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YSSP Report
Young Scientists Summer Program

Global distribution of beef production systems

Reconciling climate change mitigation, biodiversity conservation and income

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Approved by

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Program: ESM
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It was finished by Katie Lee and has not been altered or revised since.

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Abstract

Global demand for beef is growing rapidly, which is economically profitable for beef producing nations. Unfortunately, beef production also plays a significant role in depleting the world's rapidly declining biodiversity and increasing already record-high global emissions. The level of beef demand and the intensity of the production system used to produce beef can alter the impact on GHG emissions and biodiversity. For example, intensification of production may reduce GHG emissions and could lead to land sparing for biodiversity conservation. Using a global economic model (GLOBIOM) we tested scenarios of livestock system shifts (shifts towards extensive or intensive livestock production systems) for two different levels of beef demand. This report describes the potential trade-offs (and co-benefits) between GHG emissions, biodiversity conservation, and regional economic impacts of livestock system shifts both in addition to and independent from demand reduction strategies from a global perspective. This report shows that demand reduction strategies have the greatest potential for environmental benefit, and strategies that combine demand reduction with intensification have the greatest benefit for GHG emissions, biodiversity and income. Despite these benefits, we found deforestation still greatly increased, with loss concentrated in Latin America and the Caribbean, Sub Saharan Africa and South-East Asia. This suggests that more ambitious and targeted strategies would need to be explored to halt these losses.

Introduction

Global demand for beef is on the rise, with demands on the global food system predicted to escalate parallel to the world's human population, which is projected to increase from 7.8 billion people in 2020 to over 11 billion by 2100 (United Nations, Department of Economic and Social Affairs, 2017). Affluence is also on the rise and with this comes a concomitant increase in consumption, and a tendency toward meat-based products, in particular, beef (Burggraf et al., 2015; Lange et al., 2018; Myers & Kent, 2004). Beef production also plays a significant role in depleting the world's rapidly declining biodiversity and increasing already record-high global emissions. Beef production generates more greenhouse gas (GHG) emissions and requires more land and water than any other animal product (Mekonnen & Hoekstra, 2012; Poore & Nemecek, 2018). Both biodiversity and GHG emissions are highly correlated to land-cover and land-use (Haines-Young, 2009), and livestock is the largest driver of land-use change worldwide (Chaplin-Kramer et al., 2015; Goldewijk, 2001). Much of the historical habitat loss relating to agriculture has been observed in temperate forests and grasslands, but more recently rapid expansion in tropical countries is often at the expense of biodiverse tropical forests (Gibbs et al., 2010).

To reduce future trade-offs between food production and environmental outcomes, detailed studies on the beef sector with mitigation strategies from both the demand and supply side of beef production are necessary. One strategy is to reduce demand by shifting diets away from animal products (e.g. Tilman and Clark, 2014; Stoll-Kleemann and Schmidt, 2017; Springmann et al., 2018; Willett et al., 2019). This has distinct advantages as it saves land, reduces methane emissions from livestock, as well as delivering health co-benefits where beef consumption is already high (Yip et al., 2013). However, this is often only viable in countries with already high levels of economic and nutritional security. The farming of livestock currently provides income to up to 0.75 billion of the world's poorest, as well as providing additional employment in areas such as transport, trade, feed production (including nutrition and manure) and veterinary services (Otte et al., 2012). Another strategy is to intensify production. Production of beef cattle occurs under very diverse conditions driven by socioeconomic, technological and environmental factors (Bouwman et al., 2005). Due to beef cattle's relatively long reproduction cycle and low feed conversion efficiency, transformations in beef production systems are gradual (Seré & Steinfeld, 1996). However, because of increasing demand and land competition, there has been a global trend of gradual intensification of livestock production systems. This sees a concomitant increase in feed quality, and improved feed conversion efficiency (Seré & Steinfeld, 1996). Increasing the productivity of livestock systems (i.e., when transitioning from extensive rangeland systems to mixed crop-livestock systems) can halt deforestation driven by the expansion of pastures, and in turn lead to significant environmental wins (e.g. Havlík et al., 2014; Martha et al., 2012). However, it is also possible that this intensification may have some negative environmental impacts, such as habitat changes, nutrient pollution and chemical inputs as well as increased water consumption and pollution because of the larger dependence on concentrate feed in industrial systems (Mekonnen & Hoekstra, 2012).

Global studies exploring livestock system shifts and biodiversity are largely non-existent. To date, most environmental assessments of the livestock sector have focused on GHG emissions (e.g. Havlík et al., 2014; Herrero et al., 2016). Studies on the impact of livestock on biodiversity exist but are generally limited to a regional scale (e.g. Alkemade et al., 2013; Teixeira et al., 2018; Westhoek et al., 2011). Global biodiversity focused studies exist, however they rely on stylized assumptions about livestock production and do not include enough details on the beef sector to navigate the complexity of production system switches (Leclère et al., 2020; Tilman et al., 2017).

As a step towards filling these gaps, we systematically assess the demand and supply-side measures of beef production. We tested scenarios of livestock system shifts (by assuming a switch to either mixed production systems or grazing production systems) for two different levels of beef demand using GLOBIOM (Havlík et al., 2014). This report describes the potential benefits of livestock system shifts both in addition to and independent from demand reduction scenarios from a global perspective with a regional analysis that shows that benefits of different strategies are not distributed equally across the globe.

Methods

Scenarios

	No system shifts	Shifts to grazing systems	Shifts to mixed systems
SSP2 beef demand	BL-F	LG-F	MX-F
Reduced beef demand	BL-R	LG-R	MX-R

Table 1 - Matrix of scenario combinations displaying abbreviations and colours used to represent the scenarios throughout this report. Two levels of beef demand were used with shared socioeconomic pathway 2 (SSP2) "middle of the road" demand & demand reduced to 70% of SSP2 levels. Across these demand levels in two scenarios no system shifts were forced in beef production systems, in two scenarios there was a forced reduction in the number of livestock produced in mixed systems and in the final two scenarios there was a forced reduction of in the number of livestock produced in grazing systems.

We designed and analysed six scenarios to explore the potential impact that consumer demand for beef and production system intensification can have on GHG emissions and biodiversity. An outline of the scenario combinations can be found in Table 1. For all scenarios, population and GDP projections were based on the shared socioeconomic pathway 2 (SSP2) "middle of the road" scenario framework (Riahi et al., 2017).

Demand for beef

To explore demand-side measures we assumed two different levels of beef demand. The baseline scenario (BL-F) assumes by 2070 that the total global beef demand will increase by ~88% from the year 2000 in line with the SSP2 storyline of population growth and increasing affluence. This demand level was also assumed for the LG-F and MX-F scenarios. For scenarios with reduced demand assumptions (BL-R, LG-R & MX-R), adjustments to the demand for bovine meat were made to all regions (see Figure 8 in appendix). Demand was decreased linearly from 100% in 2030 to 70% in 2070 compared to the baseline scenario. Reductions were capped at 70% as for further increases additional adjustments in the model would be necessary. Within the model, production and international trade adjust to meet demand at the level of model regions displayed in Table 3.

Livestock system numbers

To explore what would happen if either extensive or intensive systems were favoured three different scenario assumptions were set up. For the baseline scenario (BL-F) each livestock system could expand freely within each country, based on relative cost-efficiency. Under the SSP2 assumptions, this typically led to increases in both intensive and extensive systems, with some regional variations. These assumptions were also held for the demand reduction only scenario BL-R. GLOBIOM uses the International Livestock Research Institute (ILRI)/FAO production systems classifications including grazing systems and mixed systems (both rainfed and irrigated) broken into the agroecological zones of arid and semiarid, humid and semihumid, and tropical highlands and temperate (Herrero et al., 2013; Robinson et al., 2011; Seré & Steinfeld, 1996). In scenarios with shifts toward mixed (MX-F & MX-R) or grazing systems (LG-F & LG-R), beef cattle numbers were assumed to decrease by a factor of 0.9 in the opposing system each decade from 2030 to 2070 as compared to 2020 levels. This was chosen to provide the largest shift without causing infeasibilities in the model due to livestock system flexibility constraints.

Modelling

The potential for different beef demand levels and livestock production system shifts to mitigate the environmental problems linked to beef consumption were explored using GLOBIOM (Havlík et al., 2014), particularly the pre-release version available from www.globiom.org. GLOBIOM is a partial equilibrium economic model designed to assess the competition between major land-use sectors. Land-use change is determined by maximizing the sum of consumer and producer surplus. For each scenario, the model was solved recursively in 10-year time steps starting from 2000 to 2070. Data has been aggregated globally and at the level of macroregions as outlined in Table 3.

Land-use in GLOBIOM

Land-use types in GLOBIOM are cropland, managed grassland, managed forest, unmanaged forest, short rotation plantations, and other natural vegetation. Because of their potential relevance to beef production, the primary land uses considered in this study were – cropland, managed grassland, unmanaged forest, and other natural land.

GHG emissions

GHG emissions were captured from sources including enteric fermentation, manure management, manure on pasture, synthetic and organic fertilisers, rice cultivation and land-use change, aggregated for different sectors as outlined in Table 2.

Livestock emissions	CH_4 from enteric fermentation CH_4 and N_2O from manure management N_2O from excreta on pasture
Crop sector emissions	N_2O fertilization emissions from synthetic and organic fertilisers CH_4 methane emissions from rice cultivation
Land-use change emissions	These are calculated based on the difference in carbon stock between initial and final land cover

Table 2 - Breakdown of emissions captured in GLOBIOM for the agricultural sector

Biodiversity

Biodiversity impacts were estimated at the end of each timestep using the Biodiversity Intactness Index (BII) with species data from the PREDICTS database (Newbold et al., 2015). The BII compares the average abundance of species in a given geographical area relative to the abundance in minimally impacted sites. Values range from 0 to greater than 1, where 0 refers to an absence of all species compared to the original state, 1 corresponds to intactness being equivalent to the reference state and greater than 1 corresponds to an increase in intactness compared to the reference state.

Results

Snapshot of beef production for the year 2000

To understand what the beef cattle industry looked like at the start of the simulation run and to provide a reference for later comparison an overview for the year 2000 is provided. Cropland and managed grasslands used 910 Mha and 700 Mha respectively. This is compared to the remaining 6700 Mha of forest and other natural land. GHG emissions from agricultural production (not including those from land-use change) were 4378.21 MT CO_2eq yr^{-1}, with the majority coming from the methane produced in enteric fermentation (2137.57 MT CO_2eq yr^{-1}; 49% of total emissions). Large regional variations exist in terms of volume and method of beef production – with the largest producers being the Latin America Caribbean region and North America region – with each region producing approximately 23% of the total global beef production, combined that's almost half of the world's production. These two regions were also the world's largest consumers of beef in absolute terms and both fall in the top 3 in terms of per capita consumption (Latin America and the Caribbean was overtaken by Oceania for per capita consumption). Considering only mixed and grazing systems (urban and other systems were excluded from this study), most beef was produced in mixed systems – 73% compared to only 27% of beef produced on grasslands. Europe and Oceania had slightly larger numbers of cattle in grazing systems compared to mixed systems. South Asia, Eastern Asia, South East Asia and to some extent the Former Soviet Union were heavily dominated by mixed production systems. All other regions had predominantly mixed systems, but with numbers in grazing systems being at least 50% of those in mixed systems. Eastern Asia was the largest importer of beef, followed by the Middle East and Northern Africa, and the Former Soviet Union. Oceania had the largest export of beef, followed by Latin America and the Caribbean, and South Asia. Land productivity for beef production, measured in kg protein ha^{-1}, varied greatly among different regions, with by far the highest land productivity found in Europe producing 65 kg protein ha^{-1}. The least productive land yields for beef were in Sub Saharan Africa producing only 1.4 kg protein ha^{-1}.

Change in livestock numbers

In the baseline scenario (BL-F), increases in beef cattle to meet future demand were distributed relatively evenly between mixed and grazing production systems (Figure 1). Favouring mixed systems leads to a lower increase in livestock numbers (MX-F & MX-R) compared to the other scenarios. Reducing beef demand with no forced system shifts (BL-R) reduced only the production from mixed systems, and still saw minor increases in livestock numbers in grazing production systems. This is likely due to the largest reductions in production coming from regions that primarily use mixed production systems; increases in grazing systems occur in small amounts across multiple regions leading to a small net increase. The largest increase in livestock numbers come from the LG-F scenario, as grazing systems are typically less productive than mixed production systems and therefore require a larger number of cattle to meet

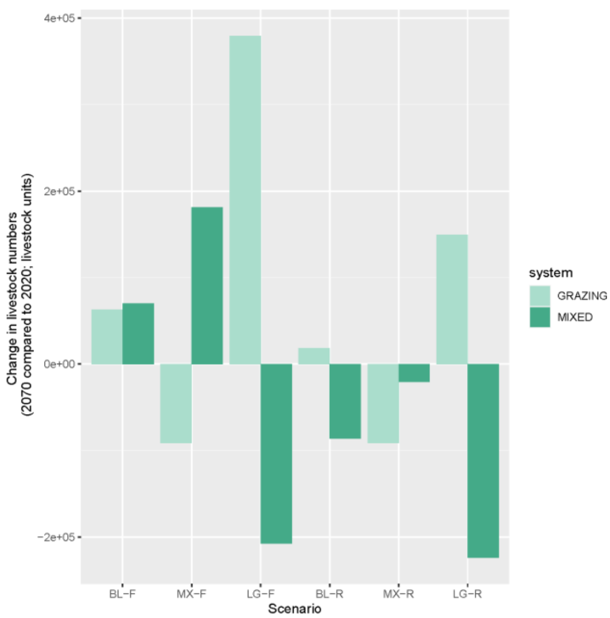

Figure 1 - The change in livestock numbers in either grazing or mixed production systems in 2070 from 2020. BL-F is the baseline scenario, the suffix -F refers to SSP2 beef demand, -R reduced beef demand, MX switches to mixed systems, LG switches to grazing systems.

the same level of demand. Comparably, this leads to scenarios with reduced grazing systems (MX-F & MX-R) to require lower livestock numbers to meet each level of demand. The regional breakdown of livestock numbers in mixed and grazing systems is shown in Figure 99 in the appendix.

Land-use change

The conversion of forest to pastures or arable land for feed production is one of the primary environmental concerns for beef production, jeopardizing biodiversity and contributing greatly to global GHG emissions (Herrero et al., 2015). All of the scenarios explored lead to a reduction in forest and other natural vegetation in 2070 compared to 2020 (Figure 2). Scenarios with reduced beef consumption (green hues) lead to less loss of forest and natural vegetation overall, and scenarios with switches toward mixed systems (MX-F & MX-R)

Figure 2 - Change in land area of major natural and agricultural land-use classes in 2070 compared to 2020. Overall diet reduction scenarios (green hues) reduce loss of forest and other natural vegetation compared to "middle of the road" demand scenarios (purple hues). Reduction of mixed systems (LG-F & LG-R) tended to lead to greater loss of forest and other natural vegetation and greater increase in managed grasslands compared to other scenarios at relevant demand level. Reduction of grazing systems (RG-F & RG-R) tended to lead to reduced loss of forest and other natural vegetation and less increase in managed grasslands compared to other scenarios at relevant demand level. BL-F is the baseline scenario, the suffix -F refers to SSP2 beef demand, -R reduced beef demand, MX switches to mixed systems, LG switches to grazing systems. Results are broken into macroregions with Middle East and North Africa (MNA), Sub Saharan Africa (SSA), Former Soviet Union (FSU), Latin American and the Caribbean (LAC), North America (NAM), South Asia (SAS), Europe (EUR), Oceania (OCE), East Asia (EAS), South East Asia (SEA).

lead to reduced loss at each demand level. Compared to the baseline scenario (BL-F), keeping the same beef demand but switching toward mixed systems (MX-F) retains approximately 43 Mha (~1.5% of total loss in BL-F) of forest and natural land. Without forcing any system shifts but reducing beef demand (BL-R) this reduction increases to 4.3% of the total loss of forest and natural land compared to the BL-F scenario. With reduced beef demand *and* switches toward mixed systems (MX-R), this further increases retention to 5.5%, or 160 Mha, compared to the BL-F scenario; there is a concomitant reduction in managed grasslands of 160 Mha. Land-use change varies greatly between different regions. For all scenarios, the largest loss of forest and natural land (and the greatest increase in cropland and managed grassland) occurs in Sub Saharan Africa (SSA). Major loss of forest also occurs in Latin America and the Caribbean (LAC) and South East Asia (SEA). Most regions experience losses in other natural lands for all scenarios, except for Europe that experience increases for all scenarios, and North America, East Asia and Oceania that gain in natural vegetation for demand reduction scenarios (green hues).

Emissions

In line with other studies (e.g. Tilman & Clark, 2014), scenarios with transitions to a diet with lower beef intake showed a significant decrease in global GHG emissions. By reducing beef consumption with no system shifts (BL-R) it is possible to reduce global agricultural non-CO_2 emissions by 482 MT CO_2 EQyr^{-1}. By switching toward mixed systems globally, as well as reducing beef consumption (MX-R) we saw a reduction of 550 MT CO_2 EQyr^{-1}, this is a marginal but promising increase compared to the reduction only scenario. Notably, the scenarios that don't assume reductions in beef consumption show larger contrast in terms of emission outcomes.

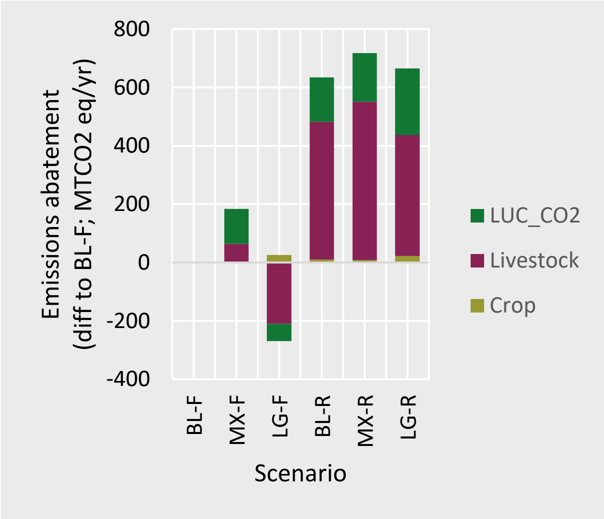

Figure 3 - GHG emission abatement compared to the baseline scenario for the year 2070 decomposed into emission source. LUC_CO2 represents CO_2 from land use change. BL-F is the baseline scenario, the suffix -F refers to SSP2 beef demand, -R reduced beef demand, MX switches to mixed systems, LG switches to grazing systems.

By switching toward mixed systems globally but maintaining an SPP2 level diet (MX-F), it is possible to save 63 MT CO_2EQyr^{-1} in agricultural non-CO_2 emissions. Figure 3 shows that in reduced demand scenarios (BL-R, MX-R & LG-R) most of the abatement comes from livestock sources. The reduced demand scenario with switches toward grazing systems (LG-R) has the largest proportion of abatement of CO_2 emissions from land-use change, as this scenario has the largest loss of forest and other natural land (relative to other reduced demand scenarios; as demonstrated in Figure 2) this is likely due to more livestock being required to meet the demand for this scenario leading to increased livestock emissions and other land-use change (not deforestation).

Biodiversity and emissions co-benefit

As measured in terms of intactness of ecosystems (BII metric), the reduction of emissions is mirrored in the benefit for biodiversity as compared to the baseline scenario. By reducing beef consumption with no system shifts (BL-R) it is possible to reduce loss compared to the baseline by ~10% of BII. By switching toward mixed systems globally, as well as reducing beef consumption (MX-R) it is possible to reduce loss by ~13% compared to the loss in the baseline scenario. By switching toward mixed systems globally but maintaining an SPP2 level diet (MX-F), it is possible to save an additional 3% of BII compared to the BL-F scenario. Comparing the abatement compared to the baseline scenario (BL-F) of both GHG emissions and BII for the year 2070 shows that globally the demand reduction scenarios (green hues) have better outcomes for both dimensions compared to SSP2 demand (purple hues) (Figure). Switching toward mixed systems has a net

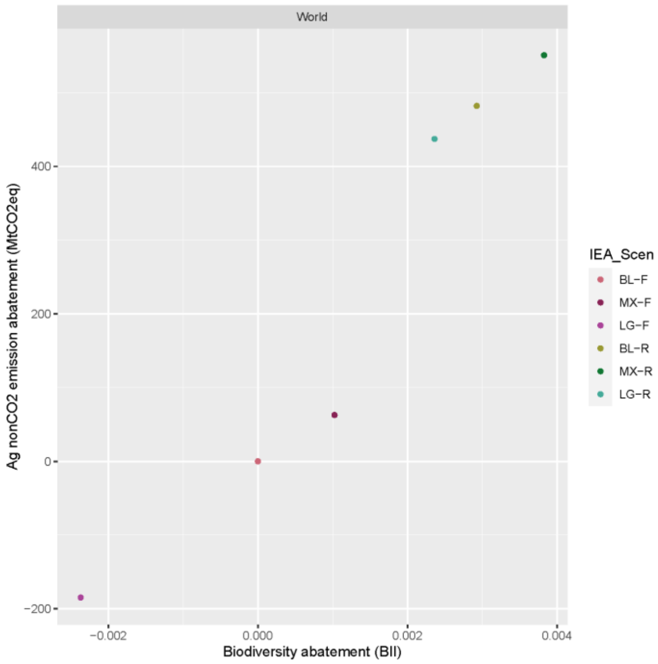

Figure 4 – Biodiversity abatement measured using biodiversity intactness indicator (abatement relative to the baseline scenario (BL-F)) vs Global GHG abatement (abatement relative to the baseline scenario (BL-F)) for the year 2070. Scenarios with reduced beef demand (green hues) led to increased GHG emissions abatement and biodiversity abatement. Reduced grazing systems scenarios tended to lead to higher emissions abatement and biodiversity abatement compared to relevant demand scenarios. BL-F is the baseline scenario, the suffix -F refers to SSP2 beef demand, -R reduced beef demand, MX switches to mixed systems, LG switches to grazing systems.

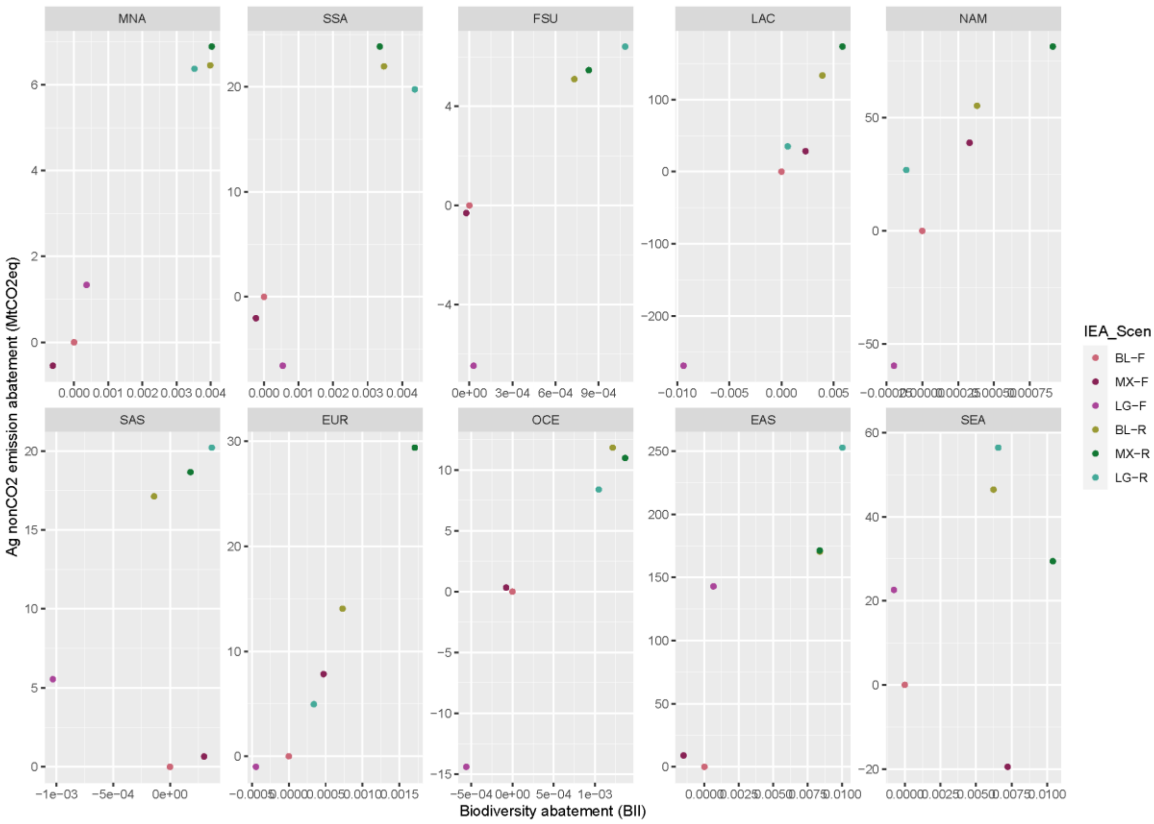

Figure 5 – Regional biodiversity abatement measured using biodiversity intactness indicator (abatement relative to the baseline scenario (BL-F)) vs Global GHG abatement (abatement relative to the baseline scenario (BL-F)) for the year 2070. Scenarios with reduced beef demand (green hues) led to increased GHG emissions abatement and biodiversity abatement. Reduced grazing systems scenarios tended to lead to higher emissions abatement and biodiversity abatement compared to relevant demand scenarios. BL-F is the baseline scenario, the suffix -F refers to SSP2 beef demand, -R reduced beef demand, MX switches to mixed systems, LG switches to grazing systems.

benefit in both reduced demand and fixed demand scenarios for both biodiversity and GHG emissions, however, this effect is not as great as for demand reduction. The picture becomes slightly more complicated at a regional scale, for example in the Former Soviet Union, South Asia and Eastern Asia reducing the number of livestock produced in mixed systems leads to larger improvements along both dimensions but only when demand is also reduced (Figure). However, overall, the globally emergent trend can be seen at a regional scale. Note that in this figure the axes are independent for each region. Due to large variations between regions, it was not possible to compare on a fixed scale.

Land productivity and emissions intensity

Over time land productivity increases for all scenarios (Figure 4). Switching toward mixed systems leads to increased land productivity and decreased emissions intensity, even more so when not assuming demand reductions. For fixed demand scenarios (purple hues), by 2070 switching to mixed-systems over grazing-systems (MX-F) leads to an increase in land productivity of 10% compared to the baseline scenario. This improvement in land productivity when moving toward mixed systems (MX – R) is mirrored in the demand

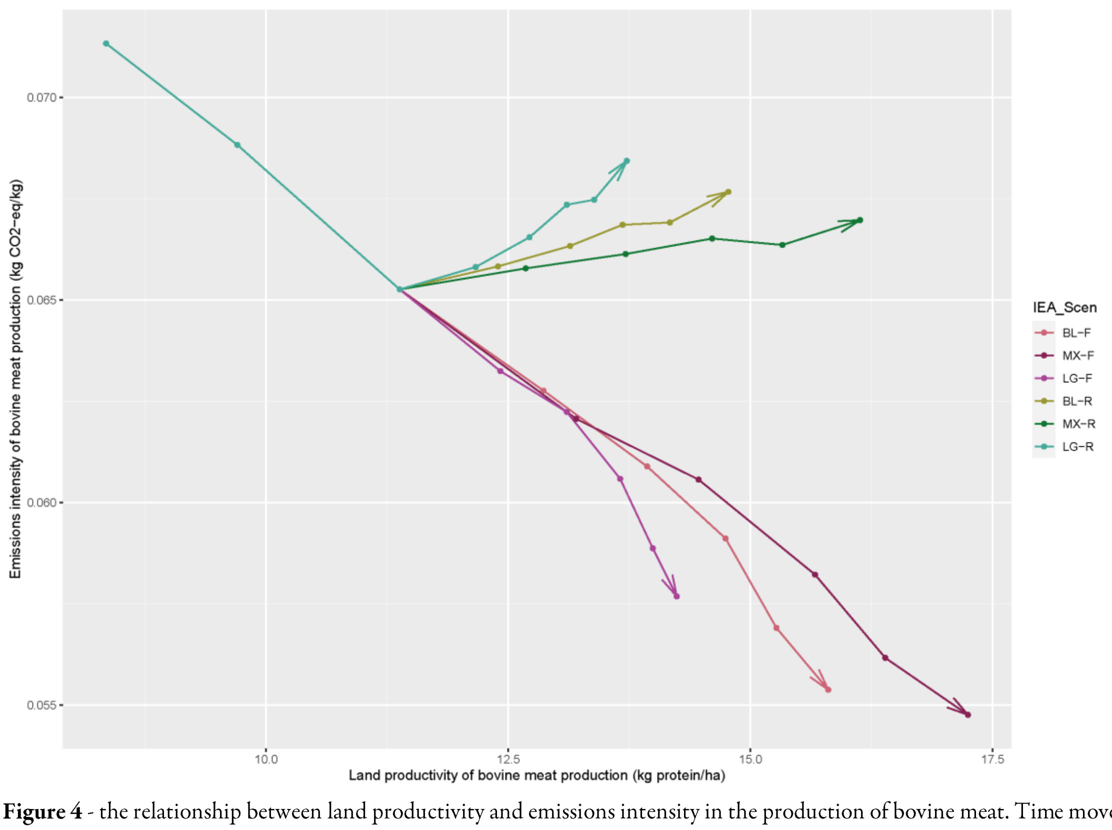

Figure 4 - the relationship between land productivity and emissions intensity in the production of bovine meat. Time moves in the direction of the arrows displayed on each scenario trendline. Over time all scenarios tend to increase in land productivity, with the largest increases occurring when switches toward mixed systems are forced. Reducing demand (green hues) tends to lead to an increase in emissions intensity. BL-F is the baseline scenario, the suffix -F refers to SSP2 beef demand, -R reduced beef demand, MX switches to mixed systems, LG switches to grazing systems.

reduction scenarios (green hues). In fixed demand scenarios (purple hues) the emissions intensity decreases over time likely due to reduced pressure on land (inducing low incentive to intensify); however, for reduced demand scenarios (green hues) there is an increase in emissions intensity compared to 2020. Switching toward mixed systems (MX-F & MX-R) leads to the lowest emissions intensity for each demand level.

Regional income

The influence that beef demand and production intensity have on regional income from beef production is not distributed equally across different regions. For fixed SSP2 demand (purple hues), shifts toward mixed systems (MX-F) has the lowest impact on income, with a net positive effect income is increased by ~1.4% in 2070 compared to the baseline (BL-F). Exploring this regionally (Figure 5), the overall increase in global income in the intensifying MX-F scenario is coming from several main regions, the Middle East and North Africa, Sub Saharan Africa, and Latin America and the Caribbean. Similarly, for the demand reduction scenarios, a shift toward mixed systems (MX-R) tracks most closely to the scenario with no system shifts (BL-R). Demand reduction scenarios (green hues) lead to the largest reductions in income from beef for all regions (globally ~45% drop compared to the baseline). Switching to grazing systems (LG-F) leads to increased income for many regions, including Latin America and the Caribbean, North America, Eastern Asia and Europe.

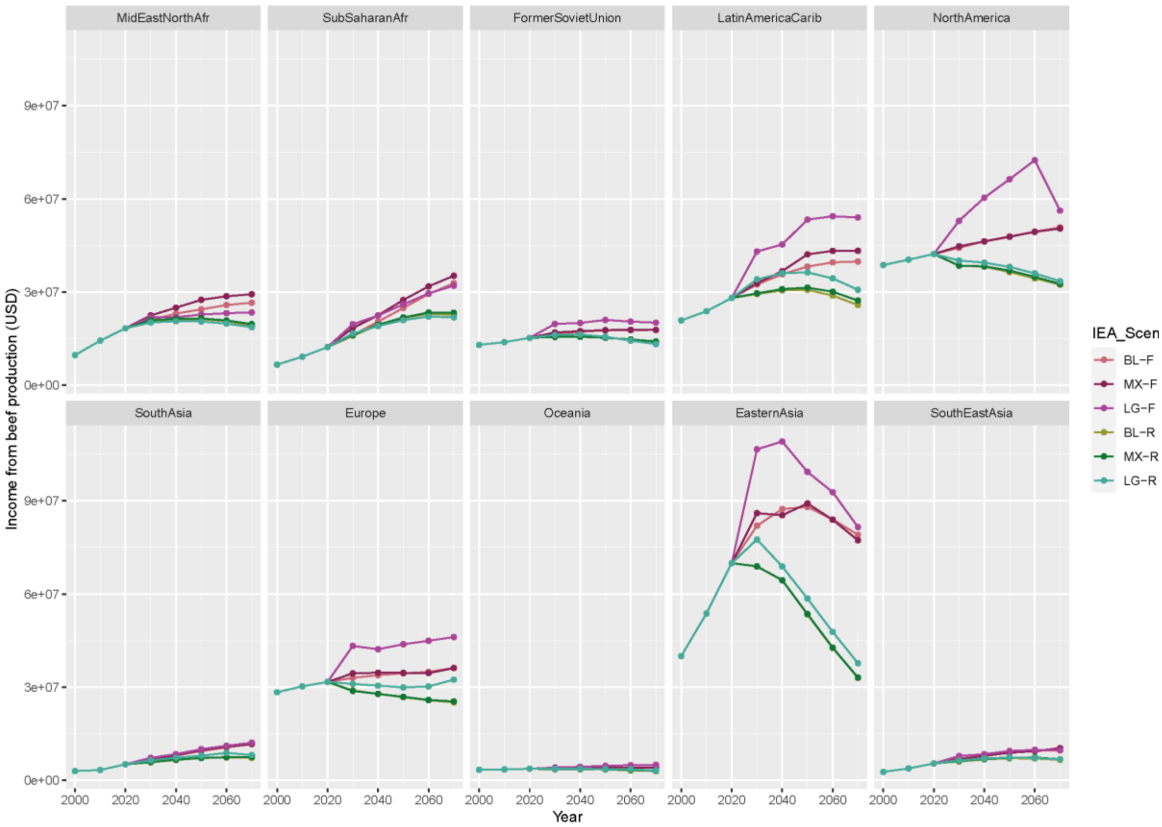

Figure 5 – The influence of beef demand and production intensity on regional income from beef production over the period from 2020 to 2070. Demand reduction scenarios (green hues) lead to the largest reductions in income for all regions. Switching to grazing systems (LG-F) leads to increased income for many regions, in particular Latin America and the Caribbean, North America, Eastern Asia, and Europe. BL-F is the baseline scenario, the suffix -F refers to SSP2 beef demand, -R reduced beef demand, MX switches to mixed systems, LG switches to grazing systems.

Discussion

This study was designed to expand the conversation on the environmental impact of beef production beyond GHG emissions and diet reduction to incorporate the impact on biodiversity and the impact of switching between intensive and extensive beef production systems. This report demonstrates that diet reduction has benefits for biodiversity as well as GHG emissions, and that switches toward mixed systems can provide benefits to both GHG emissions and biodiversity. We showed that the biggest advantages come from diet reduction, however, the benefits of intensifying livestock systems compound leading to larger benefits when both strategies are applied. It is possible that if it was feasible to apply system shifts at the same level as demand reduction the benefits would be comparable, but due to system shifts being more difficult to implement in practice it's potential benefits are bounded.

Currently, beef reduction scenarios (BL-R, MX-R & LG-R) have a conservative reduction compared to other diet reduction studies (e.g. Leclère et al., 2020; Tilman & Clark, 2014) and this reduction is distributed equally across the globe. A more ambitious reduction strategy with targeted reduction could provide better environmental outcomes and more equitable distribution of production for economically developing regions (see Appendix A.1 for a more in-depth look at targeted demand reduction). In demand reduction scenarios, the emissions intensity was shown to increase over time (Figure 4) this is likely due to reduced pressure on land-use leading to low incentive to intensify. This trend could potentially be reversed by adding some external pressure on better land-use such as implementing restoration efforts. The major forest and other natural vegetation loss seen in Latin America and the Caribbean, Sub Saharan Africa and South East Asia that occurs even for the MX-R scenario with demand reduction and favouring intensifying production show that more ambitious scenarios would be required to halt this loss.

The regional comparison of BII and emissions abatement (shown in Figure) demonstrates that the benefits of switching toward mixed systems do not apply homogenously across regions. However, the regions where this is most apparent already have very low levels of grazing – including the Former Soviet Union, South Asia, and Eastern Asia. As shifts toward mixed systems are not possible in these regions a benefit of a system shift is not possible, this implies that regionally performing system shifts based on current distribution, rather than a proportion evenly applied globally, would rectify this.

On the ground, switches between different production systems is a slow process (Seré & Steinfeld, 1996). Because of the high productivity of mixed systems, the fixed "middle of the road" demand scenario with switches toward grazing systems (LG-F) led to immediate and sharp increases in producer price. This scenario would be more realistic if system switches were performed more gradually; however, it is anticipated that the impact on emissions and biodiversity would remain similar but slightly reduced when cumulated over time.

For biodiversity, several important assumptions were made that may limit the validity of the analysis. Firstly, the biodiversity intactness index only captures one aspect of biodiversity and should be complemented by additional metrics, for example looking at biodiversity hotspots and extinction risks. This study has isolated the impacts of beef cattle to land-use, which is a simplification as livestock can impact biodiversity in a multitude of ways, through its influence on climate change, as an invasive species, as a disease vector, from over-exploitation of resources and pollution (Teillard et al., 2016). Furthermore, the current unidirectional assessment of land-use on biodiversity ignores the complicated feedbacks that exist between biodiversity and land-use (e.g. loss of pollinators). Additionally, moderate grazing can be important for vegetation diversity (Godde et al., 2018) and grassland preservation and management is not considered here.

Despite the demonstrated potential environmental benefits of shifting toward mixed systems, some obstacles exist to its implementation. The transition to more intense livestock systems can raise social concerns for smallholder and subsistence farming due to the economic and nutritional security that it provides rural areas, with livestock production directly supporting the livelihoods of 600 million smallholder farmers in the economically developing world (Godde et al., 2018; Thornton, 2010). Because of this, it is important to be aware of the potentially negative social effects of future livestock system transitions, this may be addressed to some extent using regionally targeted demand reduction strategies and system switches. Additionally, there are likely negative environmental effects of increasing mixed systems that have not been considered, for example, in mixed systems cropland would need to expand to feed the animals in these systems which is typically more intensively managed and leads to increased use of fertilizers, pesticides and irrigation water.

Next Steps

Biodiversity accounting is complicated, and it is impossible to capture this complexity using a single metric (such as the BII). To give a more complete overview of the impact of beef on biodiversity an additional biodiversity indicator will be added to the model. To complement the BII, a countryside Species-Area Relationship (cSAR) indicator will be used that measures regional extinctions rather than intactness (Chaudhary & Brooks, 2018). The cSAR indicator assesses the proportion of species not already extinct or committed to extinction in a region (but not necessarily in other regions) relative to a reference state. Ranges from 0 (all species of a region extinct or committed to extinction) to 1 (as many species of a region are extinct or committed to extinction as reference state) or larger (fewer species of a region are extinct or committed to extinction than in reference state).

Currently, beef has been removed, but not replaced with something like. Rather than just removing beef from diets, beef will be replaced with a food source of the same protein content to ensure nutritional security. Due to the global accessibility of soy and chicken, a combination of these foods will be used as a substitute for beef in diet reduction scenarios.

Increasing the flexibility of the model to handle larger reductions in beef consumption will allow the study to align more closely with other studies using diet reduction strategies, as well as show more drastic and promising increases in GHG and biodiversity abatement. Because of the difficulty in making livestock system switches a reality, in ongoing research the transitions between different systems will be made more smoothly so as not to cause huge disruptions in producer price or beef availability.

Finally, the baseline comparisons made in this study were made only to the SSP2 "middle of the road" scenario. However, productivity trends in livestock, as well as beef demand, may track very differently under different SSP scenarios, and potential futures with more technological advancements such as those explored in SSP1 or a less optimistic future such as in SSP3 are worth exploring. This will also provide an understanding of the sensitivity of the existing scenarios around the baseline.

Finally, an important link exists between beef and dairy production which was not explored in this study. Because of this dairy cattle should be considered in the environmental impact and reduction strategies and would be incorporated in future analysis. Additionally, in some regions other systems are prominent in beef production including urban and other systems and including these systems could change the outcomes of economic and environmental impacts, particularly at a regional level.

Conclusion

In line with other studies (e.g. Tilman and Clark, 2014; Stoll-Kleemann and Schmidt, 2017; Springmann *et al.*, 2018; Willett *et al.*, 2019) this study showed that reducing the consumption of beef can reduce the GHG emissions of the agriculture sector. Additional abatement of GHG emissions and biodiversity is possible using the production system shifts toward mixed systems. Further exploration using a different biodiversity indicator and larger reductions in demand as well as exploring a range of SSP futures should allow a fuller view of the potential impact of these decisions around beef production.

Appendix

Additional figures

Macroregion	Model regions	Countries
Europe (EUR)	**EU Baltic**	*Estonia, Latvia, Lithuania*
	EU Central East	*Bulgaria, Czech Republic, Hungary, Poland, Romania, Slovakia, Slovenia*
	EU Mid West	*Austria, Belgium, Germany, France, Luxembourg, Netherlands*
	EU North	*Denmark, Finland, Ireland, Sweden, United Kingdom*
	EU South	*Cyprus, Greece, Italy, Malta, Portugal, Spain*
	RCEU	*Albania, Bosnia and Herzegovina, Croatia, Macedonia, Serbia-Montenegro*
	ROWE	*Gibraltar, Iceland, Norway, Switzerland*
Former Soviet Union (FSU)	**Former USSR**	*Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Moldova, Tajikistan, Turkmenistan, Uzbekistan*
	Russia	
	Ukraine	
Oceania (OCE)	**Australia**	*Australia*
	New Zealand	*New Zealand*
	Pacific Islands	*Fiji Islands, Kiribati, Papua New Guinea, Samoa, Solomon Islands, Tonga, Vanuatu*
North America (NAM)	**Canada**	*Canada*
	United States of America	*United States of America*
Latin America and Caribbean (LAM)	**Argentina**	*Argentina*
	Brazil	*Brazil*
	Mexico	*Mexico*
	RCAM	*Bahamas, Barbados, Belize, Bermuda, Costa Rica, Cuba, Dominica, Dominican Republic, El Salvador, Grenada, Guatemala, Haiti, Honduras, Jamaica, Nicaragua, Netherland Antilles, Panama, St Lucia, St Vincent, Trinidad and Tobago*
	RSAM	*Bolivia, Chile, Colombia, Ecuador, Guyana, Paraguay, Peru, Suriname, Uruguay, Venezuela*
Eastern Asia (EAS)	**China**	*China*
	Japan	*Japan*
	South Korea	*South Korea*
South-East Asia (SEA)	**Indonesia**	*Indonesia*
	Malaysia	*Malaysia*
	RSEA OPA	*Brunei, Singapore, Malaysia, Myanmar, Philippines, Thailand*
	RSEA PAC	*Cambodia, Korea DPR, Laos, Mongolia, Vietnam*
South Asia (SAS)	**India**	*India*
	RSAS	*Afghanistan, Bangladesh, Bhutan, Maldives, Nepal, Pakistan, Sri Lanka*
Middle East North Africa (MNA)	**Middle East and North Africa**	*Algeria, Bahrain, Egypt, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Libya, Morocco, Oman, Qatar, Saudi Arabia, Syria, Tunisia, United Arab Emirates, Yemen*
	Turkey	*Turkey*
Sub-Saharan Africa (SSA)	**Congo Basin**	*Cameroon, Central African Republic, Congo Republic, Democratic Republic of Congo, Equatorial Guinea, Gabon*
	Eastern Africa	*Burundi, Ethiopia, Kenya, Rwanda, Tanzania, Uganda*
	South Africa	*South africa*
	Southern Africa (Rest of)	*Angola, Botswana, Comoros, Lesotho, Madagascar, Malawi, Mauritius, Mozambique, Namibia, Swaziland, Zambia, Zimbabwe*
	Western Africa	*Benin, Burkina Faso, Cape Verde, Chad, Cote d'Ivoire, Djibouti, Eritrea, Gambia, Ghana, Guinea, Guinea Bissau, Liberia, Mali, Mauritania, Niger, Nigeria, Senegal, Sierra Leone, Somalia, Sudan, Togo*

Table 3 - Breakdown of geographic regions used in GLOBIOM

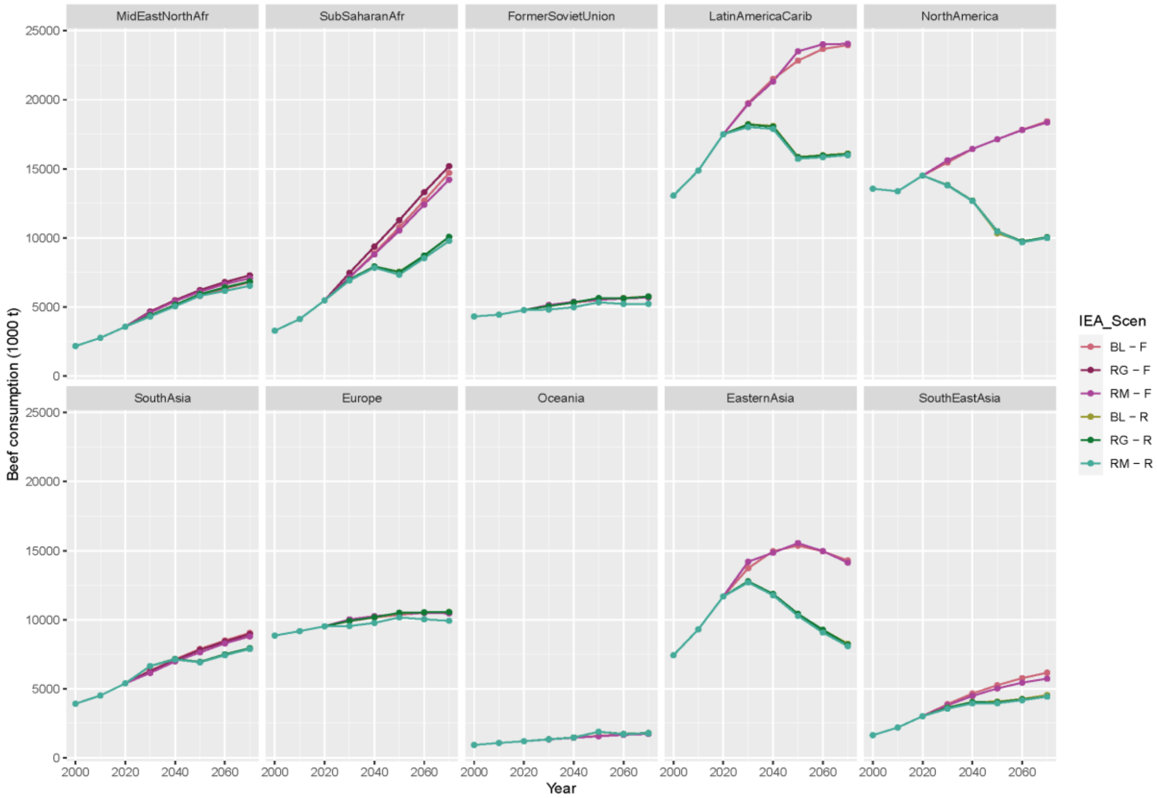

Figure 8 - Beef demand/consumption broken into each macroregion for each scenario from 2000 to 2070. BL-F is the baseline scenario, the suffix -F refers to SSP2 beef demand, -R reduced beef demand, MX switches to mixed systems, LG switches to grazing systems.

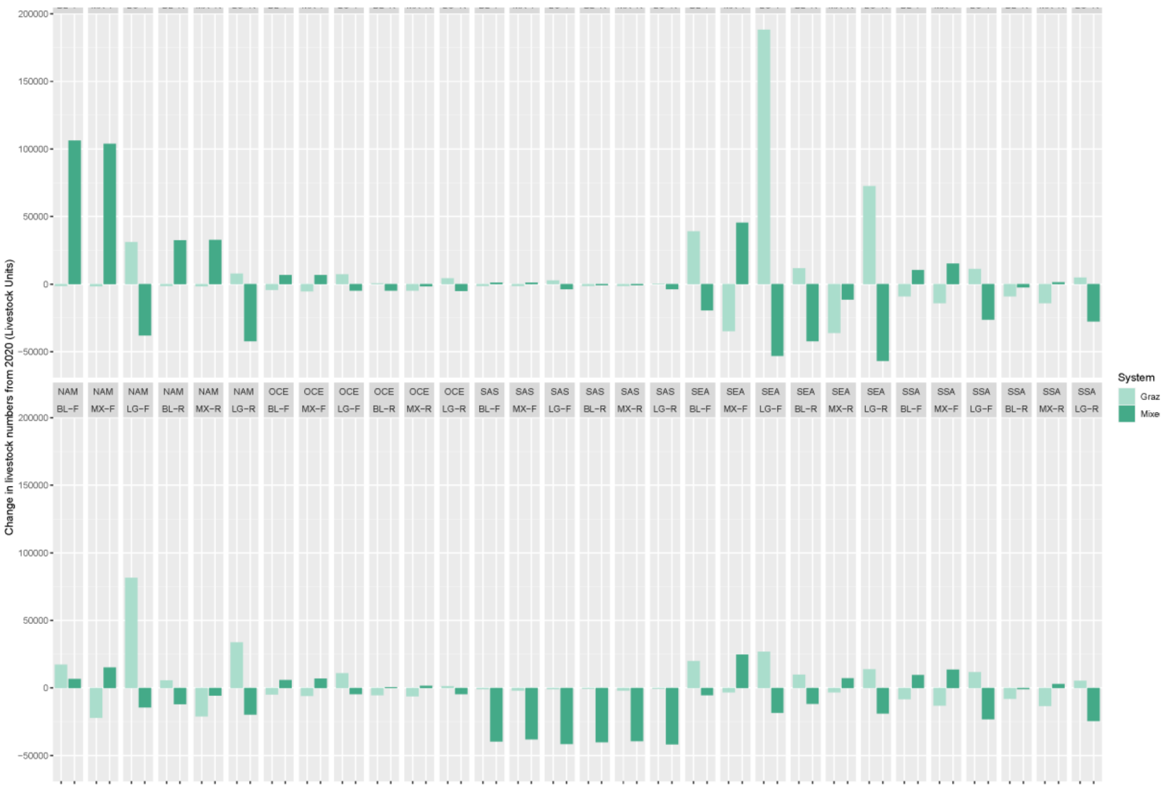

Figure 9 - Regional breakdown of livestock numbers in mixed and grazing systems for all intensity and demand scenarios. BL-F is the baseline scenario, the suffix -F refers to SSP2 beef demand, -R reduced beef demand, MX switches to mixed systems, LG switches to grazing systems.

Additional work

A.1 Targeted Demand Reduction

Using GLOBIOM, different scenarios of demand reduction were explored to determine a more efficient way of targeting demand reductions. Demand for regions that ranked in the top ten for agricultural emissions, overall beef consumption, per capita beef consumption, gross domestic product (GDP) and lowest land productivity for beef production was reduced linearly from 2030 to 2070 to 70%.

A.1.1 Method

A variety of targeted demand reduction strategies were tested to most effectively implement diet reduction strategies with the least disruption globally. Demand for regions that ranked in the top ten for agricultural emissions, overall beef consumption, per capita beef consumption, gross domestic product (GDP) and lowest land productivity for beef production was reduced linearly from 2030 to 2070 to 70%. These scenarios followed the SSP2 framework for population and GDP growth.

Table 4 - Regions targeted for different demand reduction strategies

Reduction scenario	Regions targeted
RD-EMIS	*IndiaReg, ChinaReg, BrazilReg, USAReg, RSAM, RSAS, WesternAf, EU_MidWest, EasternAf, MexicoReg*
RD-GDP	*USAReg, ChinaReg, EU_MidWest, JapanReg, EU_North, EU_South, IndiaReg, MiddleEast, BrazilReg, CanadaReg*
RD-LYLD	*SouthernAf, WesternAf, AustraliaReg, EasternAf, SouthAfrReg, CongoBasin, RSEA_PAC, BrazilReg, RSAM, MiddleEast*
RD-CALO	*BrazilReg, AustraliaReg, USAReg, Former_USSR, RSAM CanadaReg, SouthAfrReg, EU_South, SouthKorea, EU_Baltic*
RD-CONS	*USAReg, ChinaReg, BrazilReg, IndiaReg, RSAM, EU_MidWest, MexicoReg, EU_South, WesternAf, EU_North*

A1.2 Results

By reducing beef consumption in targeted regions, rather than a blanket demand reduction across the globe, we can still achieve gains for both GHG emissions as well as biodiversity. The regions targeted for each strategy can be found in Table 4, a breakdown of countries included in each broad region can be found in Table 3. Figure 6 shows that, relative to the baseline scenario (BL-F; violet), the biggest abatements of GHG and biodiversity are achieved with blanket reductions globally (BL-R; purple) which is expected. Similar gains are seen for scenarios targeting regions with the highest agricultural emissions (RD-EMIS; blue), the highest beef consumption (RD-CONS; orange) and the highest GDP (RD-GDP; green). Targeting regions with the highest per capita

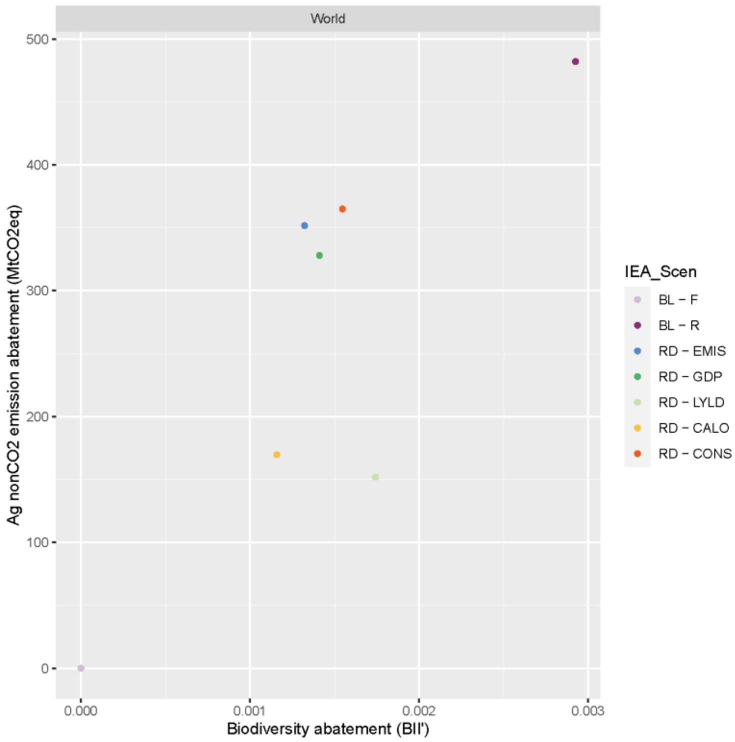

Figure 6 - GHG abatement compared to the baseline scenario vs biodiversity abatement compared to the baseline scenario for the world for the year 2070

consumption (RD-CONS; orange) was the least effective strategy. Targeting regions with the lowest land productivity (RD-LYLD; light green) scored better for biodiversity than most of the other strategies, however, saw fewer gains for GHG emissions.

A.2 Nurturing future climate change research through improved communication: Reflections from the next generation of scholars

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Abstract

The world is a set of complex systems that are affected by climate change across multiple scales. How this is communicated, in particular by the Intergovernmental Panel on Climate Change (IPCC), plays an influential role in setting the research agenda for the next generation of scholars. This essay presents perspectives from an intellectually and culturally diverse group of fellows from the 2020 International Institute on Applied Systems Analysis' Young Scientists Summer Program. We discuss the contribution of the IPCC in shaping (our) research and explore existing gaps that it can cover to nurture climate change research among early-career scientists. Faced with the imminent threat of widespread climate disasters by 2050, we argue that emerging researchers will conduct research differently than in previous decades. Calls for integration, and a need to bridge knowledge and implementation, are already driving a shift toward applied and solutions-oriented research. Using systems analysis as a basis, we demonstrate this with (1) a comparison of select literature from the past thirty years, since the establishment of the IPCC; and (2) examples from recent multi-faceted projects to highlight evolving approaches. We further argue that the IPCC narrative must change to stress optimism and provide an evidence-base for constructive discussions around climate action, by capturing local to global-level insights on best practices related to mitigation and adaptation. We advocate for increased attention to forums for cross-sectoral collaboration and exchange around promising solutions, contextual nuances, and information gaps to enable better prioritization of research for future scholars and policy-makers.

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