to_mixed' scenario, rangeland is converted into cropland, which would also potentially cause additional emissions, as rangelands contain higher levels of soil carbon (Lal 2002). Further research should deepen our understanding of co-benefits between mitigation and adaptation measures in the livestock sector.

In conclusion, we show that the global costs of climate change adaptation in agriculture amount to about 145 billion US$ in 2045 (about 3% of total production costs), which is an order of magnitude higher than the previously estimated annual agricultural productivity investments of 7.1–7.3 billion US$ required to increase calorie consumption enough to offset the detrimental impacts of climate change on the health and well-being of children (Nelson *et al* 2009). We also show that transitions in LPS can substantially reduce agricultural production costs and the demand for productivity increases in crop production, independent from the climate change scenario.

While public policy is often focussed on improving the climate resilience of crop production, our results emphasize that the livestock sector could significantly contribute to a climate-smart agriculture. As the uncertainty analysis in this paper illustrates, public support for agricultural R&D has to target a potentially wide range of future climate outcomes. In the face of these uncertainties, changes in the way livestock are reared represent an effective lever to improve agricultural resource management and economic outcome as well as a low risk adaptation measure with various co-benefits, possibly even contributing to emission reduction. If the right incentives are provided, a shift to mixed systems can reduce pressures on tropical forests from agriculture, increase market-orientated production, and improve rural livelihoods, especially in Africa and the Middle East, Latin America, and East Asia. Production standards, certification and taxation schemes targeting climate mitigation, together with agricultural R&D, planning regulations and infrastructure development aimed at climate-proofing agriculture, should be reconciled to allow livestock production to respond to both mitigation and adaptation imperatives.

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