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 CO2 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.
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 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/m² 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 fulfills 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,
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 (Narayan et al. 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 from cropland and pastures), investments into research and development (R&D) and associated yield increases, inter-regional 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 CO2 fertilization, i.e. the potential of atmospheric CO2 to stimulate net photosynthesis in C3 plants by increasing the CO2 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 CO2 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 CO2 effect as implemented in LPJmL (i.e. direct CO2 fertilization, indirect CO2 fertilization via reduced stomatal conductance, no down-regulation or feedbacks via nutrient dynamics, no effects on pests and diseases) and with static atmospheric CO2 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 1. Socio-economic regions in MAGPIE. |
|------------------------------------------|
| Regional acronyms | MAGPIE regions |
|-------------------|----------------|
| AFR               | Sub-Saharan 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) |
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, FAO, and LAM. Many other regions, especially in the Northern Hemisphere, experience an increase in precipitation. Under constant CO2 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ levels respectively), except in NAM, EUR, and PAO. In NAM, feed conversion efficiencies are higher in range-land-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 CO₂ 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 CO₂ levels). Deforestation in LAM is strongly reduced, compared to both the baseline and ‘climate_impact’ scenario and irrespective of assumptions concerning CO₂ fertilization. Required technological change rates are lower in most regions and deforestation is abated by about 76 million ha globally (27 million ha with CO₂ effect).

Results are sensitive to the choice of climate projection and assumptions about CO₂ 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 CO₂ 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 CO₂ fertilization. Including the full CO₂ 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 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 CO2 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 CO2 fertilization on agricultural yields heavily impacts on global and regional production costs. In most regions, the full CO2 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
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 CO2 effect (LPJmL and pDSSAT) show a good concordance with regard to overall adaptation costs at the global level excluding CO2 fertilization (3% and 5% respectively) as well to the beneficial effects of elevated CO2 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
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 CO2 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 CO2 levels is simulated for rangeland productivity (+14% compared to −2.3% with constant CO2 levels). In ecosystem-based experiments, grassland production increased on average by +17% due to the stimulatory effect of double CO2, with higher responses in moisture-limited and warm-season grassland systems (Campbell and Stafford Smith 2000). The size of the CO2 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 CO2 (Wang et al 2012).

Results derived within the Inter-Sectoral Impacts Model Intercomparison Project (ISI-MIP) highlight both the importance and uncertainty of CO2 fertilization for simulating climate impacts on agriculture and the critical role of model parametrization to understand differences in simulated responses to elevated CO2 (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 CO2 effect as implemented in LPJmL is relatively strong, but within a plausible physiological range.

But even results without CO2 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 CO₂ 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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References

Alkemade R, Reid R S, van den Berg M, Leeuw J and de, Jeuwen M 2013 Assessing the impacts of livestock production on biodiversity in rangeland ecosystems Proc. Natl. Acad. Sci. USA 110 20900–5
Asseng S et al 2013 Uncertainty in simulating wheat yields under climate change Nat. Clim. Change 3 827–32
Bassu S et al 2014 How do various maize crop models vary in their responses to climate change factors? Glob. Change Biol. 20 2301–20
Bodirsky B L et al 2014 Reactive nitrogen requirements to feed the world in 2050 and potential to mitigate nitrogen pollution Nat. Commun. 5 3858
Bodirsky B L, Popp A, Weindl L, Dietrich J P, Rolinski S, Scheifelle I, Schmitz C and Lotze-Campen H 2012 N2O emissions from the global agricultural nitrogen cycle—current state and future scenarios Biogeosciences 9 4169–97
Bondeau A et al 2007 Modelling the role of agriculture for the 20th century global terrestrial carbon balance Glob. Change Biol. 13 679–706
Bouwman A F, Kram T and Klein Goldewijk K 2006 Intergated Modelling of Global Environmental Change: An Overview of IMAGE 2.4 Netherlands Environmental Assessment Agency, Bilthoven, The Netherlands
Bouwman L, Goldewijk K K, Hoek K W V D, Beusen A H W, Vuuren D P V, Willems J, Rufino M C and Stehfest E 2013 Exploring global changes in nitrogen and phosphorus cycles in agriculture induced by livestock production over the 1900–2050 period Proc. Natl. Acad. Sci. USA 110 20882–7
Campbell B D and Stafford Smith D M 2000 A synthesis of recent global change research on pasture and rangeland production: reduced uncertainties and their management implications Agric. Ecosyst. Environ. 82 39–55
Cohn A S, Mosnier A, Havlík P, Valin H, Herrero M, Schmid E, O’Hare M and Obersteiner M 2014 Cattle ranching intensification in Brazil can reduce greenhouse gas emissions by sparing land from deforestation Proc. Natl. Acad. Sci. USA 111 7236–41
Collatz G, Ribas-Carbo M and Berry J 1992 Coupled photosynthesis-stomatal conductance model for leaves of C4 plants Funct. Plant Biol. 19 519–38
Collins W D et al 2006 The community climate system model version 3 (CCSM3) J. Clim. 19 2422–43
Conant R T and Paustian K 2002 Potential soil carbon sequestration in overgrazed grassland ecosystems Glob. Biogeochem. Cycles 16 1143
Cox PM, Betts R A, Bintuan C B, Essery R L H, Rowntree P R and Smith J 1999 The impact of new land surface physics on the GCM simulation of climate and climate sensitivity Clim. Dyn. 15 183–203
Delworth T L et al 2006 GFDL’s CM2 global coupled climate models, Part I: formulation and simulation characteristics J. Clim. 19 643–74
Diffenbaugh N S and Scherer M 2011 Observational and model evidence of global emergence of permanent, unprecedented heat in the 20th and 21st centuries Clim. Change 107 615–24
Erb K H, Gaube V, Krausmann F, Plutzar C, Bondeau A and Haberl H 2007 A comprehensive global 5 min resolution land-use data set for the year 2000 consistent with national census data J. Land Use Sci. 2 191–224
Fader M, Root S, Muller C, Bondeau A and Gerten D 2010 Virtual water content of temperature cereals and maize: present and potential future patterns J. Hydrol. 384 218–31
Farquhar GD, Caemmerer S and von, Berry J A 1980 A biochemical model of photosynthetic CO2 assimilation in leaves of C3 species Planta 149 78–90
Gaughan J B 2012 Basic principles involved in adaption of livestock to climate change Environmental Stress and Amelioration in Livestock Production ed V Seijan, SM K Naqvi, T Ezeji, J Lakritz and R Lal (Berlin: Springer) pp 245–61
Ghahramani A and Moore A D 2013 Climate change and broadacre livestock production across southern Australia J Anim. Ranching Environ. Res. Lett. 10 1143
Godber O F and Wall R 2014 Livestock and food security: vulnerability to population growth and climate change Glob. Change Biol. 20 3092–102
Havlík P, Leclère D, Valin H, Herrero M, Schmid E, Sousanna J F, Müller C and Obersteiner M 2015 Global climate change, food supply and livestock production systems: a bioeconomic analysis Climate Change and Food Systems: Global Assessments and Implications for Food Security and Trade ed A Elbehri (Rome, Italy: Food Agriculture Organization of the United Nations (FAO))
Havlík P et al 2014 Climate change mitigation through livestock system transitions Proc. Natl. Acad. Sci. USA 111 3709–14
Havlík P, Valin H, Mosnier A, Obersteiner M, Baker JS, Herrero M, Rufino M C and Schmid E 2013 Crop productivity and the global livestock sector: implications for land use change and greenhouse gas emissions Am. J. Agric. Econ. 95 442–8
Herrero M, Havlík P, Valin H, Notenbaert A, Rufino M C, Thornton P K, Blümmel M, Weiss F, Grace D and Obersteiner M 2013 Biomass use, production, feed efficiencies, and greenhouse gas emissions from global livestock systems Proc. Natl. Acad. Sci. USA 110 20888–93
Herrero M and Thornton P K 2013 Livestock and global change: emerging issues for sustainable food systems Proc. Natl. Acad. Sci. USA 110 20878–81
Herrero M et al 2014 Exploring future changes in smallholder farming systems by linking socio-economic scenarios with regional and household models Glob. Environ. Change 24 165–82
Herrero M, Thornton P K, Gerber P and Reid R S 2009 Livestock, livelihoods and the environment: understanding the trade-offs Curr. Opin. Environ. Sustain. 1 111–20
Herrero M, Thornton P K, Notenbaert A, Msangi S, Wood S, Kruuska R, Dixon J, Bossio D, Steeg J and Freeman HA 2010a Drivers of change in crop-livestock systems and their potential impacts on agro-ecosystems services and human well-being to 2030 CGIAR Systemwide Livestock Programme Herrero M et al 2010b Smart investments in sustainable food production: revisiting mixed crop-livestock systems Science 327 822–5
Hopkins A and Del Prado A 2007 Implications of climate change for grassland in Europe: impacts, adaptations and mitigation options Review Grass Forage Sci. 62 118–26
Izaurralde R C, Williams J R, McGill W B, Rosenberg J N and Jakas M C Q 2006 Simulating soil C dynamics with EPIC: model description and testing against long-term data Ecol. Model. 192 362–84
Jones W J, Hoogenboom G, Porter C H, Boote K J, Batchelor W D, Hunt L A, Wilkins P W, Singh U, Gijsema A J and Ritchie J T
Rosenzweig C 2007a Crop response to elevated CO2 and world food supply: a comment on ‘Food for thought...’ by Long et al 2006 Science 312 1918–21 Eur. J. Agron. 26 215–23
Tubiello F N, Soussana J-F and Howden S M 2007b Crop and pasture response to climate change Proc. Natl Acad. Sci. USA 104 19686–90
Valin H, Havlík P, Mosnier A, Herrero M, Schmid E and Obersteiner M 2013 Agricultural productivity and greenhouse gas emissions: trade-offs or synergies between mitigation and food security? Environ. Res. Lett. 8 035019
van Velthuizen H et al 2007 Mapping Biophysical Factors that Influence Agricultural Production and Rural Vulnerability (Environment and Natural Resources Series) (Rome, Italy: FAO)
van Vuuren D P, Elzen M G J, den, Lucas P L, Eickhout B, Strengers B J, van Ruijven B, Wonink S and van Houdt R 2007 Stabilizing greenhouse gas concentrations at low levels: an assessment of reduction strategies and costs Clim. Change 81 119–59
Waha K, van Bussel L G J, Müller C and Bondeau A 2012 Climate-driven simulation of global crop sowing dates Glob. Ecol. Biogeogr. 21 247–59
Wang D, Heckathorn S A, Wang X and Philpott S M 2012 A meta-analysis of plant physiological and growth responses to temperature and elevated CO2 Oecologia 169 1–15
Westhoek H, Rood T, Berg M, Janse J, Nijdam D, Reudink M, Stiehler E, Lesschen J P, Oenema O and Wolter W B 2011 The Protein Puzzle: the Consumption and Production of Meat, Dairy and Fish in the European Union PBPBL Netherlands Environmental Assessment Agency, The Hague
White J W, Hoogenboom G, Kimball B A and Wall G W 2011 Methodologies for simulating impacts of climate change on crop production Field Crops Res. 124 357–68
Williams J R 1995 The EPIC model Computer Models of Watershed Hydrology ed V P Singh (Colorado: Water Resources) pp 909–1000
Ziska L H and Bunce J A 2007 Predicting the impact of changing CO2 on crop yields: some thoughts on food New Phytol. 175 607–18