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Making the Paris agreement climate targets consistent with food security objectives

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A B S T R A C T

Climate change mitigation is crucial to limit detrimental impacts of climate change on food production. However, cost-optimal mitigation pathways consistent with the Paris agreement project large-scale land-based mitigation for bio-energy and afforestation to achieve stringent climate targets. Land demand from land-based mitigation leads to competition with food production, raising concerns that climate policy (SDG13 – climate action) conflicts with food security objectives (SDG2 – zero hunger). In this study we use the computable general equilibrium model MAGNET and the IMAGE integrated assessment model to quantify the food security effects of large-scale land-based mitigation. Subsequently, we implement two measures to prevent reduced food security: increased agricultural intensification and reduced meat consumption. We show that large-scale land-based mitigation (~600 Mha in 2050) leads to increased food prices (11%), reduced food availability (230 kcal/cap/day) and substantially more people at risk of hunger (230 million) compared to the baseline scenario in 2050, most notably in developing regions. Land-based mitigation also leads to yield increases (9%) and intensified ruminant production (11%). Additional crop yield improvement (9%) and intensification in ruminant production (3%) could prevent the negative effect of mitigation on food security. Introducing a reduction in meat consumption in high- and middle-income regions reduces required crop yield improvement (7%) and ruminant intensification (2%). Our study highlights the importance of transparency about food security effects in climate change mitigation scenarios. In addition, it provides an example of explicitly including measures to limit negative trade-offs in mitigation scenarios. In this way, we show how the Paris agreement can be made consistent with food security objectives and how multiple Sustainable Development Goals can be achieved.

1. Introduction

The Paris Climate Agreement aims to limit global warming to well below 2 degrees above pre-industrial levels and to pursue 1.5 degrees (UNFCCC, 2015). One important reason to limit global warming is the threat it poses to food production, as explicitly stated in the Paris Agreement as well as the original United Nations Framework Convention on Climate Change (UN, 20 January 1994). Indeed, many studies show that climate change is projected to have severe negative impacts on crop yields which leads to reduced food security and highlights the importance of climate change mitigation (Zhao et al., 2017, Rosenzweig et al., 2014; Nelson et al., 2014, Von Lampe et al., 2014). The importance of food security and climate change mitigation is also emphasized by the United Nations Sustainable Development Goals (SDGs) that have specific goals for both: zero hunger (SDG2) and climate action (SDG13). This underlines the importance of achieving the Paris Agreement climate target to ensure food security.

The recently published IPCC special report on 1.5 degree as well as many scenario studies conclude that to limit climate change in line with the Paris agreement requires substantial negative emissions (Riahi et al., 2017; Rogelj et al., 2018, IPCC et al., 2018). These negative emissions are needed to compensate for excessive emissions in the early stages of a decarbonization pathway and for emissions that are difficult to mitigate fully such as in agriculture. In most mitigation scenarios this is realized via large-scale afforestation (Calvin et al., 2014; Humpenöder et al., 2014) and bio-energy with carbon capture and storage (BECCS) (Azar et al., 2010, Van Vuuren et al., 2013). These land-based mitigation technologies require large areas of land which can lead to competition for land between food production and climate change mitigation. As a consequence, food prices might rise causing negative effects on food security (Hasegawa et al., 2015a; Frank et al., 2017; Kreidenweis et al., 2016). Recent studies have shown that by the

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year 2050 the impact of land-based mitigation on food security could even be larger than the negative impact of climate change (Van Meijl et al., 2018; Hasegawa et al., 2018). This raises the concern that the Paris agreement climate target and food security objectives are conflicting and cannot be achieved simultaneously.

However, there are opportunities on the supply and demand side of the food system to limit the negative effects of afforestation and BECCS on food security. The productivity of crop and livestock production systems varies widely between regions, with efficient production in developed regions such as USA and Western Europe as opposed to inefficient production in developing regions such as Sub-Saharan Africa and Southern Asia. Closing yield gaps through improved fertilization, increased irrigation and better management could lead to major increases in productivity (Neumann et al., 2010; Mueller et al., 2012, Van Ittersum et al., 2013). Similarly, livestock systems have substantial opportunity for intensification transitioning from grassland-based systems to mixed systems and through improved animal management (Havlík et al., 2014; Herrero et al., 2016). In this way, increased efficiency on the supply side of the food system would reduce land requirements and thus limit the effect of competition between food production and land-based mitigation on food security. On the demand side of the system, dietary change reducing consumption of livestock products and substituting them by crops has large potential to reduce land requirements because crop production requires less resources (including land) than livestock production (Stehfest et al., 2009; Bajželj et al., 2014; Poore and Nemecek, 2018). A transition to diets with less livestock products would therefore limit the negative effect of land competition on food security.

Solutions to the conflicting nature of climate mitigation and food security have not been formally included in scenario analyses. In this study, we explore how negative effects of land-based mitigation on food security can be prevented by implementing measures on the supply and demand side of the food system – specifically through enhanced agricultural intensification and through dietary change. In this way, we investigate how the climate targets from the Paris Agreement can be made consistent with food security objectives. To quantify this, we perform a model-based analysis using the agro-economic model MAGNET (Woltjer et al., 2014) in combination with the IMAGE integrated assessment model (Stehfest et al., 2014). First, we perform a detailed analysis of the effect of ambitious land-based mitigation on various dimensions of food security. Secondly, we investigate how much agricultural intensification is required to prevent negative effects of land-based mitigation from a food security perspective. Thirdly, we explore how dietary change, through reduced consumption of livestock products, could lower the required level of intensification to maintain food security. For expositional convenience, we make the assessment explicit at the level of six world regions (SI Table 1) in order to highlight regional differences in food security effects and food system changes.

2. Methods

2.1. Models

2.1.1. MAGNET

The Modular Applied GeNeral Equilibrium Tool (MAGNET) (Woltjer et al., 2014) is based on the standard GTAP model (Hertel, 1997), which is a multi-regional, static, applied computable general equilibrium (CGE) model based on neoclassical microeconomic theory. It covers all sectors of the economy (agriculture, manufacturing and services) and all regions and major countries in the world. The core of MAGNET is an input–output model, which links industries in value added chains from primary goods to final goods and services for consumption. Input and output prices are endogenously determined by the markets to achieve supply and demand equilibrium. The agricultural sector is represented in high detail compared to standard CGE models. In MAGNET, factor markets are divided (segmented) into agricultural and non-agricultural labour and capital. This reflects empirical evidence on imperfect mobility of labour (De Janvry et al., 1991), and is thus an improvement above other CGEs which assume perfect mobility. Land is modelled as an explicit production factor described by a land-supply curve, which specifies the relation between total agricultural land supply and the real land price given constraints related to bio-physical availability (potential area of suitable land) and institutional factors (agricultural and urban policy, conservation of nature). The land supply curve is constructed with land availability data provided by IMAGE (Van Meijl et al., 2006; Dixon et al., 2016).

Households are assumed to distribute income across savings and (government and private) consumption expenditures according to fixed budget shares following a Cobb-Douglas (CD) expenditure function. Private consumption expenditures are allocated across commodities by introducing a richer representation of income effects in the demand system. In particular, marginal budget shares vary with the expenditure level using a non-homothetic constant differences of elasticity (CDE) expenditure function. Government consumption is allocated across commodities according to fixed budget shares using a CD expenditure function. Labour, capital and natural resources are fully employed in each region and the aggregated supply of each factor equals its demand (equilibrium). Thus, factor markets are competitive between sectors but not between regions. MAGNET assumes that products traded internationally are differentiated by country of origin following the Armington assumption. This assumption generates smaller and more realistic responses of trade to price changes than implied by models of homogeneous products (Armington, 1969).

2.1.2. IMAGE 3.0

IMAGE 3.0[1] is an integrated assessment modelling framework that simulates the interactions between human activities and the environment (Stehfest et al., 2014), to explore long-term global environmental change and policy options in the areas of climate, land and sustainable development. IMAGE consists of various sub-models describing land use, agricultural economy, the energy system, natural vegetation, hydrology, and the climate system. Most socio-economic processes are modelled at the level of 26 regions. Most environmental processes are modelled on the grid-level at 30 or 5 arc-minutes resolution. Data exchange takes place either through hard-coupling with annual exchange of data, or soft-coupling using an iterative approach of scenario data exchange.

Agriculture, forestry and land-use dynamics are modelled on the grid-level in the IMAGE-Land Management model (Doelman et al., 2018). Demand for crop and livestock products, trends in agricultural intensification and trade dynamics are provided by MAGNET (section 2.1.1). Gridded land-use dynamics are implemented in the dynamic global vegetation model LPJmL to model effects on the carbon and hydrological cycle (Sitch et al., 2003; Bondeau et al., 2007). LPJmL provides data on potential crop and grass yields, land-use change emissions and irrigation water use. The simulation model TIMER represents the energy system with high technological detail for 12 primary energy carrier including bio-energy (Van Vuuren, 2007). Land use for the production of bio-energy as determined by TIMER is implemented on the grid-level in IMAGE-LandManagement. Greenhouse-gas (GHG) emissions from energy, industry and land use are input to the simple climate model MAGICC which emulates complex climate models to calculate global mean temperature change (Meinshausen et al., 2011). Finally, data on food availability, energy use and climate change are input to the GISMO model which calculates changes in human development in relation to the global environment (Hilderink et al., 2008).

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[1] For more background info visit the online IMAGE documentation: http://themasites.pbl.nl/models/image/index.php/Welcome_to_IMAGE_3.0_Documentation.

2.1.3. *Food security indicators*

The Food and Agricultural Organization (FAO) distinguishes four dimensions of food security: availability, access, utilization, and stability (FAO, 1996). In this study we present indicators covering the first two of these dimensions as these are well-represented in the implemented models. The availability dimension is represented by two indicators. First, food availability which is defined as ‘kilocalories per capita per day available for consumption’ as calculated by the MAGNET model. Second, ‘the number of people at risk of hunger’ which is a fraction of the population below a minimum level of dietary energy requirements following a method proposed by the FAO (FAO, 2008). It is calculated using the GISMO model (Hilderink et al., 2008) and is based on food availability data from MAGNET, a coefficient of variation dependent on GDP per capita as proposed by Hasegawa et al. (2015) and region, sex and age specific dietary energy requirements. The food access dimension relates to people's food purchasing power and therefore to food prices, dietary patterns, and income developments (Lele et al., 2016). This dimension is represented by two indicators calculated by MAGNET. First, the average price development of food including primary agricultural products and processed foods, which neglects the income dimension. Second, as a proxy for the food purchasing power we use the price development of a food consumption basket in relation to income developments of a particular income group. Specifically, we calculate the change in food purchasing power for a cereal diet of unskilled workers working in agriculture (cereal sector) and other sectors by subtracting the change in wages from the change in the price level of the cereal diet.

2.2. *Scenario implementation*

2.2.1. *Baseline*

As a baseline scenario we use the ‘1% World’ scenario (ONEPW) from the FOODSECURE project (van Dijk et al., this issue). The four stakeholder-based FOODSECURE scenarios are designed along two dimensions of equality and sustainability. The ‘1% World’ scenario describes a world where wealth is very unequally distributed. However, people do care about sustainability and protection of biodiversity and the environment. There is substantial investment in technology leading to high technological development in the agricultural sector ensuring that everyone is fed and to ensure protection of biodiversity and the environment. We choose this scenario as it describes an unequal world open to sustainability issues such as mitigating climate change. Moreover, in the 1% World scenario food security increases throughout the scenario period highlighting the difference between improving food security in a baseline scenario and negative impacts on food security in a mitigation scenario. In addition, the scenario does not include dietary change which is important to analyse the potential of reduced livestock product consumption.

Globally, wealth increases with average GDP rising from 9500 US$/capita to 21,300 US$/capita (Table 1; Fig. 1). However, regional differences remain very large with GDP in the OECD countries increasing up to 77,400 US$/capita whereas Sub-Saharan Africa achieves 2900 US$/capita. Similarly, global population continues to rise up to 9.6 billion people, with the largest increases in developing regions. The global share of people living in Sub-Saharan Africa and South/South-East Asia increases from 12% to 19% and from 32% to 34%, respectively. Exogenous land productivity improvements are high, especially in developing regions (Sub-Saharan Africa and South/Southeast Asia) as agricultural productivity catches up with global standards related to high technological development. Agricultural land availability is low in developed regions (< 20% of current agricultural land) as large areas are excluded from agricultural expansion due to high environmental protection standards.

2.2.2. *Land-based mitigation*

MAGNET does not model land-based mitigation directly. Therefore, the land area required for land-based mitigation is implemented exogenously and forces a certain reduction in actual agricultural land use over the scenario period (Fig. 3). As a consequence, also the land-supply curve of MAGNET is shifted in line with the implemented land area requirement. Fig. 2 shows a graphic representation of the approach. In the baseline scenario, no distinction is made between total land supply and agricultural land supply. Land demand is shown by the yellow line which intersects in point A providing total land supply (LS) and land price in the baseline scenario (P-base). In a mitigation scenario, total land supply (LS-tot) is distinguished from agricultural land supply (LS-agr) where the difference is accounted for by the land-based mitigation area. The agricultural land supply curve is shifted to the left (less supply) to accommodate the area required (green arrow) leading to a new equilibrium in point B at a higher land price (P-LBM). The restricted land use results in adjusted food prices, food consumption, trade and agricultural efficiency which consequently affect food security (Tabeau et al., 2017).

Areas required for land-based mitigation to achieve the Paris agreement climate target are derived from literature on the SSP scenarios as implemented by several integrated assessment models (IAMs) in a coordinated effort (Popp et al., 2017). Across-model average areas of land-based mitigation (i.e. afforestation and bio-energy with and without CCS) are calculated for the SSP2 scenario combined with an RCP 1.9 climate change target for five world regions as presented in Rogelj et al. (2018). We decided to use this scenario as it is the most ambitious climate-change mitigation target in recent literature which is highly relevant in the current discussions on achieving the 1.5-degree target. We take the average land-based mitigation area from four models: AIM/CGE (Fujimori et al., 2014), GCAM4 (Wise et al., 2014), GLOBIOM (Havlík et al., 2014) and REMIND-MAgPIE (Popp et al., 2014). The land-based mitigation area varies substantially between the models ranging from 410 Mha (AIM/CGE) to 950 Mha (GCAM4) in 2050. These results represent the state-of-the-art of land-based mitigation estimates to achieve stringent climate targets, illustrating the large

Table 1
Macro-economic and land supply assumptions in the baseline scenario, and land-based mitigation assumption in LBM mitigation scenario.

Regions	GDP	Population	GDP per capita	Exogenous land productivity improvement	Share of current agricultural land in total available land (%) in 2010	Average land supply elasticity	Land-based mitigation in 2050 (% agricultural land reduction relative to baseline)
	Average annual growth (%) (2010–2050)						
World	2.9	0.8	2.0	1.0	74	0.08	15
OECD countries	2.2	0.5	1.7	0.7	83	0.02	13
Latin America	3.1	0.8	2.3	0.8	63	0.23	28
Russia/Middle East	3.5	0.9	2.6	1.1	83	0.03	11
Sub-Saharan Africa	3.9	1.9	2.1	1.6	67	0.09	15
South/Southeast Asia	4.6	1.0	3.6	1.4	63	0.18	12
China +	4.4	−0.1	4.5	0.4	89	0.02	12

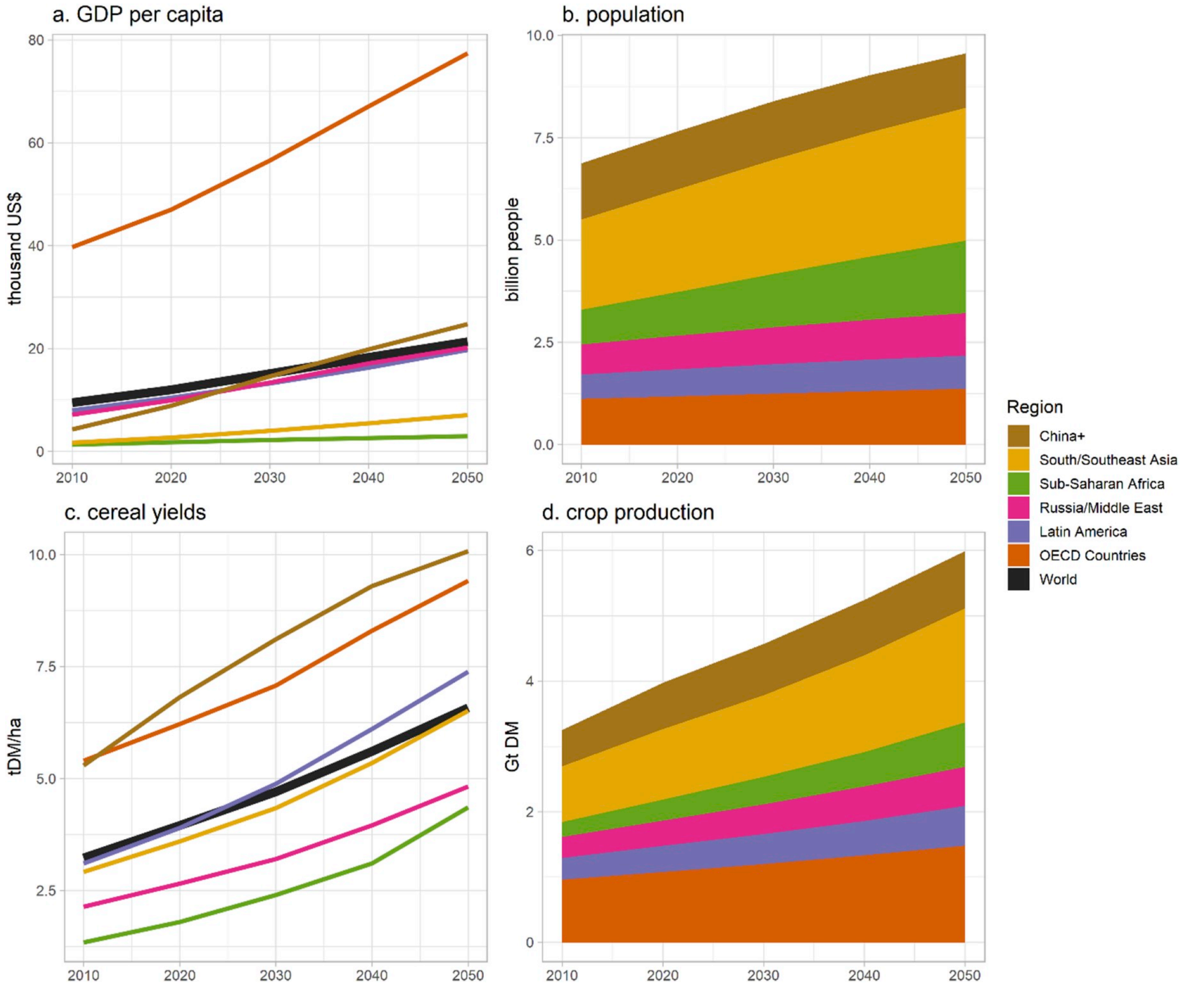

Fig. 1. GDP, population, yield and crop production in the '1% World' (ONEPW) scenario.

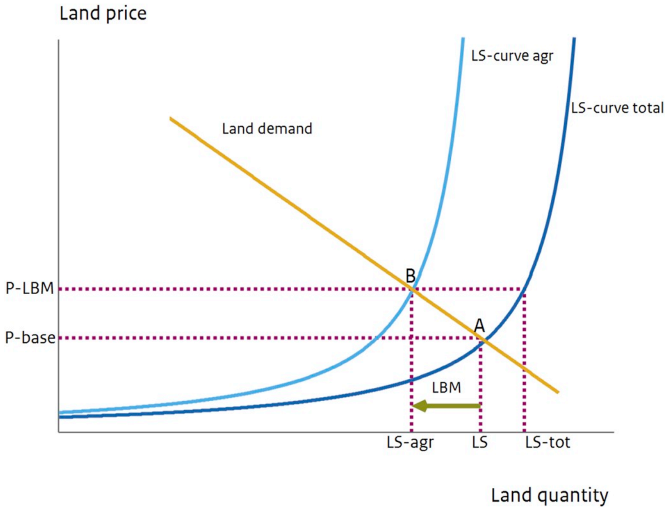

Fig. 2. Graphic representation of total land supply curve (LS-curve total) and agricultural land supply curve (LS-curve agr). In a baseline scenario land demand (yellow line) is in equilibrium in point A with land supply LS and land price P-base. In a mitigation scenario total land supply (LS-tot) is distinguished from agricultural land supply (LS-agr) where the difference is land-based mitigation (LBM, green arrow). The agricultural land supply curve is shifted to accommodate this area leading to a new equilibrium in point B at a higher land price (P-LBM). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

uncertainty that is present in the literature. We use the average reduction in cropland for food and feed and the reduction in grazing land per world region of the four aforementioned models. Globally, this implies a reduction in agricultural land use of ~600 Mha compared to baseline. In absolute terms, the largest change takes place in Latin America with a 28% reduction in agricultural land use compared to baseline levels (160 Mha) (Table 1). The changes in other regions range from 11% to 15%.

2.2.3. *Agricultural intensification*

Additional agricultural intensification, e.g. through closure of the yield gap or increased efficiency in the livestock sector, can prevent negative effects of land-based mitigation on food security. To investigate the level of required intensification, a scenario is designed to keep average agricultural price in a mitigation scenario at the same level as in the baseline scenario in each region. To achieve this, the average agricultural price is exogenously fixed at the baseline level. The level of land productivity in the agricultural sector is endogenously determined (increasing uniformly across all agricultural commodities) within the model run for each region. In this way, we assume that the average agricultural price change caused by mitigation is compensated by additional intensification in the agricultural sectors. The model endogenously determines the level of agricultural intensification required in each region to absorb the effect of land-based mitigation on average agricultural price. By fixing average agricultural prices on baseline levels, also total food availability is similar to the baseline because prices levels are the same as in the baseline and income levels are close to the baseline.

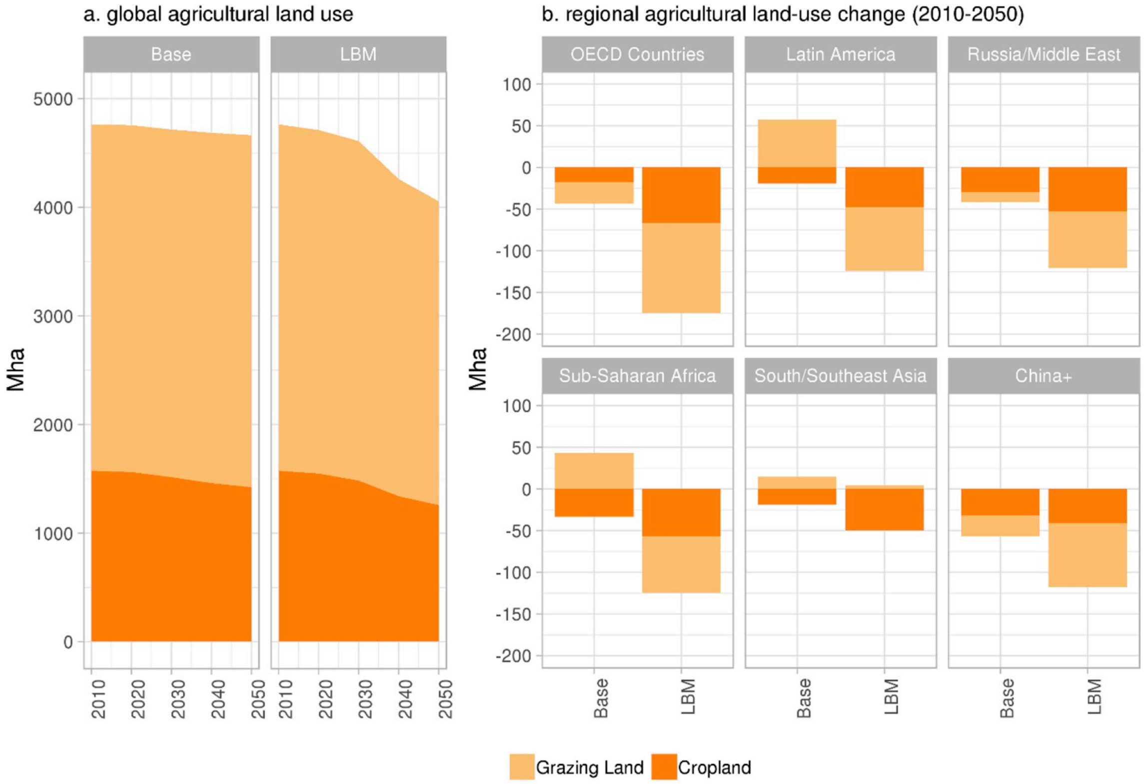

Fig. 3. a) Global cropland for food/feed and grazing land in baseline and LBM mitigation scenario and b) regional land-use change in baseline and LBM mitigation scenario.

2.2.4. *Diet change*

Next to agricultural intensification, changes in diet towards less meat consumption reduces demand for agricultural land, and thus can help to prevent negative effects of land-based mitigation on food security. To test how diet change can help to reduce concerns for food security a low meat diet pattern is introduced. A reduction in the consumption of ruminant and non-ruminant meat is implemented by exogenously prescribing meat consumption. In contrast to the standard settings, consumer preferences concerning meat are endogenously determined. Total food consumption volume is kept constant to assure that the reduction in meat is replaced by consumption of crops and dairy products. To achieve this, consumer preferences concerning overall food consumption are also endogenously determined. The low meat diet changes include strong reductions in China and Latin America (from 640 to 370 kcal/cap/day and from 420 to 270 kcal/cap/day, respectively, from baseline to diet scenario) and moderate reductions in Russia/Middle East and the OECD countries (from 240 to 130 kcal/cap/day and from 560 to 470 kcal/cap/day, respectively, from baseline to diet scenario resp.). No reductions are assumed in Sub-Saharan Africa and South/Southeast Asia as meat consumption in these regions is already comparatively low. The implemented changes are modest compared to the recommended meat consumption of 92 kcal/cap/day in the recently proposed healthy diet from sustainable food systems by Willett et al. (2019).

2.2.5. *Scenario definitions*

Four scenarios are implemented in this study (Table 2). As described in section 2.2.1, the ONEPW scenario is used as a baseline (Base). To investigate the effect of land-based mitigation on food security, the baseline is combined with a prescribed land area for land-based mitigation derived from IAMs (section 2.2.2) in the Land-Based Mitigation (LBM) scenario. In the LBM-Yield scenario yields are endogenously increased to achieve food prices as in the baseline scenario (section 2.2.3). Additional diet change is implemented in the LBM-Diet-Yield scenario and yields remain endogenously determined to achieve baseline food prices (section 2.2.4). Land-based mitigation, agricultural intensification and dietary change are implemented in the MAGNET model; subsequently, trends in agricultural demand, production, intensification and trade are implemented in IMAGE to determine spatial explicit land-use dynamics and number of people at risk of hunger (Section 2.1). As the focus of this paper is the impact of land-based mitigation on food security we do not consider negative effects of climate change on food security.

Table 2
Table with definitions of implemented scenarios, land-based mitigation is based on several IAM 1.5 degree scenarios (see section 2.2.2).

Scenario name	Start settings	Land-based mitigation	Yield increase to achieve baseline food prices	Preference change for low-meat diet
Base	ONEPW	–	–	–
LBM	ONEPW	~ 600 Mha	–	–
LBM-Yield	ONEPW	~ 600 Mha	Yes	–
LBM-Diet-Yield	ONEPW	~ 600 Mha	Yes	Yes

3. Results

3.1. *Food security effects of land-based mitigation*

In the baseline scenario major improvements in food security are achieved. The availability dimension of food security shows an increase of global average food availability by 230 kcal/cap/day (Fig. 5a) and a decrease in the number of people at risk of hunger of 402 million (Fig. 6), from 2010 to 2050. Regionally, the largest changes take place in the developing regions with strong increases in food availability in Sub-Saharan Africa and South/Southeast Asia (500 and 560 kcal/cap/

day resp. from 2010 to 2050) driven by high increases in per capita income (Fig. 1a) and by strong technological growth in crop productivity, especially in developing regions that are catching up with developed regions. This trend is also reflected in the number of people at risk of hunger which decreases by 254 million people in South/Southeast Asia from 2010 to 2050. In Sub-Saharan Africa, characterised by low GDP per capita growth, the reduction is only 35 million people from 2010 to 2050 as the average food availability is still lower than in other regions, and because the fraction of people at risk of hunger is reduced but the absolute number of people is strongly increasing. China, with a much higher GDP per capita growth, shows a reduction in number of people at risk of hunger, even though food availability is going down slightly. This is possible as the coefficient of variation decreases with the high increase in GDP resulting in improved distribution of food across the population.

The access dimension of food security also improves in the baseline scenario. Aggregated food prices show a moderate decrease of 4% by 2050 on the global level. Regionally, stronger decreases take place most notably in Latin America and Russia/Middle East (14% and 19% resp. by 2050). Increases in food prices occur in South/Southeast Asia and China, among others related to continued population growth in combination with limited possibilities to expand agricultural land (Table 1). At the same time, purchasing power more than doubles for unskilled workers in other sectors than agriculture as a result of increasing wages in combination with reducing food prices in most regions (Fig. 5d). Unskilled workers in the cereal sector experience less improvement in food purchasing power than their equivalent in other sectors due to lower increase in wages that are partly induced by the lower agricultural prices and the segmentation of the labour market (Fig. 5c).

Land-based mitigation in the LBM scenario leads to increased land scarcity, from a food production perspective, which negatively affects food prices and food security. As a consequence, the improvements in food availability are reduced with global average food availability 100 kcal/cap/day lower in LBM in 2050 compared to the baseline. The same effect takes place in the number of people at risk of hunger, with 232 million more people at risk of hunger in LBM in 2050 compared to the baseline. Regionally, reductions in food availability are fairly similar between regions (3%–5% in LBM in 2050 compared to Base). However, the number of people at risk of hunger is unevenly distributed with 181 million people extra in Sub-Saharan Africa and South/Southeast Asia compared to 51 million people in other regions (LBM compared to Base in 2050). This is due to the relatively low food availability compared to other regions which increases the number of people below the threshold indicating risk of hunger. Globally averaged food prices go up by 11% in LBM compared to the baseline in 2050, with a very strong increase in South/Southeast Asia (32%) due to the tight land market. Purchasing power goes down for all unskilled labour mainly driven by the higher food prices.

Land-based mitigation also affects crop and livestock intensification through price-induced substitution effects. As land prices increase relatively to wages and capital rents, land will be substituted by capital and labour in agriculture and consequently leads to a higher land productivity. This partially counterbalances the negative effect of land-based mitigation on food security. Globally averaged crop yields in 2050 increase due to intensification by an additional 8% in the LBM scenario compared to the baseline (Fig. 7). This is caused by the increased land competition and induced higher land prices due to land-based mitigation which causes a 13% reduction in agricultural land in LBM compared to Base. Crop yields increase more due to intensification with further reduction in agricultural land. For example, in 2050 in Latin America agricultural land is reduced by 22% and yields increase by 21% in LBM compared to the baseline, while in South/Southeast Asia agricultural land is reduced by 11% and yields increase by 5%.

Production of ruminant products such as meat and dairy is predominantly grass-based and responsible for two thirds of agricultural land use. Total ruminant production (in ton dry matter) relative to grassland area provides an indication of ruminant production system efficiency. In 2050 in the LBM scenario, ruminant efficiency increases by 11% compared to baseline due to reduced land availability. Between regions, efficiency increases vary from 6% in South/Southeast Asia to 18% in Latin America in 2050 in LBM compared to the baseline, roughly at similar levels as crop yield increases. In Sub-Saharan Africa however, the ruminant efficiency increase is substantially higher with 12% compared to a crop yield increase of 6% in 2050 in LBM compared to the baseline. This is related to low initial ruminant efficiency.

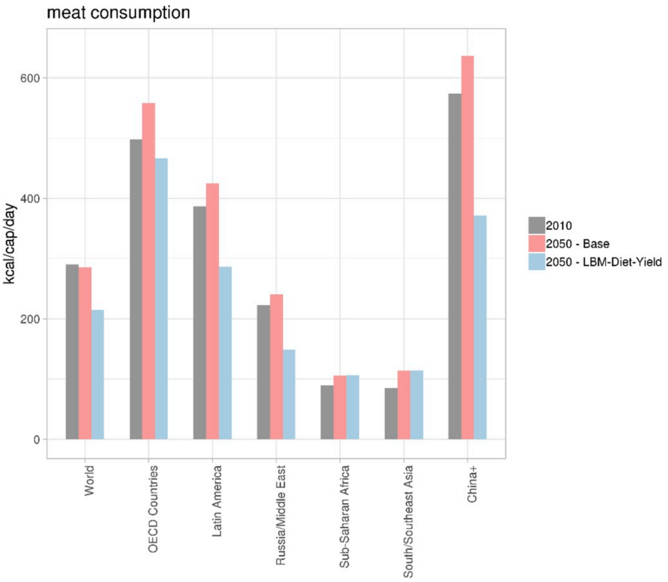

Fig. 4. Meat consumption changes as implemented in the LBM-Diet-Yield scenario.

3.2. Preventing negative effects of land-based mitigation on food security

To prevent negative effects of land-based mitigation on food security, we increase agricultural intensification until food prices and food availability are at the same level as the baseline scenario. It is shown that, in 2050 on the global level, an additional 9% increase in crop yields and an additional 3% increase in ruminant efficiency is sufficient to prevent negative food security impacts of land-based mitigation, as is shown by comparing the LBM-Yield scenario to the LBM scenario in (Fig. 7). The larger increase in crop yields compared to ruminant efficiency is due to the relatively higher cost share of cropland compared to grassland in agricultural prices. As our exercise returns food prices to baseline level through increases in capital and labour to boost land productivity, more production factors are needed in the crop sector than the livestock sector leading to higher increases in crop yield than in ruminant efficiencies. Regionally, additional crop yield increases range from 5% in China to 12% in the OECD countries (LBM-Yield compared to LBM in 2050). Changes in ruminant efficiency range from a 9% increase in Latin America to a 0.5% decrease in efficiency in OECD countries (LBM-Yield compared to LBM in 2050). The decrease in OECD countries is also due to the abovementioned effect that the majority of production factors is needed to stimulate crop productivity.

To investigate how diet change helps to limit negative effects on food security we reduce meat consumption and subsequently analyse how much agricultural intensification is still required to achieve food prices and food availability as in the baseline scenario. On the global level, the required crop yield increase is 2% lower and the required ruminant efficiency increase is 1% lower in the LBM-Diet-Yield scenario compared to the LBM-Yield scenario in 2050. The beneficial effects are more substantial on the regional level, most notably in Latin America and China as in these regions we implement the largest reductions in

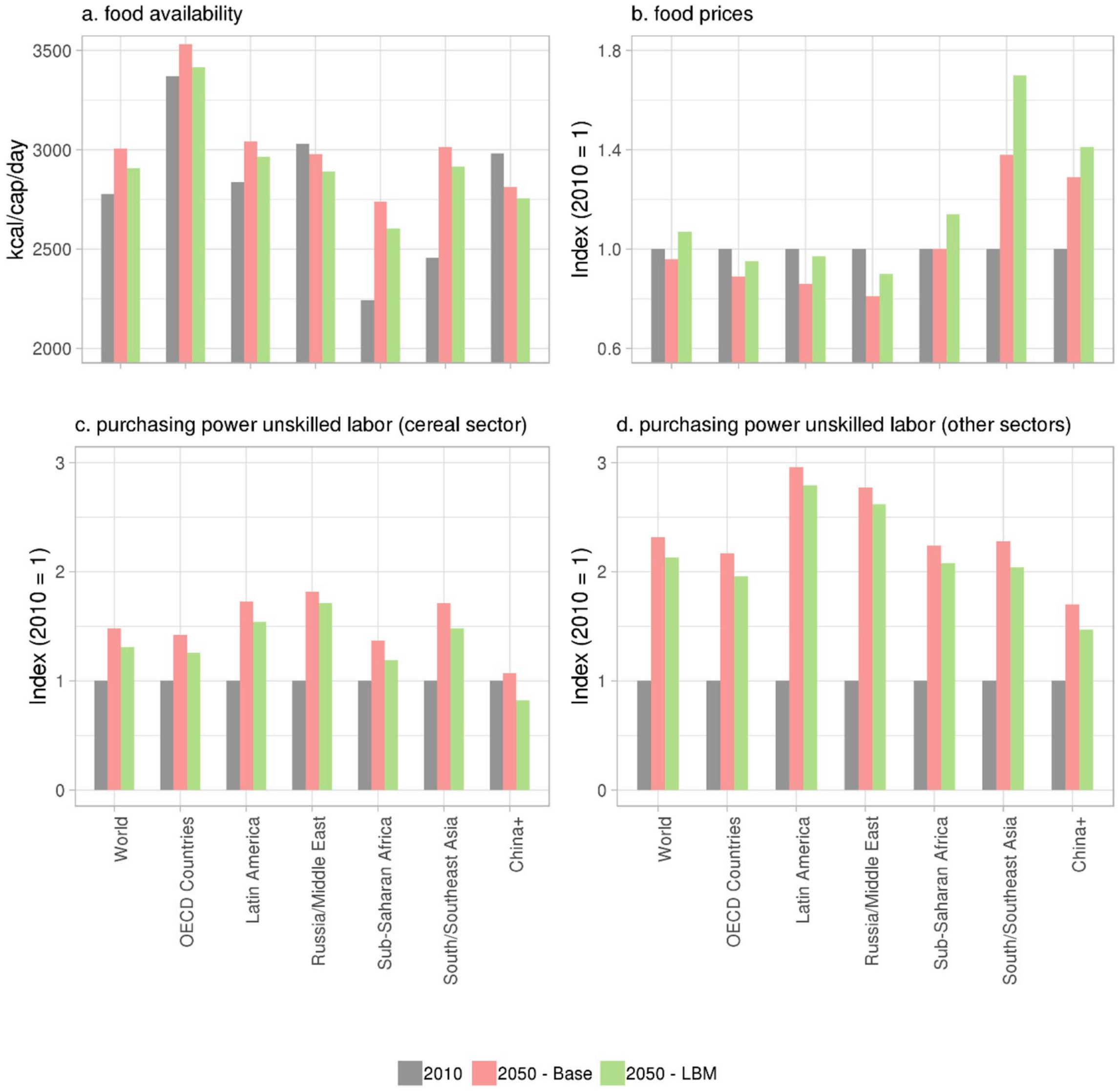

Fig. 5. Global and regional a) food availability, b) food prices, purchasing power of unskilled labour in c) the cereal sector and in d) other sectors in the baseline and LBM scenarios for 2010 and 2050.

meat consumption (Fig. 4). In Latin America, little additional improvement in crop yield or ruminant efficiency is required to achieve baseline food security (< 2% when comparing LBM and LBM-Diet-Yield in 2050). In China, crop yield improvements required to achieve baseline food prices and food availability in LBM-Diet-Yield in 2050 are even below those in the LBM scenario, however improvements in ruminant efficiency are not substantial. In Sub-Saharan Africa and South/Southeast Asia, crop yields and ruminant efficiencies slightly increase as they do not experience reduced demand internally, but do slightly increase their export of crops due to increased demand from other regions. Counterintuitively, Russia/Middle East also shows an increase in both crop yields and ruminant efficiency. This is due to increased crop exports and a substantial shift from meat to dairy products, respectively. The shift to dairy products results in increased ruminant efficiency as dairy is substantially more productive than meat per unit of grassland.

4. Discussion

Land-based mitigation as implemented in this study is based on four IAMs that assume uniformly implemented carbon price globally, i.e. in the energy, agriculture and forestry sectors. These results generally represent the most cost-optimal solution to climate change mitigation, however whether the scale at which BECCS and afforestation are applied in response to this uniform carbon price will in reality be feasible from a governance and a social-acceptance perspective is an open question (Nemet et al., 2018). Assuming that large-scale land-based mitigation is realistic, the results of this paper show that a cost-optimal approach across all sectors has significant trade-offs with food security. This is confirmed by other studies with IAMs that have assessed the effect of land-based climate change mitigation reporting significant rises in food prices (Calvin et al., 2014; Kreidenweis et al., 2016), decreased food availability and increasing numbers of people at risk of hunger (Hasegawa et al., 2015a; Frank et al., 2017; Hasegawa et al., 2018, Van Meijl et al., 2018). The sensitivity of food consumption to changes in food prices, i.e. the food demand elasticity, is highly debated. Empirical analyses show that food demand elasticities are low, most notably in high-income countries (Muhammad et al., 2011). Elasticities vary substantially between agro-economic models, with some models assuming zero elasticity (MAgPIE (Lotze-Campen et al., 2008)) or zero elasticity of all staple crops (GCAM (Calvin et al., 2014)). A model intercomparison of 9 agro-economic models showed that the elasticity of food demand to food price change in MAGNET is in the middle range compared to other models (Nelson et al., 2014), however

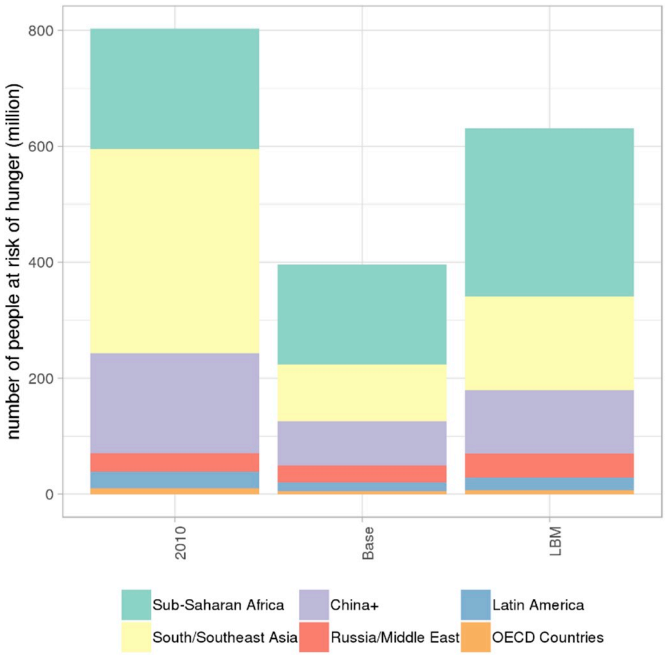

Fig. 6. Number of people at risk of hunger in 2010, in 2050 in the baseline scenario and in 2050 in the LBM scenario.

especially under large shocks such as the land-based mitigation areas implemented in this study it is uncertain how food demand will exactly be affected. This implies that uncertainties in food demand elasticities play a fundamental role in food security assessments and therefore require continued research as well as transparent communication of assumptions.

Our results show that additional agricultural intensification can prevent negative effects of land-based mitigation on food security. Historically, cereal yields have shown a continuous linear increase since 1961 (SI Fig. 2) (FAOSTAT, 2017), with a doubling over the 1970–2010 period. An additional increase of 9% in crop yields (LBM compared to LBM-Yield in 2050) is required on the global level to maintain food security at baseline levels, which is equal to 4 years of historical cereal yield increases. Regionally, historical cereal yield increases in 1970–2010 ranged from 53% in Russia/Middle East to 154% in China +. The regional additional crop yield increases required to maintain food security ranges from 5% to 12% which is well within this range. These yield increases do need to take place in addition to baseline yield increases. The ONEPW scenario used in this scenario shows an increase in yields from 2010 to 2050 of slightly over 100%. This implies a continuation of historical trends which is in line with the scenario assumption on high investment in technological developments leading to strong increases in agricultural productivity. Compared to other scenarios in the literature these yield projections are on the high end (Popp et al., 2017; Alexandratos and Bruinsma, 2012; FAO, 2018), but baseline projections of yields are very uncertain and the high yields are consistent with the technology-oriented world view in this ONEPW scenario. It is widely acknowledged that there is major potential for increased production in developing regions with large yield gaps (Neumann et al., 2010; Mueller et al., 2012, Van Ittersum et al., 2013); for developed countries, however, studies argue that yield levels will not continue to increase at historical rates, but rather level off due to biological limits of crop productivity (Grassini et al., 2013). Negative impacts of climate change, which are very uncertain and not included in this study, might further reduce the possible future increase in crop yields (Zhao et al., 2017, Rosenzweig et al., 2014). In conclusion, although baseline projections of yields are uncertain, the additional yield requirements to ensure food security are modest compared to historical yield trends.

Ruminant efficiencies have historically shown a linear increase with a total increase of 60% over the period 1970–2010 (SI Fig. 3; SI Fig. 4). In the scenario period, improvements continue linearly with a 50% improvement from 2010 to 2050. The required intensification to maintain food security is modest in our results (3% in LBM-Yield compared to LBM). Livestock system efficiencies vary widely, most notably between developed and developing regions (Bouwman et al., 2005; Herrero et al., 2013), indicating high potential for efficiency improvements. This is confirmed by studies focusing on climate mitigation benefits of increased livestock efficiencies (Havlík et al., 2014; Herrero et al., 2016). On the other hand, a substantial share of ruminant production takes place on marginal lands through traditional, smallholder production systems (Mcdermott et al., 2010) where intensification might be infeasible. Still, as our results only show a modest acceleration in ruminant efficiency improvements our estimates seem to be relatively conservative compared to the potential of livestock intensification discussed in the literature. Our results show more intensification in the crop sector than in the livestock sector even though the latter also has large intensification potential. Part of the reason for this is that we considered intensification in both sectors simultaneously through changing land productivity. Follow-up research might consider both options separately to identify differences between these approaches.

Multiple studies have shown the benefits of reduced livestock product consumption as it has large potential to reduce land requirements because crop production requires less resources (including land) than livestock production (Stehfest et al., 2009; Bajželj et al., 2014; Poore and Nemecek, 2018; Frank et al., 2019). This study confirms that reduced meat consumption also helps to reduce impacts on food security through reduced land demand. On the global scale, the effects in our results are limited as we only reduce meat consumption in high- and middle-income countries, while meat consumption still increases moderately in low-income countries. In regions with large changes however (Latin America, China +), the effects are also large leading to lower agricultural intensification requirements. As our assumptions are above recommended intake levels in all high- and middle-income regions (Willett et al., 2019) (section 2.2.4), the role of diet change could in fact be larger than presented in this study. On the other hand, a major uncertainty is how a lifestyle change such as reduced meat consumption can in practice be achieved.

5. Conclusions

Climate change mitigation is important to prevent negative impacts of climate change on food production. However, in this study we show that large-scale land-based mitigation in cost-optimal pathways consistent with the Paris climate agreement also leads to negative impacts on food security due to competition for land. On the global level, we show that both the availability and the access to food, two important dimensions of food security, are significantly reduced compared to baseline levels due to large-scale land-based mitigation. On the regional level, especially developing regions are affected as the number of people at risk of hunger increases most notably in Sub-Saharan Africa and South/Southeast Asia. Possible solutions to limit the negative effects of land-based mitigation on food security are additional agricultural intensification and dietary change. We explicitly include these options in our scenarios, showing that a modest increase in crop yields and livestock efficiency can prevent negative effects on food security, although the feasibility of future yield increases remains an important uncertainty. Reduced meat consumption lowers the required improvements, most notably in regions where meat consumption is currently relatively high.

Achieving food security for all (SDG2) as well as preventing climate change (SDG13) are important aspects of a sustainable future as defined by the Sustainable Development Goals. Both our study and various

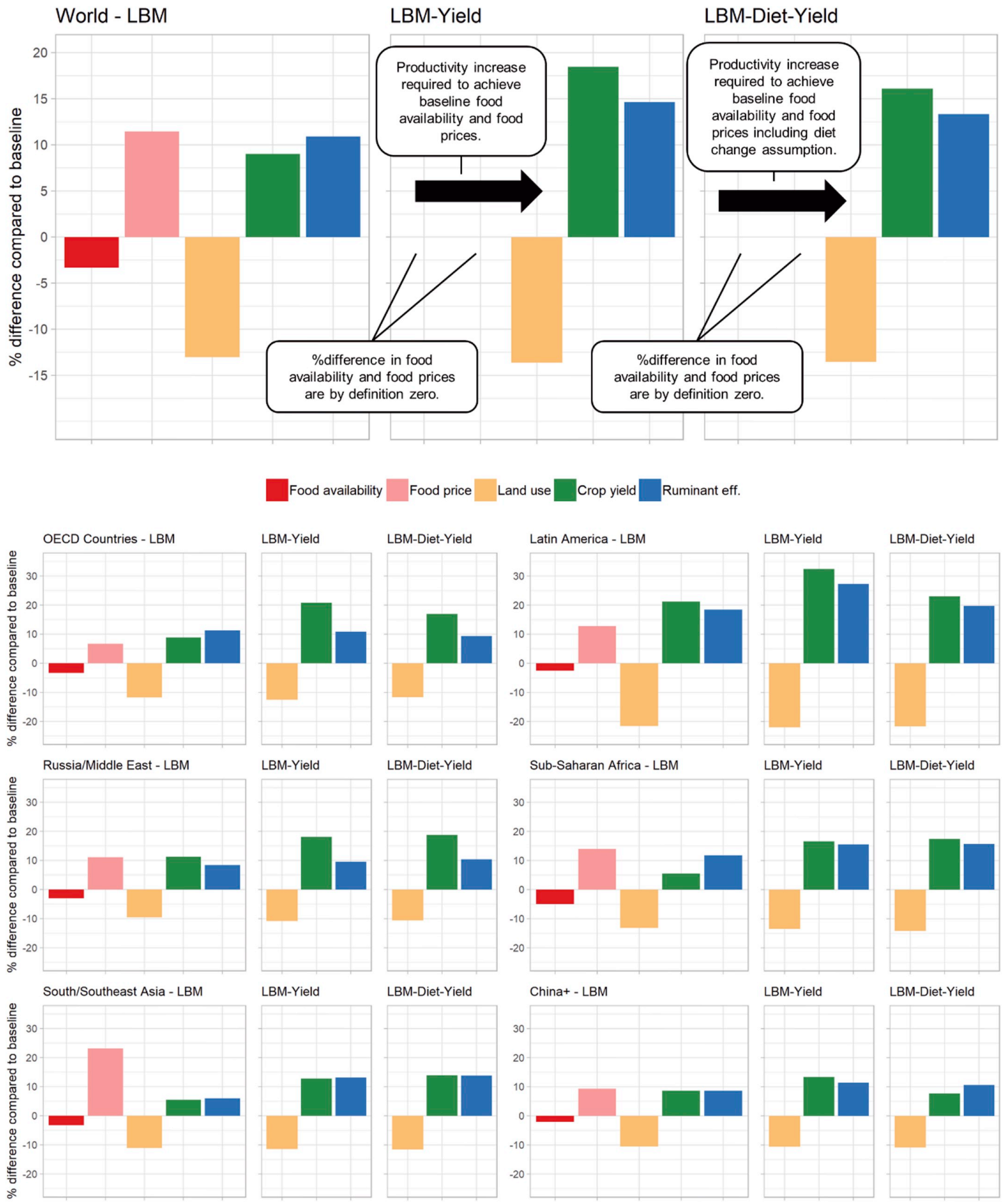

Fig. 7. Percentage difference in food availability, food prices, land use, crop yields and ruminant efficiency (ruminant meat and dairy production divided by grassland area) for the LBM, LBM-Yield and LBM-Diet-Yield scenarios compared to the baseline scenario on the global and the regional level. Comparing LBM to LBM-Yield shows the increases in yield and ruminant efficiency required to achieve zero change in food availability and food prices compared to the baseline scenario. Comparing LBM to LBM-Diet-Yield shows the increases in yield and ruminant efficiency required to achieve zero change in food availability and food prices compared to the baseline scenario when additional diet change is assumed.

other studies have identified the negative effects on food security that arises in cost-optimal pathways that mitigate climate change. Scenario studies need to be transparent about this trade-off and where possible include explicit policy to prevent negative effects. Our study provides an example of explicitly including measures to prevent negative trade-offs in scenarios. In this way, we show how pathways in line with the Paris agreement can be made consistent with food security objectives and how multiple Sustainable Development Goals can be achieved.

Conflicts of interest

There are no conflicts of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gfs.2019.04.003.

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