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Supplemental Paper to The 2019 Global Consultation Report of the Food and Land Use Coalition
Growing Better: Ten Critical Transitions to Transform Food and Land Use

Towards sustainable food and land-use systems: Insights from integrated scenarios of the Global Biosphere Management Model (GLOBIOM)

Authors:

Andre Deppermann, Hugo Valin, Mykola Gusti, Frank Sperling, Miroslav Batka, Jinfeng Chang, Stefan Frank, Petr Havlík, Pekka Lauri, David Leclère, Amanda Palazzo, Marcus Thomson, Michael Obersteiner

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1. Context: The shifting demands for food and land-use

In many ways the history of agriculture has been a success story. The ability to modify the environment, grow crops, and domesticate livestock, have allowed societies to become more complex and contributed to the expansion of civilizations (Lev-Yadun, Gopher, and Abbo 2000; Zeder 2011). The increase in food production during the 20th century eliminated or at least greatly reduced the risk of famines in most world regions. At the global scale food production outpaced population growth. The progress, that was made during the Millennium Development Goals (MDGs) towards the objective of halving the prevalence of hunger between 1990 and 2015, nurtured the ambition of the successive Sustainable Development Goals (SDGs) to achieve universal food security by 2030.

The demands on and context for agriculture are however changing. There is some debate whether with the arrival of agriculture and despite the ultimate increase in caloric supply and food security, the quality of diet may have deteriorated during the transition from hunter gather societies (e.g. Larsen 2002). The legacy of these choices are still present in our discussions about the relationship between agricultural produce, diets and human health. It is not only about supplying sufficient calories per capita, it also about improving diets. The recent declining trends in prevalence of hunger that were observed over the last decades have recently grinded to a halt. The absolute number of people suffering from hunger is increasing again, over 820 million people experience chronic hunger today, while in parallel a worldwide rise in obesity is observed (FAO et al. 2019).

Not only are food systems confronted with the shifting diets of a growing population due to increasing affluence and global inter-connectedness, but they also play a central role in addressing key environmental challenges. Agricultural activities are vulnerable to climate change, while according to recent estimates, agriculture alongside forestry and other land-use contributes around 23 percent of the global total greenhouse gas emissions from human causes (IPCC, 2019). Agricultural activities and land-use changes are also a major driver of global biodiversity loss, which due to human activities is now estimated to exceed the natural background rate of extinction 1000 fold (Pimm et al. 2014).

With human activities now dominating earth system processes at a global scale (Crutzen 2002), strategic decisions on land-use play a central role in transitions towards sustainable development pathways. Agricultural activities have to be viewed as embedded within the broader food and land-use systems, which have to be transformed (Schmidt-Traub, Obersteiner, and Mosnier 2019; Sachs et al. 2019) if we want to meet the challenges of the Anthropocene (Crutzen 2002) where humankind holds the key sustaining or undermining the earth's life support systems (Rockström et al. 2009).

The report of the Food and Land-Use Coalition argues that 10 transitions need to take place to put food and land-use systems on a sustainable path (FOLU 2019). IIASA's Global Biosphere Management Model (GLOBIOM) has previously been employed to investigate nexus issues relating to food security, land-use, climate change and environment (Valin et al. 2013; Havlík et al. 2014; Frank et al. 2018;

Leclère et al. 2018; Hasegawa et al. 2018). The following report describes how GLOBIOM has been applied to contribute with an integrated assessment modeling approach to the analytics of the FOLU report.

2. The Global Biosphere Management Model: An Overview

GLOBIOM is a global recursive dynamic bottom-up partial equilibrium model integrating the agricultural, bioenergy and forestry sectors (Havlík et al. 2014; 2011). It employs a linear programming techniques based on the spatial equilibrium approach developed by Takayama and Judge (1971). Based on a welfare maximizing objective function an agricultural and forest market equilibrium is computed subject to resource, technology, demand and policy constraints.

For detailed assessment of forest dynamics, in particular in response to climate change mitigation policies, GLOBIOM is often linked with the G4M model (Kindermann et al. 2006), a global forest model which supplies spatially explicit simulations of the forest sector and projected emissions from land-use change. Lauri et al. (2019) provide a detailed description of the representation of the forest sector in GLOBIOM and the linkage to G4M. For economy wide integrated climate change mitigation assessments, GLOBIOM/G4M integrated assessment modeling has been coupled to the energy system model MESSAGE (Riahi et al. 2012), which provides the trajectories for carbon prices and biomass for energy demand over time (Fricko et al. 2017).

In the version of GLOBIOM used for the FOLU report, results are initially calculated for 37 regions, either representing large countries or country aggregates, and then aggregated to 10 global regions (Middle East and North Africa, sub-Saharan Africa, the former Soviet Union, Latin America and Caribbean, North America, South Asia, Europe, Oceania, Eastern Asia, and Southeast Asia). A market equilibrium is established for each product and region based on endogenous adjustments in market prices and demand and supply quantities as well as trade. The model calculates the optimal land-use allocation by maximizing consumer and producer surplus.

GLOBIOM is calibrated to the FAOSTAT database, provided by the Food and Agriculture Organization of the United Nations (http://www.fao.org/faostat/en/#data) for the year 2000 (average 1998 - 2002) and is solved in 10-year time-steps until 2050. The starting conditions for each time period are informed by the solutions of the simulations for the previous period. In addition to the market balance constraint which ensures that regional production plus imports equals regional consumption plus exports, additional constraints can be added (e.g. on land-use changes from one type to another) to examine the effect of particular strategies on the results.

On the demand side, a representative consumer is modeled for each region mimicking the behavior of the aggregate population for a respective region. Food demand projections are based on the interaction of three different drivers: population growth, income per capita growth, and response to prices. Price effects are endogenously computed while the first two drivers are exogenously introduced into the model.

On the supply side, the model is built on a spatially explicit, bottom-up set-up. The basis is a detailed disaggregation of land into so-called *Simulation Units*. Simulation Units are clusters of pixels that belong to the same country, have similar altitude, slope and soil characteristics and cannot exceed the size of 0.5° x 0.5° (Skalský et al. 2008). In the model version applied for the work at hand, simulation units are re-aggregated to 2° x 2° cells, disaggregated by country boundaries and by three agro-ecological zones.

Nine different land cover types are considered in the standard model: cropland, grassland, managed forest, unmanaged forest, short rotation plantations, other natural vegetation, other agricultural land, wetland and non-relevant land. Transition is modeled between the first six land cover types, while the remaining three are assumed to be constant over time.

Economic activities are associated with cropland, grassland, managed forest and short rotation plantations. In principle, each spatial simulation unit can contain all nine land cover types. Land conversion over the simulation period is endogenously determined for each spatial simulation unit within the available land resources. Such land use change movements imply conversion costs, which are increasing with the area of land that is converted and which are taken into account in the producer optimization behavior. Land conversion possibilities are further restricted through biophysical land suitability and production potential, as well as through a matrix of potential land cover transitions. The latter defines which land type can be transformed into which other land type.

For the model version applied in the FOLU project several adjustments have been made to the model, including the introduction of new land cover classes (i.e., afforested land, restored land, abandoned land). Furthermore, seafood, aquatic and oceanic based production systems have been introduced as an additional modeling component to allow for an examination how shifts in the production and consumption-based proteins may affect land-use dynamics.

GLOBIOM represents globally 18 major crops, i.e. barley, beans, cassava, chickpeas, corn, cotton, groundnut, millet, palm oil, potato, rapeseed, rice, soybean, sorghum, sugarcane, sunflower, sweet potato, wheat.

Land use data for crops are based on FAOSTAT statistics, which are introduced at the national level and which are spatially allocated using data from the Spatial Production Allocation Model (SPAM; http://mapspam.info/), which provides estimates of crop distributions (You and Wood 2006). Production technologies, as indicated by SPAM data, are specified through fixed proportions production functions. Four different management systems (irrigated – high input, rainfed – high input, rainfed – low input and subsistence) are simulated by the biophysical process-based crop model EPIC (Williams 1995; Izaurralde et al. 2006) and fitted to national averages of FAOSTAT yield data for around 2000 (average 1998 - 2002). Over the course of a scenario, regional yields are changing with changes in the management system, spatial reallocation, or an exogenous component representing technical change.

The representation of irrigated cropland production systems considers both the biophysical suitability and irrigation water requirements of crops at a monthly level which is simulated by EPIC and harmonized with the country-level statistics for water withdrawn for irrigation available from AQUASTAT, FAO's global information system on water resources and agricultural water management.(FAO 2017; Palazzo et al. 2019) GLOBIOM represents the spatial and temporal nature of water demand and supply by building on the work from Sauer et al. (2010) to consider the suitability of irrigation systems and crops by considering the biophysical conditions as well as the physical and economic suitability of crops for irrigation (Palazzo et al. 2019; Pastor et al. 2019, 2014; Palazzo et al. 2017). The water balance for irrigation is spatially explicit for both the irrigation water demand and water supply availability and takes into account the source of water used for irrigation (surface water and groundwater), seasonality of water, environmental flow requirements, and the socioeconomic and climate change impacts on water availability and demand.

The livestock sector component of the model uses the International Livestock Research Institute (ILRI)/FAO production systems classification. Four production systems are considered: grassland based, mixed, urban and other. The first two systems are further differentiated by agro-ecological zones: arid/semi-arid, humid/sub-humid and temperate/tropical highlands. Monogastrics are split into industrial and smallholder farming systems. Eight different animal groups are considered: bovine dairy and meat herds, sheep and goat dairy and meat herds, poultry broilers, poultry laying hens, mixed poultry and pigs. Animal numbers are at the country level consistent with FAOSTAT. The livestock production system parameterization relies on the dataset by Herrero et al. (2013).

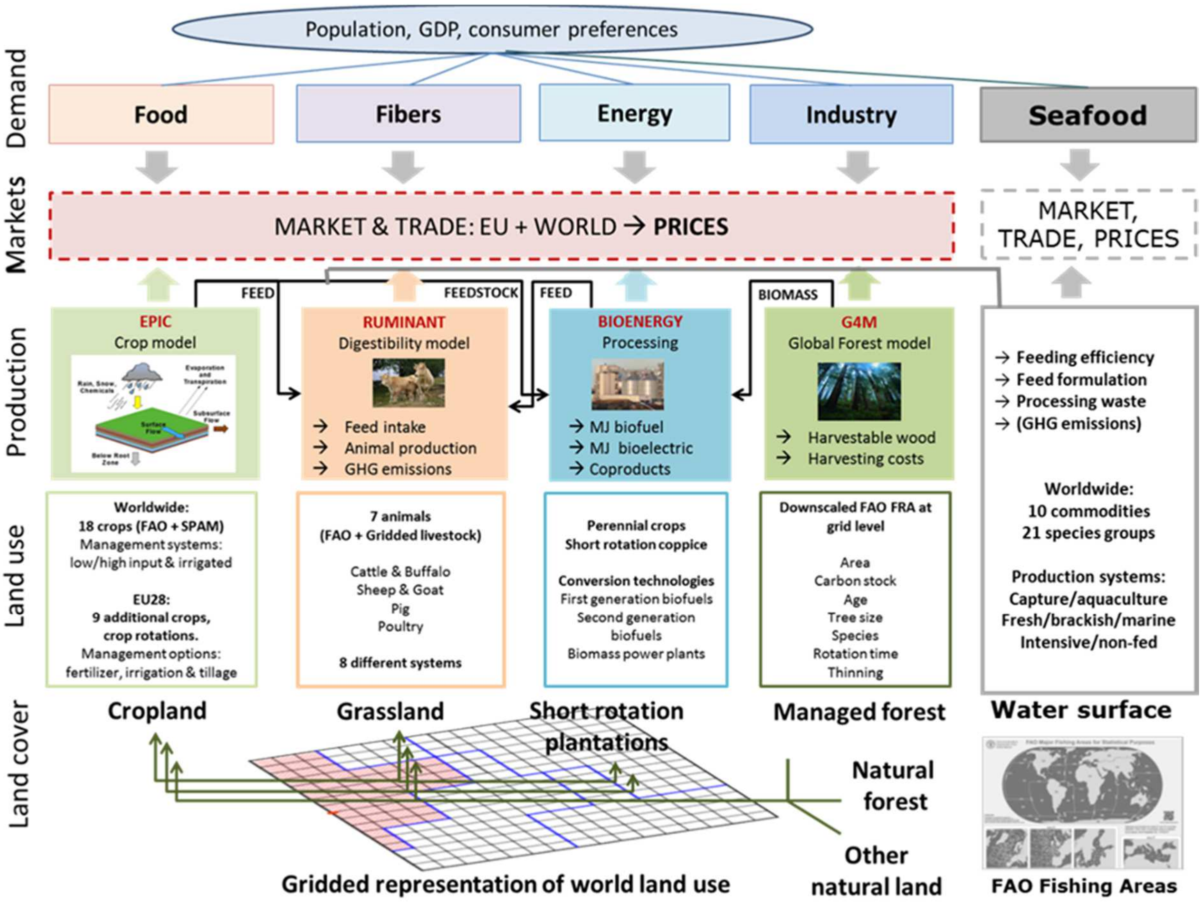
For the forest sector, five primary forest products are represented in the GLOBIOM model (saw logs, pulp logs, other industrial logs, fuel wood and biomass for energy). For projecting forest related CO_2 emissions and sinks in this report, we apply in a first step the Global Forest Model (G4M). In a second step, afforestation and deforestation trends as estimated by G4M are implemented into GLOBIOM. Trends in afforestation are implemented via a lower bound for different climate change mitigation pathways on a regional level. Deforestation trends from G4M are usually estimated higher compared to a stand-alone version of GLOBIOM since only a share of total deforestation is caused by agriculture. The difference of the two estimates is implemented exogenously in GLOBIOM and the remainder of the deforested land which is not transformed into agricultural land is transformed into other natural land. For this report, G4M is calibrated to match the average afforestation and deforestation rates over the historical period on the country scale. For the tropical countries we apply data from Hansen et al. (2013) (Hansen et al. 2013), for the Kyoto Protocol Annex-I countries we apply data obtained from the country submission to the UNFCCC (UNFCCC 2015) and for the remaining countries we apply data obtained from the FAO's 2015 Global Forest Resource Assessment (FAO 2015). In this context it should be noted that Hansen et al. (2013) data on forest loss and gain should be considered as the upper estimate of deforestation and afforestation rates as they include temporary forest loss and subsequent regeneration or replanting of the forest (Curtis et al. 2018).

In the seafood sector, GLOBIOM covers all finfish, crustaceans, and mollusks in the International Standard Statistical Classification of Aquatic Animals and Plants (ISSCAAP) Divisions 1-5. The model differentiates production between three production systems (capture, extensive aquaculture, and intensive aquaculture), three aquatic environments (marine, brackish water, and fresh water), 27 large spatial units (FAO Major Fishing Area for Statistical Purposes), and 25 species groups. Seafood trade and consumption is disaggregated into 11 species groups. In contrast to trade in other commodities in the model, seafood trade is not specified bi-laterally due to lack of the necessary global data.

GLOBIOM computes bilateral trade flows (except for seafood products) endogenously through the minimization of total trading costs. As an underlying assumption, goods are assumed to be homogenous which means that within the same industry goods are perfect substitutes and have the same price.

When bilateral trade flows between two regions are observed in the base year, a linearized constant elasticity trade cost function represents further trade relations between these two regions. It is required that the difference in prices between trading partners is equal to marginal trade costs (i.e., transportation costs plus tariffs). If no trade between two regions is observed in the base year, trade relations are represented by a quadratic trade cost function.

Trade in GLOBIOM is modeled in a **recursive dynamic** way, which means that in every solution period the initial traded quantity between two regions is set equal to the solution of the previous period. This way, the initial trade costs are combined with the updated quantity in every solution period.



3. Scenarios and Assumptions

Two scenarios are considered. A business as usual scenario (“*Current Trends*”), which assumes a continuation of present trends and a “*Better Future*” Scenario, where development and environmental objectives are collectively addressed.

The ‘Better Futures’ scenario implements a series of key policy recommendations, informed by the critical transitions of the FOLU Global Report, to model the outcomes for the food and land use system. A summary of the key distinctions between the two scenarios is provided in Table 1. Each scenario is individually discussed in additional detail in sections 3.1. and 3.2.

Table 1: Summary of Model Scenario Assumptions

	Current Trends	Better Futures
Climate Change mitigation policies	• Increasing global final energy demand (+52 percent from 2020 to 2050) • Continuation of current nationally implemented climate policies • Energy from biomass going down from current levels (56 EJ) to 41 EJ in 2050 with lower traditional fuel wood consumption	• Reduction of global final energy demand by 40 percent (between 2020-2050) (Grubler et al., 2018) • Staying with the limits of the 1.5 °C target • Carbon price of \$129 per tCO2-eq in 2050 (increasing value from 2030 on) • Additional energy demand from biomass of 11 EJ in 2050 compared to Current Trends
Food loss and waste improvements	• Food loss and waste (FLW) amounts to 31 percent global average based on dry matter production of modelled products in 2010 (based on Gustavsson et al., 2011). • The regional and product specific shares of FLW are kept constant over time	• There is a 25 percent reduction of food loss and waste compared to Current Trends in 2050 • The reduction is modelled as a linear reduction from 2020 onwards
Technical Progress	• 44 percent yield growth 2010-2050 (global average across crops) based on historical trends.	• Closing crop yield gaps by 25 percent with current technologies + additional 0.1 percent annual growth for technical change • Overall this results in a 56 percent yield growth 2010-2050 (global average)
Biodiversity conservation and restoration policies	• No additional conservation or restoration effort beyond 2010	• Better management of protected areas (preventing BII decreasing land use change in existing and new protected areas) and expansion of protected areas in 2020 to all remaining wilderness areas and key biodiversity areas • Development of incentives for restoration and landscape-level land use planning: subsidy for positive changes (and tax for negative changes) in biodiversity, with progressively increasing value from 2020 to 2050 (reaching 300\$/ha of biodiverse land in 2050).
Healthy diets	• Future demand patterns follow past consumption trends	• Global population changes its diets to follow the dietary recommendations of the planetary health diet (Willet et al., 2019). • In addition, declines in overconsumption and food loss and waste reduction at the consumer level in high-income countries allow food supply to decrease to an average level of 3000 kcal/cap/day by 2050
Food Security	• No specific policies	• Additional food production to achieve universal food security and SDG 2 target by 2030
Ocean proteins	• Marine capture fishing pressure continues at current levels, implying that production decreases through 2050 • Freshwater capture and marine aquaculture stable at current levels • Aquaculture fishmeal and fish oil feed requirements remain at current levels • Freshwater and mollusk aquaculture growth slows down	• Marine wild capture reform of half of global stocks, leading to stable production through 2050 • Freshwater capture stable at current levels • Aquaculture fishmeal and fish oil feed requirements decrease 50 percent by 2050 • Marine aquaculture doubles by 2050 • Freshwater aquaculture growth continues at current levels • Mollusk aquaculture growth accelerates.
Afforestation and Deforestation	• Afforestation and deforestation trends calibrated to historical data	• Afforestation and deforestations patterns are driven by the low energy demand pathway assumptions (Grubler et al., 2018) • Zero net deforestation after 2020, due to the application of a carbon tax
Trade	• No policy change compared to 2010.	• 50 percent tariff cut within Sub-Sahara Africa • Trade policies unchanged for other countries

3.1. *Current Trends scenario*

The Current Trends scenario draws on the Shared Socioeconomic Pathways (SSPs) (O'Neill et al. 2017; Keywan Riahi et al. 2017), which describe five broad level narratives and socioeconomic pathways of future development. The Current Trends scenario emulates the "Middle of the Road" Scenario (SSP2), where social, economic and technological trends represent a continuation of historical patterns, development progress is uneven, some gains in resource use and energy efficiency are made over time, but environmental degradation remains an issue (see Riahi et al. (2017) for a synthesis). In the standard SSP2 scenario, population growth is moderate and stabilizes by mid-century. Projections for income growth and SSP2 scenario assumptions with respect to land use are described in detail in Fricko et al. (2017). For this report, the population data has been adjusted to include projections from the University of Washington's Global Burden of Disease database to facilitate a feedback loop from a global transition to healthier diets on population trends.

Regarding technical progress in crop production over the course of the scenario, exogenous yield growth shifters are applied. Yield response functions to GDP per capita for 18 crops were estimated using a fixed effects model with panel data. The response to GDP per capita was differentiated over four income groups oriented at World Bank's income classification system (i.e.: <1.500, 1.500-4.000, 4.000-10.000, >10.000 USD GDP per capita). Country-level yield data was provided from FAOSTAT, while GDP per capita was based on World Bank data (1980-2009). A detailed discussion of the methodology is presented in Havlík et al. (2012) and Herrero et al. (2014).

Technological change in the livestock sector is represented by feed conversion efficiencies. Feed conversion efficiency projections were quantified as part of the ANIMALCHANGE project (Herrero et al. 2014; Soussana 2012) based on past trends and biophysical feasibility. More details and quantification of the SSP2 scenario are presented in Herrero et al. (2014) and Fricko et al.(2017).

Projections for food demand and diets in the Current Trends scenario are based on the assumptions that the future demand patterns follow the past consumption trends. Food demand increase due to rising global population, but also following income increase from economic growth, and a switch to higher standard food products (meat, fish, etc.) and more processed products (Valin et al. 2014). Our assumptions on future diets in this scenario follow those from FAO at horizon 2050 (Alexandratos and Bruinsma 2012). Under this scenario, food security is expected to only slowly improve, as food supply increases but no specific improvement is observed in terms of inequality of food distribution, which still lets a significant share of the population go undernourished by 2050 (Hasegawa et al. 2015). Additionally, no notable food waste and losses management policies are considered under this scenario, and the share of these in consumption and food supply chains (Gustavsson, Cederberg, and Sonesson 2011) are assumed to stay constant.

Regarding ocean proteins, the Current Trends scenario rests on the analysis of University of California Santa Barbara emLab provided to Systemiq as a part of this project. This analysis indicates that if fishing efforts and pressures continue at current levels without a reform in the management of global fisheries, the status and the overfishing of global fish stocks will further deteriorate, and as a result the global annual marine capture production will decline from current levels of 75-80 million metric tons (Mt) (live-weight equivalent) to approx. 61.7 Mt in 2050. We further assume that global freshwater and inland capture production will remain at current levels through 2050. As a result of the decline in marine catches, which are the primary source of fishmeal and fish oil, the scenario results in decreased availability of these two key ingredients in the diets of farmed fish, especially carnivorous ones. In addition, in the absence of large investments into the aquaculture sector, the recent progress in aquaculture feed efficiency improvements is halted, and the feed requirements of farmed fish in the model are assumed to remain stagnant at their 2020 levels. For both of these reasons, the options of further growth in the output of fishmeal and fish oil intensive aquaculture species is severely limited. Marine aquaculture production, which heavily relies on these feeds, remains at current levels of approximately 11.7 Mt. The production of freshwater fishmeal and fish oil intensive species grows by a mere 3 Mt to 2050. There are only two truly significant sources of growth in the supply of ocean-based protein. One is non-fishmeal and fish oil intensive freshwater aquaculture, which grows by 30 Mt to 2050. The other is bivalve/mollusk aquaculture, which grows by 11 Mt. However, this growth rate remains lower compared to what has been observed in the sector in recent years, reflecting the saturation of demand and growing constraints on further expansion of bivalve farms.

3.2. Better Futures scenario

The Current Trends baseline is contrasted with a transformative “Better Futures” Scenario, where the dimensions of the food and land-use system are approached in an integrated manner with the aim of accounting for trade-offs and synergies between key development and environmental objectives in the land-use space. The following sections highlight the different assumptions between the Current Trends scenario and the Better Future Scenario with regards to diets and food security, climate change mitigation, biodiversity, technical progress, food waste reduction and ocean protein.

Diets and Food Security. In the Better Future Scenario, consumers are assumed to adopt more environmentally friendly and healthy diets at the time horizon 2050, and the sustainable development agenda towards 2030 is strictly enforced. Informed by SDG2, the aim is to achieve universal food security from 2030 onwards. We assume the global population changes its diets to follow the dietary guidelines from the EAT-Lancet Commission (Willett et al. 2019). These correspond to radical changes in the consumption of some products. For example, this implies for an adult male diet: 14 g of red meat (beef, pork) per capita day, 250 g of dairy products, 500 g of fruits and vegetables, 50 g of nuts (peanuts, tree nuts), and 75 g of soybean and other legumes. All regions are converging to these recommendations in their dietary mix by 2050. We additionally assume that overconsumption and food loss and waste reduction at the consumer level in high-income countries allow to decrease food supply to an average level of 3000 kcal/cap/day by 2050, a level to which developing countries also converge to. In addition, population undernourished in developing countries is assumed to receive an extra calorie supply corresponding to their food deficit to achieve SDG2 in 2030. The described assumptions reflect the basis for exogenous shifts of the demand function which are implemented into the model. The final results will deviate from these values, due to feedback effects from price changes.

Food Loss and Waste. The primary policy goal is to achieve reduced food loss and waste by 2050 in order to alleviate the effect of increasing global food demand. This scenario is created in the model by exogenously reducing food loss and waste by 25% in the ‘Better Futures’ scenario, starting from values presented in Gustavsson et al. (2011) which are assumed to remain constant in the Current Trends scenario.

Agriculture and Livestock. As noted above, the Current Trends scenario is guided by SSP2 driver assumptions. For the Better Futures scenario, we simulate a technical progress rate that closes regional yield gaps by 25% in 2050. Exogenous yield shifters from the Current Trends scenario are replaced with the respective shifters only if the technical progress rates are higher than under Current Trends assumptions, drawing on the methodology of Valin et al. (2013). In addition, a yield growth trend of 0.1% per year is assumed for all crops and regions, reflecting for example breeding successes or other technological and practice improvements.

For the productivity of the livestock sector, the same assumptions are applied for the Better Future as under the Current Trends scenario, because we face a significant demand shift away from livestock products. In light of these developments, we assume that investment in the sector stagnates and no additional efficiency gains are created.

Climate Change. The SSPs are complemented by Representative Concentration Pathways (RCPs), which define increases in atmospheric greenhouse gas concentrations and the expected radiative forcing. In the case of the Current Trends scenario, RCP6.0 has been selected, which represents a radiative forcing of 6 W/m^2 and an approximate greenhouse gas concentration of 850 ppm CO_2eq when emissions are projected to stabilize after the end of the century (van Vuuren et al. 2011) for a comparative overview of the RCPs). For the Better Futures scenario, we assume that we stay within the emission pathway of the 1.5 °C target and use RCP 2.6 to reflect this assumption. Both RCPs have been quantified by the climate model HadGEM2-ES and the crop model EPIC and projected crop yields in GLOBIOM are impacted accordingly, also taking into account CO_2 fertilization effects (for more details see (Leclère et al. 2014). The described impacts refer only to the long-term climate change effects on crop yields. Potential impacts of increased climate variability and extreme events frequency are not accounted for.

The Better Future Scenario explores the effects of realizing food security and improvements in diets, while also pursuing a development pathway that is in line with limiting global warming to 1.5 °C above preindustrial levels and halting and reversing biodiversity loss. The final results of the Better Future Scenario are based on the low energy demand (LED) pathway without BECCS deployment, based on an assumed 40% reduction in final energy demand through energy efficiency improvements by 2050 (Grubler et al. 2018). Grubler et al. (2018) concluded that the rapid implementation of a LED pathway through transformational changes on the demand side reduces considerably the dependency on negative emission technologies, specifically bioenergy carbon capture and storage (BECCS). Following a LED pathway would allow to achieve the 1.5 °C target with limited additional energy demand from biomass of only around 11 EJ and a carbon price of 129 USD/t per CO_2eq by 2050.

For comparison, a second alternative 1.5 °C mitigation scenario was also considered. This alternative 1.5 °C mitigation scenario is characterized by a medium increase in energy demand and requires wide-spread deployment of negative emission technologies. This scenario results in an additional demand for 91.4 EJ from biomass for energy use by 2050 on top of the Current Trends baseline level of 41.3 EJ globally in 2050 and in a carbon price of 238 USD/t per CO2eq.

Note that in all the scenarios above, biomass for bioenergy also includes a fixed contribution of 4.8 EJ from 1st generation biofuels in 2050, but these are not assumed to contribute largely to mitigation and are kept constant over scenarios.

Forestry. Simulated decisions on deforestation, afforestation or continuation of current land-use in G4M are based on a comparison of net present values (NPV) of agriculture and forestry. Deforestation takes place if the agriculture NPV including the revenue from one-time selling of the deforested wood exceeds the forestry NPV. Afforestation occurs if the forestry NPV is greater than the agriculture NPV, there is free land for planting the trees and the environmental conditions allow forest growth. In climate change mitigation scenarios, a carbon tax for the carbon lost at deforestation and payments for the additional carbon accumulated due to afforestation are included in the forestry NPV and thus influence the land use change decisions. The Better Futures scenario is based on a Low-Energy-Demand scenario (Grubler et al. 2018), which has been quantified with by G4M for the forest sector.

Zero net deforestation (ZND) is a result of the mitigation policy (i.e. the application of a carbon tax) that is implemented in the Better Future Scenario. With a substantial carbon tax, deforestation reduces to a minimum and afforestation increases such that from 2030 on we already see a net increase in forest areas globally.

Biodiversity. Aside from climate change, addressing biodiversity loss represents a major concern for more sustainable food and land-use systems and is hence a key feature of the Better Futures scenario.

Biodiversity is a complex concept, as it entails the variety of life across scales, including, inter alia, diversity at the genetic, population, species and ecosystem levels. Often primary focus is placed on protecting biodiversity at the species level. Yet measures of species richness conceal that different species may be of different importance to ecosystem functioning. Focusing on maintaining biodiversity at the species level may also ignore the extinction of individual populations and associated local impacts. As the web of life is appreciated but incompletely understood, estimating the economic value of species and biodiversity is imperfect and fraught with uncertainty. These complexities should be kept in mind when considering modeling results on biodiversity.

Nevertheless, it is important that proxy indicators of biodiversity are included in an integrated assessment of food and land-use systems. Land-use changes for agriculture and other human activities as well as unsustainable use of renewable natural capital, are major drivers for biodiversity loss, further compounded by human induced climatic change, pollution and other environmental changes. Solutions to addressing biodiversity loss and climate change require international and global scale efforts. International strategies focused on climate change alone, may promote solutions, which undermine biodiversity conservation efforts, e.g. by displacing biodiversity rich ecosystems with land for bioenergy.

Using select biodiversity indicators, Leclere et al. (2018) explored through an integrated modeling approach how various supply and demand measures and combinations thereof could constrain land-use changes and help “bending the curve” on biodiversity loss.

For this report, we emulated this approach with a focus on the effects of land-use constraints, mitigation, and dietary shifts under the “Better Future” Scenario in comparison to the Current Trends scenario. The Biodiversity Intactness Index (BII) is used as primary performance indicator. The BII estimates how much of a region’s originally present biodiversity has been perturbed by humans, as measured by the local composition of wildlife communities, relative to if the region were still covered with primary vegetation and facing minimal human pressures (Scholes and Biggs 2005). We rely on the relationship between land use activities and BII modelled from the PREDICTS database of biodiversity and land use records (Leclère et al. 2018; Newbold et al. 2016). With most of the data being on insects and plants, this estimate of BII response to land use provides one of the few indicators not predominantly based on vertebrates. The Index ranges from 100–0% with 100 representing an undisturbed or pristine natural environment with little to no human footprint. The most recent global estimates suggest that the BII fell globally from 81.6% in 1970 to 78.6% in 2014. The BII is calculated for each grid cell of the model for the year 2000 as starting point for the projections under the Current Trends and Better Futures scenarios.

For the Better Futures scenario the model applies two complementary strategies. First, we assume that all protected areas a) become better managed (so that any land use change that decreases BII cannot occur at any time after 2020) and b) increase in extent (to all Key Biodiversity Areas and intact Wilderness Areas, in addition to all areas currently protected under the World Dataset of Protected Areas). Second, we assume a pervasive effort to landscape- and regional- progressive reconfiguration of managed land towards restoration and reduced biodiversity impact, by applying a subsidy for positive biodiversity changes and a tax for negative changes. The subsidy starts at 10 USD/ha in 2020 and grows exponentially to 300 USD/ha in 2050. The tax or subsidy applies to a change in the regional biodiversity stock that accounts for the extent to which different grid cells potentially hold more or less biodiversity, and the extent to which different land uses prevent this potential to materialize (see Leclere et al. (2018) for further detail). The model accounts only for land-use related biodiversity changes.

The area restored for biodiversity purposes is assumed to correspond to forest type of vegetation in grid cells where this type of vegetation is best suited for biodiversity (e.g., excluding grassland ecosystems). To delineate these grid cells, we use the LUH2 information on whether natural vegetation is forested or not in a particular grid cell (for more details, see the technical documentation http://gsweb1vh2.umd.edu/LUH2/LUH2_v2f_README_v6.pdf). In these grid cells, the restored area is considered as a form of afforestation: it is however considered as slightly less performing at sequestrating carbon than G4M-infered, carbon sequestration-dedicated afforestation (which could rely on different species mix and management). The restoration-related afforestation (both area and carbon gain) are conservation-driven and occur in addition to the afforested areas inferred from G4M simulations. The afforested areas inferred from G4M are considered as equivalent to timber activities from a biodiversity standpoint, and therefore less beneficial than restored areas. In the results presented in the report, however, we combine the two different afforestation classes.

Ocean protein. In the Better Futures scenario, through a concerted reform effort in the management of half of the world's marine fish stocks, by 2050, annual capture production is stabilized at a sustainable level of 75 Mt. Freshwater/inland capture remains stable at the current level of 12 Mt, same as in the Current Trends scenario. Continued investment in aquaculture technology and management results in a 50% decrease, relative to 2020, of aquaculture fishmeal and fish oil feed requirements by 2050. As a result, the growth of fishmeal and fish oil intensive aquaculture is much less constrained. Marine aquaculture production nearly doubles and reaches 22.4 Mt annually. Freshwater fishmeal and fish oil intensive aquaculture grows nearly twice as fast as in the Current Trends case, and annual production reaches 8.7 Mt. Freshwater non-fishmeal and fish oil intensive aquaculture grows slightly faster than in the Current Trends case by 40 Mt annually by 2050. Mollusk/bivalve production and consumption continues to grow and is boosted to 4% p.a. (as opposed to the average annual growth rate of the last ten years of 3.1%) due to policy incentives towards eating low carbon food. This results in an output of 65.2 Mt per year.

Trade. In the context of the Better Future Scenario a globally moderate and open approach to global trade is maintained while facilitating increased interregional trade within Sub-Saharan Africa due to greater investments in connectivity across the continent. The model achieves this by halving the cost of tariffs within the Sub-Saharan Africa macro region and keeping all other tariffs constant.

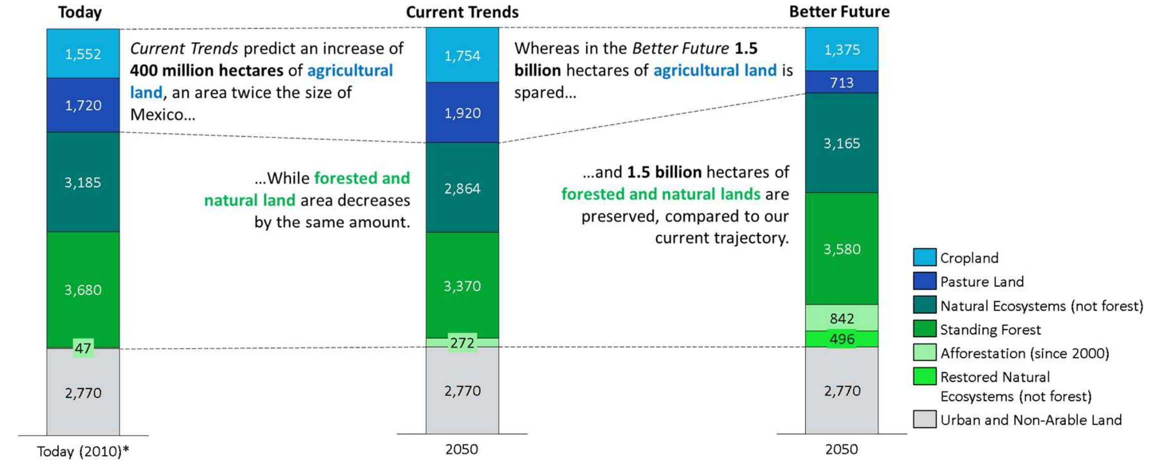
4. Main Results and discussions

The results illustrate the benefit of an integrated approach to food and land-use systems in reaching multiple development and environmental objectives. Through the combination of supply and demand-based measures, there is the potential to reduce trade-offs between these objectives, which are currently present in many land-use systems, and instead strengthen synergies, allowing for the generation of multiple benefits.

In comparison to the Current Trends scenario, we see strong land use changes taking place under the Better Futures scenario (Figure 1). Roughly 1.5 Gha (Giga hectare) of agricultural land which is projected to be used for crop and livestock production in the Current Trends scenario is projected to be used for other purposes in the Better Futures scenario in 2050. Most of the 1.5 Gha would be used as pasture land in the Current Trends scenario. Pasture land in our classification accounts for all the land that is significantly used for livestock production. Pastures without significant contribution to total livestock production are included in the category natural land since we assume that the impact of changes in livestock production will only be marginally impacting these areas.

Figure 1: Land use changes in the Current Trends and Better Futures Scenario

Total Surface Land Use: million hectares



Current Trends predict an increase of **400 million hectares** of agricultural land, an area twice the size of Mexico…

…While forested and natural land area decreases by the same amount.

Whereas in the *Better Future* **1.5 billion** hectares of agricultural land is spared…

…and **1.5 billion** hectares of forested and natural lands are preserved, compared to our current trajectory.

* Baseline data forecast from 2000

Note: According to our estimates, parts of the permanent pastures, as defined in the IPCC 2019 Special Report on Climate Change and Land report, are pastures without significant contribution to total livestock production and thus, are included in the land use classification 'Natural Ecosystems Land'. The 'Pasture' land use classification includes only grassland utilized for agricultural production.

A combination of different drivers leads to these results in the Better Futures scenario. On the demand side, the main driver of land use change in the model is the shift towards the planetary health diet (which contains much lower livestock proteins than current diets in many regions). As the demand for livestock products is substantially reduced, this decreases also the need for grazing areas. Furthermore, pressure on agricultural land is alleviated due to lower feed crop requirements, while also overconsumption in high-income countries and food loss and waste are reduced. Together these projected developments have a greater effect than the demand on food production arising from the objective of meeting universal food security by 2030. Additionally, under the Better Futures scenario livestock proteins in human diets are substituted with ocean proteins, which are roughly 30% higher in 2050 than in the same year under the Current Trends scenario.

On the supply side, the implementation of a carbon price shifts agricultural production towards less emission intensive production. This implies a shift towards more productive livestock systems and reduces the demand for pasture land (compare Havlik et al, 2014). The carbon price causes also almost a complete stop in global deforestation as of 2030 and incentivizes afforestation efforts.

Technical progress induces yield increases of 56% between 2010 and 2050, while the Current Trend scenario assumes an increase of 44%. This reduces the amount of land that is needed for the same amount of crop production.

The results presented in this paper do not include the impact of urban expansion on cropland and other land-use types. This is currently outside the scope of the model. Other available studies can provide some insight into the order of magnitude of change. A recent study by Bren d'Amour et al. 2017 suggests that between 2000 and 2030 27-35 Mha of cropland will be lost due to urbanization. Another study by He et al. (2019) quantifies urban expansion between 1992 and 2016 to 35 Mha globally. If urban land expansion continues to expand accordingly, scenario results would only be impacted marginally, and the main statements concerning the effects of the Better Future Scenario on land-use are not affected.

The drivers described in the Better Future Scenario shape a solution space, where a) food security targets (i.e., the elimination of hunger) are reached, b) emission reduction targets for the land use sector in line with limiting global warming to 1.5 °C above pre-industrial levels can be realized, and c) at the same time the declining biodiversity trend can be stopped and the intactness of biodiversity towards the end of the scenario improved.

In the Better Futures Scenario we reach carbon neutrality in the land use sector in 2050. The implementation of climate change mitigation measures is in line with limiting global warming to 1.5°C above preindustrial levels. The low energy demand (LED) pathway without BECCS deployment serves as a basis for the implementation, relying on an assumed 40% reduction in final energy demand through energy efficiency improvements by 2050 (Grubler et al, 2018).

Yet, in the Better Futures scenario, emissions in 2050 are reduced to an even stronger extend because of the additional assumptions on dietary changes, technical progress, ocean proteins, and reduced food waste. These additional measures on the one hand reduce more emissions and on the other hand prevent an increase in food prices which usually would be expected in a pure mitigation scenario (for price effects of climate change mitigation compare Hasegawa et al. 2018). In fact, in the Better Futures scenario we see lower prices in 2050 in comparison to the same year in the Current Trends scenario. This holds for the average of all agricultural products at the global level. The strongest negative impact on prices, however, comes from livestock products while the scenarios would show increasing prices for some crops in some regions.

Negative emissions only occur in the scenario due to afforestation or re-growth of other natural vegetation on areas used for biodiversity restoration. If land is simply abandoned without active management of re-growth, no sequestration effect would be accounted for in the model. In 2050 the Better Futures scenario shows that sequestration from afforestation and restoration (-4.4 GT CO2-eq per year) outweighs all the remaining positive emissions still occurring. Positive emissions are associated with agricultural production (2.3 GTCO2-eq/year) and other agricultural activities such as clear-burning of savannah and from crop residues (0.6 GTCO2-eq/year), whereby the latter (in contrast to agricultural production emissions) is not endogenously modelled and is assumed constant over time and thus, is likely to be overestimated in the Better Future scenario as it can be expected to be reduced as well.

Deforestation emissions of almost 1.6 GTCO2-eq/year are still reported in the Better Futures scenario in 2050 despite the fact that deforestation almost completely stops as of 2030[1]. The bulk of the remaining deforestation emissions can be attributed to soils and peatland that were deforested in earlier years and still continue to emit. In our scenarios we did not assume measures such as rewetting of these peat ecosystems to reduce CO2 emissions in later years since this process is currently not implemented in the model.

For the scenarios calculated for the FOLU Global Report, afforestation and deforestation trends are calibrated to historical data on the country scale. For the tropical countries we apply data from Hansen et al.(Hansen et al. 2013), for the Kyoto Protocol Annex-I countries we apply data obtained from the country submission to the UNFCCC (UNFCCC 2015) and for the remaining countries we apply data obtained from the FAO's 2015 Global Forest Resource Assessment (FAO 2015).

The input data influence the result of the modelling regarding both, historical and projected land use change. In general, Hansen et al. (2013) data on forest loss and gain should be considered as the upper estimate of deforestation and afforestation rates as they include temporary forest loss and subsequent regeneration or replanting of the forest (Curtis et al. 2018). When calibrating our models to data from FAO's 2015 Global Forest Resource Assessment (FAO, 2015) instead, we estimate emissions of 11.5 GTCO2-eq per year for 2010 for the whole land use sector (including agriculture, forestry and land use change), with 6 GTCO2-eq/year coming from deforestation instead of 9.1 GTCO2-eq from deforestation, as estimated for the scenarios of this report.

In the Current Trend scenario, a continuation of biodiversity losses approximately equal to that between 1970 and 2010 is projected between 2010 and 2050 (Figure 2). In contrast, the Better Futures scenario entails a reversal of this negative biodiversity trend due to habitat loss, and even a slight recovery by 2050. However, this reversal could not be sustained unless we avoid the large-scale use of bioenergy with carbon capture and storage for climate mitigation.

In a different version of the Better Futures scenario, we replace the assumptions of the low energy demand pathway with assumptions also designed to reach 1.5 °C mitigation targets, but relying on a medium increase in overall energy demand and requiring wide-spread deployment of negative emission technologies. The effect of the large-scale production of bioenergy for BECCS would lead to a substantial amount of woody biomass plantations in the scenario (252 Million hectare globally in 2050) which have a relatively poor biodiversity value and would prevent global biodiversity from recovering.

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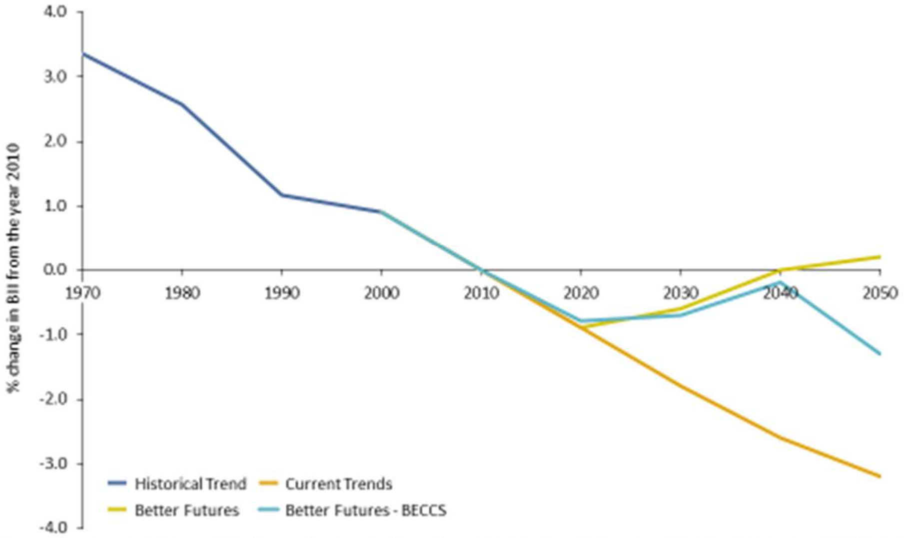
[1] Stopping deforestation only refers to preventing that forest areas are continuously changed to other land uses. Forest, however, can still be managed and it is ensured that wood demand from industries is satisfied in all the scenarios.

Figure 2: Biodiversity trends for different scenarios

Biodiversity Intactness Index (BII): evaluates impacts on local biodiversity in terrestrial ecosystems



Source: Leclère et al., "Towards Pathways Bending the Curve Terrestrial Biodiversity Trends within the 21st Century," 2018, for historical reconstruction

Taken together, the implementation of biodiversity policies (i.e., supporting better management practices of protected areas and the subsidy for positive biodiversity changes) together with the shift to healthy diets (including a substitution of meat proteins with ocean proteins), the reduced food loss and waste, and the increased crop yields, play a significant role in reducing biodiversity loss. In addition, the climate change mitigation scenario will play an important role. Besides the above described impact from bioenergy production, the implementation of a carbon tax causes an almost complete stop in global deforestation, incentivizes afforestation efforts, and reduces the demand for pasture land. Hence, it is the combination of demand and supply based measures to meet food and energy needs, which determines whether positive outcomes for biodiversity and climate mitigation can be realized.

When interpreting the results of this study, important caveats need to be kept in mind. The model results are obviously dependent on and influenced by the input data. For example, for analysis concerning food supply, all of our calculations are based on the FAO Food Balance Sheets (http://www.fao.org/faostat/en/#data), which operate on the food availability and not on the food intake. The discrepancy between food availability and food intake is largely related to household domestic waste, but reliable data on the extent of waste and losses are relatively scarce. Therefore, it is not possible to derive from this study good projections on the level of food intake, and the model results should be compared with care to dietary surveys performed at national levels (see for more discussion on this issue Hawkesworth et al., 2010).

Further, we assume that food security challenges can be solved by an increased availability. However, we do not look at other pillars of food security, such as food access, utilization and stability. Supplying extra calories corresponding to the food deficit can only be useful if the corresponding food is distributed to those in needs, and inequality of food access are consequently reduced. This is beyond the scope of this scenarios, but it is important to recall that only if the appropriate enabling structures at national and local level are provided will improved food availability also lead to desired outcome of improved food security.

This underscores the importance to further contextualizing the global picture provided here. This study sought to examine the broad level possibilities. However, to obtain this picture a considerable level of aggregation is necessary. For example, the targets considered for food were designed as a globally universal mix of food products which does not take into account initial regional differences to build more tailored diets adapted to regional preferences and local production structure.

Regarding the estimation of biodiversity trends, the model accounts for local impacts from restoration activities such as assisted or natural regeneration of habitats in areas previously used for agriculture or forestry. Over a few decades, the local abundance of wildlife species present before the land was put into production is expected to increase towards original levels, resulting in an increase in BII. Because some species may have gone extinct, and because the composition of population across species in restored areas differ from that of pristine vegetation, the BII values of restored areas are lower than that of pristine vegetation. As we do not model recovery dynamics and assume instead immediate recovery, the estimated BII improvements from restoration activities provides an optimistic boundary of how fast ecosystems might recover under restoration.

Regarding the potentials for aquaculture expansion in GLOBIOM, it should be kept in mind that only feed inputs required for this type of production are taken into account, and therefore only limitations placed on aquaculture expansion by the availability of fishmeal, fish oil, and crop feeds are considered. In reality, there are other constraints (e.g. environmental, regulatory, logistical) at play, not covered by this analysis. Furthermore, there is a large amount of aggregation inherent in this type of a global report, for example in terms of regions, fish species, and production technologies. The exogenous shocks to capture production and the assumed limitations on aquaculture growth are applied evenly across the globe, whereas in reality, there would likely be a great deal of differentiation between different regions of the world.

Finally, GLOBIOM is a partial equilibrium model, which does not represent the full economy of a country or region. Instead, the focus is placed on the detailed representation of select sectors, which are of particular relevance to food and land-use systems. This implies that economy wide feedbacks are not included. There is also limited representation of the impacts arising from some environmental changes. This applies for example to climate related feedbacks. While changes in average climatic conditions and associated effects on agricultural productivity can be considered to some extent, the analysis does not consider the implications of change in the exposure to climatic extremes and shocks as well as possible knock-on effects across sectors and regions.

The Better Futures scenario illustrates the potential that the integrated pursuit of development and environmental objectives holds for maximizing synergies and minimizing trade-offs between various goals. Agricultural activities should no longer be considered in isolation but as integral part of a wider effort to attain sustainable food consumption and land-use practices. The full spectrum of demand and supply based efforts should be considered when implementing strategies and policies. This requires rethinking the relationship of measures across sectors. On the one hand, the analysis underscored that pursuit of objectives of one sector, e.g. improved human health through better diets, can help realize objectives in another, e.g. improved environmental and climate services due to reduced pressure on natural resources and land. On the other hand, it also illustrated that the aggressive pursuit of a singular objective, e.g. limiting global warming to 1.5 °C while meeting rising energy demand, can constrain or make solutions for another objective impossible, e.g. halting biodiversity loss in the face of massive deployment of negative emission technologies in the land-use space. A more balanced approach to limiting global warming offers solutions that also address biodiversity concerns, if measures to achieve 1.5 °C target are accompanied also with a focus on substantially lowering energy demand. Hence, underscoring the value of systems-based approach to address these concurrent global challenges in the land-use space.

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