Annex B:

Technical Annex

Technical Annex i) Integrated Scenarios for Sustainable Food and Land-Use: An Overview of IIASA's Global Biosphere Management Model

IIASA's Global Biosphere Management Model (GLOBIOM) underpins the analytics for the FOLU Global Consultation Report. GLOBIOM has previously been employed to investigate nexus issues relating to food security, land use, climate change and environment.[1–5] The modelling completed for this report draws on these experiences and applies an integrated assessment approach to the policy scenarios discussed.

Central to the GLOBIOM-FOLU analysis is the comparison of the baseline, known in the report as the "Current Trends" scenario, with a "Better Futures" scenario. The Current Trends scenario was designed to deliver a picture of a future grounded in (recent) historical trends. This future would see considerable progress and innovation (for example with regards to agricultural productivity) within the framework of the current system. Current Trends mainly relies on the standardised set of assumptions that has informed the analysis of the Intergovernmental Panel on Climate Change's 5th Assessment Report, coupled with the matching set of climate assumptions. The 'Current Trends' scenario is defined by the Shared Socio-Economic Pathway 2 (Middle-of-the-Road) and by the climate assumptions of the Representative Concentration Pathway 6.0.[52] Under this scenario, the world is unlikely to meet the Sustainable Development Goals or the Paris Agreement targets.

The Better Futures scenario implements a series of key policy recommendations, informed by the ten critical transitions of the FOLU Global Report, to model the outcomes for food and land use systems. A summary of the key distinctions between the two scenarios is in the table below.

Technical Annex Table 1: Summary of Model Scenario Assumptions

	Current Trends	Better Futures
Climate Change mitigation policies	• Continuation of current nationally implemented climate policies • Increasing global final energy demand (+52 percent from 2020 to 2050)	• Staying with the limits of the 1.5-degrees Celsius target • Reduction of global final energy demand by 40 percent (between 2020-2050)[6] • Carbon price of $129 per tonne of carbon dioxide equivalent (tCO2e) in 2050 (increasing value from 2030 on)
Food loss and waste improvements	• Global average food loss and waste is reduced by 31 percent based on dry matter production of modelled products in 2010[7] • The regional and product specific shares of food loss and waste 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)

[52] In 2016, public investments in infrastructure amounted to ~$620 billion including government expenditure and development flows while total credit from private/commercial banking sector to producers in agriculture and, forestry and fisheries accounted for ~$560 billion. Including investments from other value chain actors would bring the share of additional investment requirements further down. See https://www.un.org/pga/71/wp-content/uploads/sites/40/2017/02/New-Climate-Economy-Report-2016-Executive-Summary.pdf

Technical Annex Table 1: Summary of Model Scenario Assumptions (Cont.)

	Current Trends	Better Futures
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 a decline in the Biodiversity Intactness Index, BII, by reducing the extent of 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 per hectare 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 human and planetary health diet[8] • In addition, declines in overconsumption and food loss and waste at the consumer level in high-income countries allow food supply to decrease to an average level of 3000 kcal per capita per day by 2050
Food Security	• No specific policies	• Additional food production to achieve universal food security and SDG2 target to end hunger, achieve food security and improved nutrition and promote sustainable agriculture 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 bivalve 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 • Bivalve aquaculture growth accelerates
Afforestation and Deforestation	• Afforestation and deforestation trends calibrated to historical data[i]	• Afforestation and deforestations patterns are driven by the low energy demand pathway assumptions6 • Zero net deforestation from 2020 onwards, due to the application of a carbon tax
Trade	• No policy change compared to 2010	• 50 percent tariff cut within sub-Saharan Africa • Trade policies unchanged for other countries

[i] Tropical countries based on Hansen et al.[9], Kyoto Protocol Annex-I countries based on country submissions to the United Nations Framework Convention on Climate Change (UNFCCC)[10], remaining countries based on FAO's 2015 Global Forest Resource Assessment.[11]

GLOBIOM: A Structural Overview

GLOBIOM is a global recursive dynamic bottom-up partial equilibrium model integrating the agricultural, bioenergy and forestry sectors.[2,12] It employs a linear programming approach based on the spatial equilibrium approach developed by Takayama and Judge.[13] Based on a welfare maximising objective function, an agricultural and forest market equilibrium is computed subject to resource, technology, demand and policy constraints.

For a detailed assessment of forest dynamics, in particular in response to climate change mitigation policies, GLOBIOM has been linked with the G4M model,[14] a global forest model which supplies spatially explicit simulations of the forest sector and projected emissions from land use change. Lauri et al. provide a detailed description of the representation of the forest sector in GLOBIOM and the linkage to G4M.[15] For economy wide integrated climate change mitigation assessments, GLOBIOM/G4M integrated assessment modelling has been coupled to the energy system model MESSAGE,[16] which provides the trajectories for carbon prices and biomass for energy demand over time.

In the version of GLOBIOM used for the FOLU Global Consultation 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 maximising consumer and producer surplus.

GLOBIOM is calibrated to the FAOSTAT database, provided by the Food and Agriculture Organization of the United Nations (FAO),[17] 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 of 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 specific policies on the results.

On the demand side, a representative consumer is modelled for each region mimicking the demand behaviour of the aggregate population for the 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.

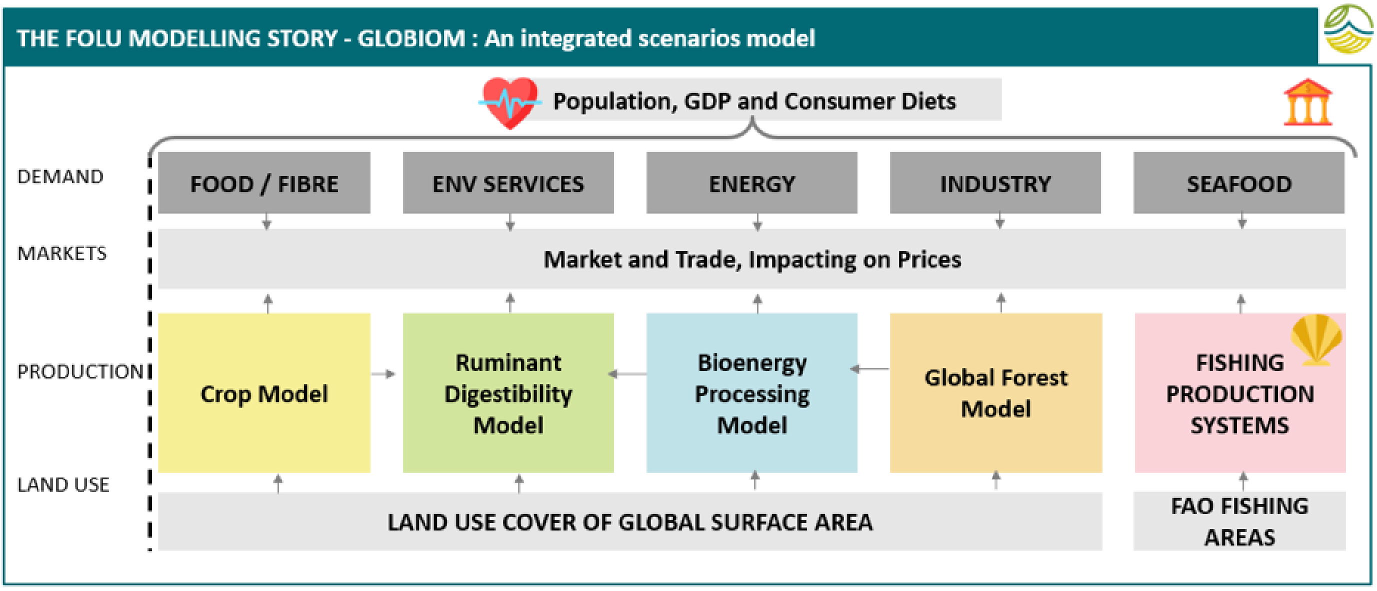
On the supply side, the model is built on a spatially explicit, bottom-up set-up. The basis is a detailed disaggregation of land into so-called "Simulation Units". Simulation Units are clusters of pixels that belong to the same country, have similar altitude, slope and soil characteristics and cannot exceed the size of 0.5° x 0.5°.[18] 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 modelled 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 optimisation behaviour. 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 modelling component to allow for an examination of how shifts in the production and consumption-based proteins may affect land-use dynamics.

Technical Annex Exhibit A: Simplified representation of IIASA's GLOBIOM Model (Source: IIASA).



Sector representation

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),[19] which provides estimates of crop distributions. 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[20,21] 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.

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

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 harmonised 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.[22,23] GLOBIOM represents the spatial and temporal nature of water demand and supply by building on the work by Sauer et al.[24] It considers the suitability of irrigation systems and crops given the biophysical conditions and the physical and economic suitability of crops for irrigation.[23,25–27] 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. Non-ruminants 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 consistent with FAOSTAT at the country level. The livestock production system parameterisation relies on the dataset by Herrero et al.[28]

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 to be higher as 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, data from Hansen et al.[9] is applied; for the Kyoto Protocol Annex-I countries, data obtained from the country submission to the United Nations Framework Convention on Climate Change (UNFCCC)[10] was applied; and, for the remaining countries, data obtained from the FAO's 2015 Global Forest Resource Assessment[11] was applied. In this context it should be noted that Hansen et al.[9] 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.[29]

In the seafood sector, GLOBIOM covers all finfish, crustaceans, and molluscs 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.

Trade

GLOBIOM computes bilateral trade flows (except for seafood products) endogenously through the minimisation 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 linearised 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 modelled 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.

Scenarios and assumptions

Two scenarios are considered. A business as usual scenario, "Current Trends", which assumes a continuation of current trends and a "Better Futures" Scenario, where development and environmental objectives are collectively addressed.

Current Trends scenario

The Current Trends scenario draws on the Shared Socioeconomic Pathways (SSPs),[30,31] 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.[31] for a synthesis). In the standard SSP2 scenario, population growth is moderate and stabilises by mid-century. Projections for income growth and SSP2 scenario assumptions with respect to land use are described in detail in Fricko et al.[32]. 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.[33] and Herrero et al.[34]

Technological change in the livestock sector is represented by feed conversion efficiencies. Feed conversion efficiency projections were quantified as part of the ANIMALCHANGE project[34,35] based on past trends and biophysical feasibility. More details and quantification of the SSP2 scenario are presented in Herrero et al.34 and Fricko et al.[32]

Projections for food demand and diets in the Current Trends scenario are based on the assumptions that the future demand patterns follow past consumption trends. Food demand increases due to rising global population, but also due to income increases from economic growth, and a switch to higher standard food products (meat, fish, etc.) and more processed products.[36] The assumptions on future diets in this scenario follow those from FAO at horizon 2050.[37] Under this scenario, food security is expected to improve only slowly, as food supply increases but no specific improvement is observed in terms of equality of food distribution. This still leaves a significant share of the population undernourished by 2050.[38] Additionally, no notable food loss and waste management policies are considered under this scenario, and the share of these in consumption and food supply chains[39] are assumed to stay constant.

Regarding ocean-based proteins, the Current Trends scenario rests on the analysis of University of California Santa Barbara Environmental Market Solutions Lab (emLab) provided to FOLU as a part of this project. This analysis indicates that if fishing efforts and pressures continue at current levels without reforms in the management of global fisheries, the status of global fish stocks will further deteriorate due to overfishing. 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 the 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 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.

Better Futures scenario

The Current Trends scenario is contrasted with a transformative "Better Futures" scenario, where the dimensions of food and land use systems 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 Futures scenario with regards to diets and food security, climate change mitigation, biodiversity, technological progress, food loss and waste reduction and ocean-based protein.

Diets and Food Security. In the Better Futures scenario, consumers are assumed to shift to a planetary health diet by 2050,[8] and that universal food security is assured from 2030 onwards. The changes in diet result in 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, 29 g of chicken and other poultry, 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. In addition, reduction in overconsumption and food loss and waste at the consumer level in high-income countries allow food supply to decrease to an average level of 3000 kcal per capital per day by 2050, a level to which lower income countries also converge to. In addition, the population undernourished in lower income countries is assumed to receive extra calories corresponding to their food deficits to achieve SDG2 in 2030. These assumptions form 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 percent in the 'Better Futures' scenario, starting from values presented in Gustavsson et al.[39] 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 percent 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.[1] In addition, a yield growth trend of 0.1 percent 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 Futures as under the Current Trends Scenario, because of the significant demand shift away from livestock products. This leads to the assumed stagnation of investment in the sector and no additional efficiency gains are created in comparison to the Current Trends scenario.

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. 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 the Low-Energy-Demand scenario[40] (see also next section) 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 Futures scenario. With a substantial carbon tax, deforestation reduces to a minimum and afforestation increases such that from 2020 onwards there is already a net increase in forest areas globally.[ii]

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 watts per square metre (W/m2) and an approximate greenhouse gas concentration of 850 parts per million (ppm) carbon dioxide equivalent when emissions are projected to stabilise after the end of the century (see van Vuuren et al.[41] 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-degrees Celsius 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 CO2 fertilisation effects (for more details see Leclère et al.[42]). 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 Futures scenario explores the effects of realising food security and improvements in diets, while also pursuing a development pathway that is in line with limiting global warming to 1.5-degrees Celsius above pre-industrial levels and halting and reversing biodiversity loss. The final results of the Better Futures scenario are based on the low energy demand (LED) pathway without BECCS deployment, based on an assumed 40 percent reduction in final energy demand through energy efficiency improvements by 2050.[40] Grubler et al.[40] 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-degrees Celsius target with limited additional energy demand from biomass of only around 11 EJ and a carbon price of 129 USD per tonne of carbon dioxide equivalent (tCO2e) by 2050.

For comparison, a second alternative 1.5-degrees Celsius mitigation scenario was also considered. This alternative 1.5-degrees Celsius 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 (those produced from food crops) in 2050, but these are not assumed to contribute largely to mitigation and are kept constant over scenarios. Overall, in the Current Trends scenario, energy from biomass declines from current levels of 56 exajoules (EJ) to 41 EJ in 2050 due to reduced traditional fuel wood consumption. In the Better Futures scenario energy demand from biomass increases an additional 11 EJ in 2050 compared to Current Trends, but remains below current levels.

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 at very different levels, 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 modelling results on biodiversity.

[ii] Note: The FOLU Global Consultation Report recommends a broader toolbox beyond a carbon tax, including regulatory and policy measures, to drive a Zero Net Deforestation agenda (see chapter 3, critical transition 3 on protecting and restoring nature).

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.[4] explored through an integrated modelling 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, this approach was emulated with a focus on the effects of land use constraints, mitigation, and dietary shifts under the Better Futures 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 what they would be if the region were still covered with primary vegetation and facing minimal human pressures.[43] The model relies on the relationship between land use activities and BII modelled from the PREDICTS database of biodiversity and land use records.[4,44] 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 percent 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 percent in 1970 to 78.6 percent in 2014.[4] 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. It is important to recognise that although this may not seem like a significant decline, it is concomitant with the loss of half of all wildlife species on the planet during the same period.

For the Better Futures scenario the model applies two complementary strategies. First, it assumes 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, it assumes a pervasive effort to reconfigure 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 per hectare in 2020 and grows exponentially to 300 USD per hectare in 2050. The tax or subsidy applies to a change in the regional biodiversity stock. This accounts for the varying extent to which different grid cells potentially hold more or less biodiversity, and the extent to which different land uses prevent this potential to materialise (see Leclere et al.[4] 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, a new set of global land-use forcing datasets called 'land use harmonisation' (LUH2) are used to inform whether natural vegetation is forested or not in a particular grid cell.[344] In these grid cells, the restored area is considered as a form of afforestation. It is however considered to sequester carbon at a slightly lower level than afforestation dedicated to carbon sequestration as inferred from G4M parameters (as it could rely on different species mix and management). This restoration-related afforestation (both area and carbon gain) is conservation-driven and occurs 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-based protein. In the Better Futures scenario, through a concerted reform effort in the management of half of the world's marine fish stocks, annual capture production is stabilised at a sustainable level of 75 Mt by 2050. Freshwater/inland capture remains stable at the current level of 12 Mt, the same as in the Current Trends scenario. Continued investment in aquaculture technology and management results in a 50 percent 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 grow nearly twice as fast as in the Current Trends scenario, 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. Mollusc/bivalve production and consumption continues to grow and is boosted to 4 percent per annum (as opposed to the average annual growth rate of the last ten years of 3.1 percent) 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 Futures 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.

Technical Annex ii) The Construction of Socio-Economic Scenarios with the "Shockwaves" Model of The World Bank

The Better Futures scenarios constructed in GLOBIOM did not include a direct estimate of the impact of transforming food and land use systems on inclusion, one of the key goals of the food and land use systems transformation advocated in this report. This called for complementary and interlinked analysis.

The tool chosen for this task was the model that informed the analysis of *Shockwaves*,[345] the World Bank 2016 flagship publication. That model (referred to here for simplicity as the Shockwaves model) had been coupled with results from GLOBIOM to arrive at the estimates of the poverty impacts of climate change presented in the Shockwaves publication.[1]

The distributional impacts of the baseline and Better Futures scenarios are based on the World Bank's Global Monitoring Database (GMD). The GMD is a harmonised collection of household income and expenditures surveys covering 140 countries, and is currently used for monitoring progress towards SDG1 (the share of the world population living below the international poverty line). As information detailed enough for the scenario modelling is available for only half the 140 countries, the modelling results are reweighted following standard procedures adopted by the World Bank for estimates based on the GMD.

For the purposes of this report, the Shockwaves model has been used to contrast different indicators of inclusion under the baseline results of SSP2 with those of a Better Futures scenario. SSP-based projections of population and economic growth, urbanisation, and education are used to define the baseline scenario in 2030, while key aggregate trends produced by GLOBIOM's Better Futures (food prices, aggregate productivity) and some specific policy actions integral to the ten critical transformations advocated in this report are used to define the Better Futures scenario.

Identifying the elements of the critical transformations most relevant for rural livelihoods, and parametrising the corresponding policy shifts has been challenging, given how the literature emphasises both the heterogeneity of impacts and the potential of "bundled" interventions to overcome the significant barriers that poorer farmers face.[iii] Rather than trying to capture the effects of the whole package of investments in physical and human capital and of the extensive institutional changes envisioned by the Better Futures, these scenarios focus on a few policy levers. Their potential impacts on rural livelihoods have been parametrised aiming to be both consistent with broad findings in the literature where applicable and transparent about the inescapable degree of arbitrariness in conducting this global exercise, in a context of complete change.

Technical Annex Table 2 details assumptions made in constructing the scenarios. The features of the Better Futures scenario that are modelled as key to changes in rural livelihoods include: new income sources for payments for ecosystem services; productivity growth due to training; and employment shifts, due to higher demand for low skilled labour for the production of fresh fruit and vegetables and the development of local agro-processing.

[iii] E.g. review by Farmer income lab (2019) https://www.farmerincomelab.com/Content/Theme/docs/What%20Works_FINAL_9.19.pdf

Technical Annex Table 2: Assumptions used in constructing the Better Futures rural livelihood scenario for 2030

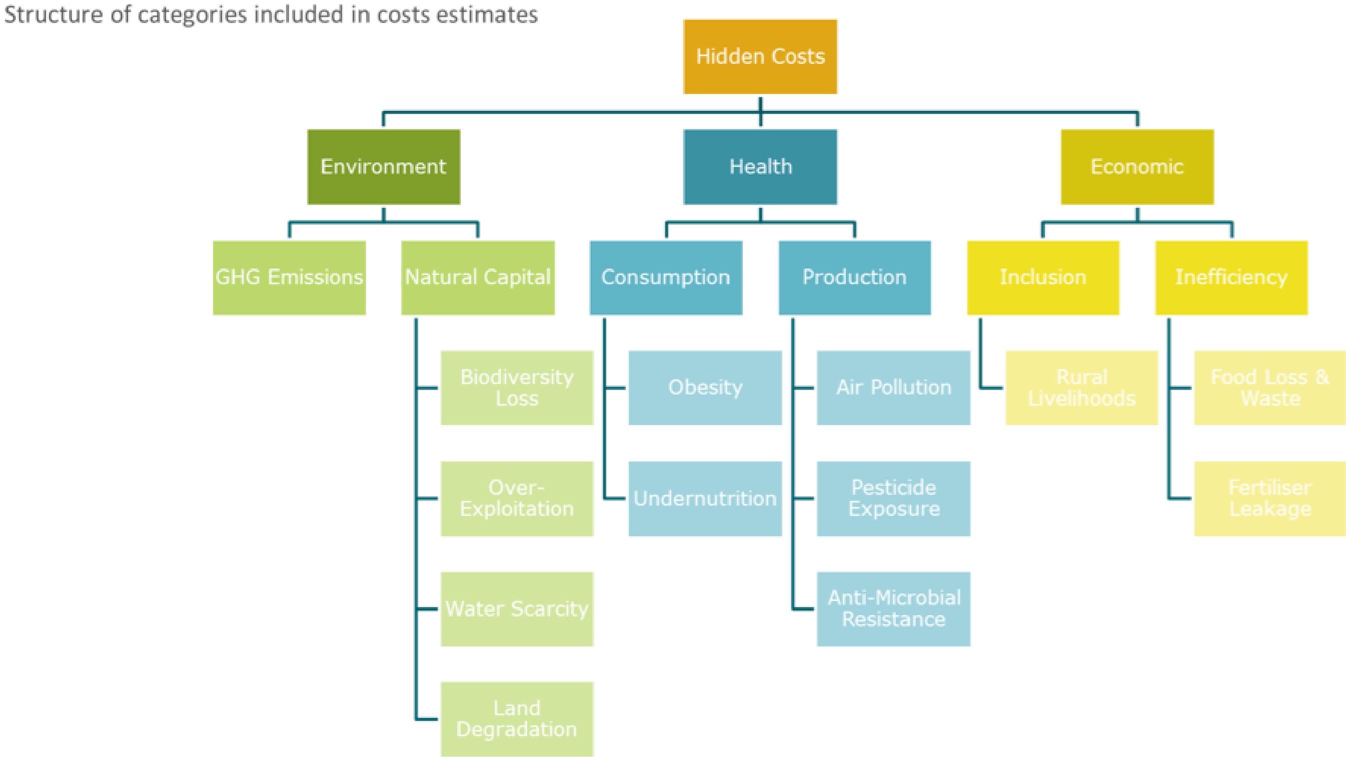
Key driver	Policy lever	Changes to rural livelihoods in addition to those of the Current Trends (SSP2 based)
Income sources	Payments for ecosystem services, PES	60 percent of the budget of the REDD+ payments are directly allocated to farmers in the 30 tropical countries with the greatest extent of tropical forest for PES provision. Country allocations of these funds are assumed to be proportional to forest cover. This is an unrealistic assumption in terms of how this finance will actually flow, but still gives a reasonable picture of the livelihood impact.
Productivity growth	100 million farmers trained	75 percent of those who receive training see their income increase, halving the skill gap between those low skilled and high skilled workers.
Employment growth	Growing demand for fruit and vegetables	Low skilled labour demand grows by an additional 5 percent
	100 million entrepreneurs trained	Three quarters of those who receive entrepreneurship training use them in their jobs and create low skilled jobs in farming (30 million), and agri-processing (60 million in services, 50 in manufacturing).

Technical Annex iii) Methodological Note on "Hidden Costs" Analysis

This note explains the methodological approach followed to estimate the "hidden costs" of global food and land use systems, as presented in in this report. The note also provides an account of the data sources and assumptions used in our calculations. A separate document offers a complete discussion of this exercise and provides more detail on the methodology and assumptions employed for projecting costs to 2050.[1]

Hidden costs refer to the negative externalities and inefficiencies that arise from our current means of production and consumption of food. This includes economic, health and environmental costs. The full list of categories considered is shown in the diagram below:

Technical Annex Exhibit B: Overview of Hidden Cost Categories



This analysis does not adopt a strict economic definition of externalities, but instead includes more broadly the top sources of lost value or of human and social costs related to global food and land use systems. Depending on the specific issue, this could include estimates of abatement costs, social costs, productivity losses or the lost economic value from inefficient resource use. In addition, the extent to which different losses or costs could be effectively quantified varies significantly across the three dimensions considered. As a result, this exercise provides a reasonably reliable indicative measure of the order of magnitude of hidden costs, but not in any way a conclusive answer. A key aim is to inform debate on this subject and inspire future research.

In the report estimates of the "economic prize" from hidden cost reduction by 2030 and 2050 are also presented. These figures are calculated as the difference in the global hidden costs under the Better Futures and Current Trends scenarios. They provide an indicative estimate of the potential benefits accruing to the global economy from following the better future development path relative to remaining on the current trend trajectory. To be sure, this

is not a direct benefit in terms of value-add to GDP, but rather a reduction in the size of the externalities currently stemming from food and land use. Removing the externalities indirectly results in greater GDP growth.
Technical Annex Table 3 summarises the key steps for calculating the costs for each category, as presented in Technical Annex Exhibit B. The table presents in each row the different elements of the calculation, with a brief description of each variable included in the analysis, as well as the data source. The estimates and assumptions presented have been corroborated by third-party sources and expert interviews whenever possible, to validate estimation approaches, key metrics and scope. All costs are presented in 2018 prices.

To project the hidden costs into the future the analysis relies on the outputs of different modelling exercises (GLOBIOM, the World Bank Shockwaves model and the IHME GBD database), combined with the recommendations of this report. In particular:

- For obesity: the IHME provides us with forecasts of DALYs from obesity for every year to 2050, forming the basis of our cost projections.
- For air pollution and undernutrition related DALYs, the IHME forecasts from the GBD foresight database to 2040 have been extrapolated to 2050.
- For GHG emissions, water scarcity, land degradation, biodiversity costs, food loss and waste and fertiliser leakage the analysis relies on GLOBIOM results. The current cost estimates for these categories are projected forward based on model outputs for relevant variables in their calculation; the costs themselves are not endogenous to the model.
- Rural welfare costs are calculated endogenously in the World Bank Shockwaves model. Since this model only projects to 2030 these values are maintained to 2050 in the hidden costs calculations.

For a complete account of the methodology used to project hidden costs, please refer to the methodological note on this subject. It provides a full account of the assumptions and techniques used in our calculations.

Technical Annex Table 3: Summary of the calculations for the hidden costs analysis, with notes on the assumptions and input sources

Category	Cost	Value	Units	Comment	Source
Health	Obesity	148 million	DALYs	Loss of productive life measured by Disability-adjusted life years (DALYs_ caused by over-consumption. DALYs = years of life lost to death or disability. Obesity and overweight proxied by DALYs related to high-body mass index (BMI) risk factor.	IHME GBD (2017)[2]
		x			
		$17,971	GDP/ Capita ($ PPP)	Global average output (gross domestic product or GDP) per capita in 2018 international dollars (using purchase power parity or PPP exchange rates).	World Bank (2018)[3]
	+				
	Undernutrition	101 million	DALYs	Loss of productive life measured by DALYs caused by under-consumption. Undernutrition proxied by DALYs related to child growth failure, including child stunting, wasting and underweight.	IHME GBD (2017)
		x			
		$17,971	GDP/ Capita ($ PPP)	Global average output per capita in international dollars.	World Bank (2018)

Category	Cost	Value	Units	Comment	Source
Health	+				
	Air Pollution	90 million	DALYs	Loss of productive life measured by DALYs caused by ambient particulate matter and ozone pollution.	IHME GBD (2017)
		x			
		$17,971	GDP/ Capita ($ PPP)	Global average output per capita in 2018 international dollars.	World Bank (2018)
		x			
		23%	Percent	Proportion of total global GHG emissions from food and land use systems.	IPCC (2019)[4]
		+			
		60 million	DALYs	Loss of productive life measured by DALYs caused by pollution from household solid cooking fuels.	IHME GBD (2017)
		x			
		$17,971	GDP/ Capita ($ PPP)	Global average output per capita in 2018 international dollars.	World Bank (2018)
		x			
		90%	Percent	Proportion of solid cooking fuels from biomass (including agricultural residues, biomass, charcoal, dung, and wood).	IEA (2017)[5]
	+				
	Pesticide Exposure	0.02/ kg.	DALYs per kg.	Loss of productive life measured by DALYs caused by application of the pesticides. Measured in DALYs per kilogram applied of insecticide, herbicide, fungicide & bactericide, respectively.	Fantke & Joliet (2016)[6]
		x			
		4 million	Tonnes	Total global annual pesticide application. Calculated separately for insecticides, herbicides, fungicides & bactericides.	FAOSTAT (2016)
		x			
		$17,971	GDP/ Capita ($ PPP)	Global average output per capita in 2018 international dollars.	World Bank (2018)

Category	Cost	Value	Units	Comment	Source
Health	+				
	Anti-Microbial	$1,377	$ billions	Total global annual GDP loss attributable to AMR (net present value 2010-2050). Study covers HIV, tuberculosis, malaria and infections from E. coli, S. aureus, K. pneumoniae.	RAND (2014)[7]
		x			
		22%	Percent	Percentage of AMR related to food systems.	CDC (2013)[8]
Environment	Greenhouse Gas (GHG) Emissions	13.75	Gt. CO_2e / year	Total global annual GHG emissions from food and land use systems, including agricultural production, deforestation and supply chain.	IPCC (2019)
		x			
		$100	$/ tonne CO_2e / year	Average of range of marginal abatement costs for global GHG emissions from 2020-2050.	CPLC (2017)[9]
		+			
		122 million	Tonnes /year	Global production of nitrogen fertiliser.	FAOSTAT (2016)
		x			
		6.2	tCO_2e / tonne	Average GHG emissions from production of nitrogen fertiliser.	Fertiliser Europe[10]
		+			
		$100	$/ t$CO_2$e	Average of range of marginal abatement costs for global GHG emissions from 2020-2050.	CPLC (2017)
	+				
	Land Degradation	666 million	Hecta-res	Total global area of degraded cropland.	FAO GLASOD[11]
		x			
		$1,542	$ per hectare	Annual value of crop production per hectare of cropland.	FAOSTAT (2016)
		x			
		8%	Percent	Yield loss from land degradation.	Panagos et al. (2017)[12]

Category	Cost	Value	Units	Comment	Source
Environment	Land Degradation	+			
		913 million	Hecta-res	Total global area of degraded pastureland.	FAO GLASOD
		x			
		$387	$ per hectare	Annual value of livestock production per hectare of grassland.	FAOSTAT (2016)
		x			
		8%	Percent	Yield loss from land degradation.	Panagos et al. (2017)
		+			
		1578 million	Hecta-res	Total global area of degraded land.	FAO GLASOD
		x			
		$897	$ per hectare	Economic value of soil ecosystem services per hectare.	Jónsson & Davíð-sdóttir (2016)[13]
		x			
		25%	Percent	Loss of soil biodiversity from land degradation.	Expert opinion (2019)
	+				
	Water Scarcity	2769 km^3	Km^3/ year	Total global annual freshwater withdrawals for agriculture.	FAOSTAT (2016)
		x			
		$1.15	$ per m^3/ year	Global average scarcity cost of water.	FAO (2014)
		x			
		25%	Percent	Share of freshwater withdrawals for agriculture that are unsustainable or at risk of becoming unsustainable (defined as extraction levels that are unsustainable for at least 1 month per year).	GLOBI-OM

Category	Cost	Value	Units	Comment	Source
Environment	+				
	Biodiversity Loss	$5,324	$ per hectare	Economic value of ecosystem services from tropical forest per hectare.	De Groot et al. (2012)[14]
		$232, 103	$ per hectare	Economic value of ecosystem services from mangroves per hectare.	
		x			
		5.4 million	Hecta-res	Annual rate of deforestation caused by agriculture.	Global Forest Watch (2018)[15]
		8,400	Hecta-res	Annual rate of mangrove loss caused by aquaculture.	
		+			
		$89	$ billions	Total water contamination and biodiversity costs from eutrophication caused by agricultural fertiliser runoff. Based on country-specific studies, converted to global estimate via benefit transfer method & scaled to total food production.	FAO (2014) [16]
		+			
	Over-Exploitation	$430	$ billions	Total global annual value of crop production reliant on pollinator services..	IPBES (2018)[17]
		x			
		24%	Percent	Global average yield reduction from loss of pollinators.	Garibaldi et al. (2013)[18]
		+			
		$83	$ billions	Total annual economic cost of over-fishing beyond maximum global sustainable yield.	World Bank (2017)[19]
Economic	Rural Welfare	$5.50	$ per day	Poverty line for upper middle-income countries.	World Bank (2018)[20]
		x			
		40%	Percent	Average global rural poverty gap as a share of the upper middle-income country poverty line.	Walsh & Rozen-berg (2019)[21]

Category	Cost	Value	Units	Comment	Source
Economic	Rural Welfare			x	
		3.7 billion	Number of people	Total population living below $5.50 poverty line (calculated regionally).	Walsh & Rozenberg (2019)
				x	
		68%	Percent	Share of world's poor in rural areas (calculated regionally.	Walsh & Rozenberg (2019)
				x	
		40%	Percent	Share of rural poor employed in agriculture.	Walsh & Rozenberg (2019)
				+	
	FLW	32%	Percent	Share of total food production that is lost or wasted (measured in terms of weight).	FAO (2011)[22]
				x	
		$3.725	$ trillions	Total annual value of global agricultural production.	FAOSTAT (2016)
				+	
	Fertiliser Leakage	44%	Percent	Average leakage rate of nitrate fertilisers.	YARA[23] Roberts & Johnston (2015)[24]
		50%	Percent	Average leakage rate of phosphate fertilisers.	
				x	
		110 million	Tonnes	Total global application of nitrate fertilisers.	FAOSTAT (2016)
		48 million	Tonnes	Total global application of phosphate fertilisers.	
				x	
		$135	$ per tonne	Global average price of nitrates (nutrient).	World Bank (2019)[25]
		$74	$ per tonne	Global average price of phosphate (nutrient).	

Technical Annex iv) Methodological Note on "Investment requirements"

This note explains the approach taken to estimate the investment requirements of the Better Futures scenario to 2030 via the ten critical transitions identified in the report.

The investment requirements are based on the additional capital investment expenditures (CAPEX) and long-term operational expenditure (OPEX) needed to deliver the ten critical transitions. Both public and private investments are included. These estimates do not include investment requirements for food production outside the key areas of the transformation or to meet goals not covered by the critical transitions. The costs of policy implementation or re-allocation of existing subsidies are also not included. The Better Futures scenario also depends on other sectors delivering their part to reach the Paris Agreement targets on climate change – investments for that purpose are not included.

These estimates could be considered too high in certain domains, especially if technological advancements or shared economy models bring future costs down (e.g. solar-powered pumps for irrigation, shared tractors and warehouses for mechanisation and storage, or regenerative farmer "hubs" to lower cost of inputs and machinery through joint purchases). In other cases, disruption of current markets through innovation could be greater than estimated (e.g. cultured meat and offshore mariculture) and require more investment.

A full account of the data sources and assumptions used in these calculations is provided below. Key variables from GLOBIOM (e.g. population numbers, areas reforested, new irrigated areas) have been used to tailor the assumptions to the Better Futures scenario. If estimates were not readily available, they have been produced by the authors in the Blended Finance Taskforce at SYSTEMIQ.

Estimates have been generated for yearly investment requirements for the period 2018 to 2030, assuming the critical transitions are going to be achieved by 2050, in line with the modelling for the Better Futures scenario outcomes in GLOBIOM. All costs are presented in 2018 prices. Estimates and assumptions have been corroborated by third-party sources and expert interviews whenever possible, to validate estimation approaches, key metrics and scope. These are summarised in Table 4 below.

Technical Annex Table 4: Estimated additional yearly investment requirements and related assumptions in the Better Futures scenario to 2030 via ten critical transitions

Category	Critical Transition	Investment requirement (M$/yr) 2018-2030	Assumptions	Source
Nutritious Food	1: Healthy Diets	17,000	**Product Reformulation** 15 percent of revenues from the food processing and handling sector are spent to upgrade equipment for product reformulation; the size of the product reformulation market 2018-2030 is estimated at a compound annual growth rate (CAGR) of 5 percent, starting from a ~$45 billion 2016 market. 1 percent of the $2 trillion processed food market is spent on research and development (R&D) and one third is allocated towards product reformulation.	McKinsey (2018)[1,2]
		7,000	**Global Nutrition Targets** $7 billion annual investment is needed to meet the Global Nutrition Targets of reducing stunting, female anaemia and low birth weight, halting the increase of childhood overweight, increasing breastfeeding and reducing wasting.	World Bank (2016)[3]; WHO (2014)[4]
		5,200	**Targeted School Feeding Programmes** 50 percent of 209 million school children with stunting and wasting receive targeted school feeding programmes at an average cost of $50 per child per year.	World Bank (2016)[5] Kristjansson et al. (2016)[6]
		1,600	**R&D** Public and private R&D spending across food and land use systems grows from 0.07 percent GDP (2018) to 0.1 percent of GDP by 2030. Total additional R&D spending 2018-2030 is $197 billion. 10 percent of the additional R&D spending is allocated to nutritious food for product reformulation of HFSS foods, evaluating the impact of targeted school feeding programmes and evaluating progress on nutrition targets at the national level.	Pardey et al. (2016)[7]

Category	Critical Transition	Investment requirement (M$/yr) 2018-2030	Assumptions	Source
Nature-Based Solutions	2: Productive & Regenerative Agriculture	4,500-5,500	**Implementation of Regenerative Farming Practices** 30 percent of farmed land implements regenerative farming practices, building from the 20 percent already implementing some form of regenerative farming practice today. The average cost for expert agronomist training and long term OPEX is $132 to 173 per hectare in developed countries and $103 to 120 per hectare in developing countries.	FAOSTAT (2016)[8]; McKinsey Global Institute (2011)[9]; Interviews with experts and practitioners
		13,500-15,500	**Closing the Productivity Gap** 100 million low skilled farmers receive basic extension services at an average cost of $100 to $170 per farmer depending on crop type and geography. Capital equipment is improved across 262 million ha at an average cost of $575 to 644 per hectare.	McKinsey Global Institute (2011)[10]; Interviews with experts and practitioners
		4,300	**Irrigation Efficiency** Irrigation efficiency is improved across 5 percent of current irrigated cropland in developing countries (243 million ha) at an average cost of $4,232 per hectare.	IFPRI (2017)[11]
		6,700	**Organic and Biofertiliser Production** 5 percent of revenues from the chemical fertiliser market are invested in organic and biofertiliser production each year to support additional market growth, starting from a $105 billion market growing at a CAGR of 3.7 percent to 2030.	The Business Research Company (2019)[12]
		3,100	**Organic and Biopesticide Production** 5 percent of revenues from the chemical pesticide market are invested in organic biopesticide production each year to support additional market growth, starting from a $48 billion market in 2018, growing at a CAGR of 3.1 percent to 2030.	Mordor Intelligence (2018)[13]

Category	Critical Transition	Investment requirement (M$/yr) 2018-2030	Assumptions	Source
Nature-Based Solutions	2: Productive & Regenerative Agriculture	3,300	**R&D** Public and private R&D spending across food and land use systems grows from 0.07 percent GDP (2018) to 0.1 percent of GDP by 2030. Total additional R&D spending 2018-2030 is $197 billion. 20 percent of the additional R&D spending is allocated to regenerative practices for soil health (fertiliser optimisation compounds, gene edited plants with improved nitrate absorption); water (water productivity enhancements, groundwater sustainability, agricultural water pollution); agrobiodiversity (agroecological intensification, crop diversification, biodiversity mapping).	Pardey et al. (2016)[14]
	3: Protecting & Restoring Nature	29,000- 49,000	**Forest Restoration (incl. Peatlands)** 294 million hectares of global forest and peatland are restored in the Better Futures 2030 scenario at an estimated cost of $1200 to 2000/ha (costs range from $454/ha to $7,373 and mainly depend on costs of labour and type of restoration intervention).	Verdone (2016)[15] case studies
		14,000	**REDD+ Programme for Forest Conservation** REDD+ financing to halt deforestation reaches $50 billion per year in 2030, growing from $1 billion investment in 2019.	Boucher (2008)[16]
		870-1,300	**Forest Management** Total area of existing forest grows by 80 million hectares by 2030 in the Better Futures 2030 scenario, with a gradual yearly increase of total hectares to be managed at an average cost of $20 to 30 per hectare.	Case studies
	4: A Healthy & Productive Ocean	4,200	**Sustainable Fisheries** Governments compensate for 20 per cent of the estimated cost for fleet decommissioning and fishermen re-training to reduce wild catch to a level commensurate with maximum sustainable yields.	Sumaila et al. 2012[17]

Category	Critical Transition	Investment requirement (M$/yr) 2018-2030	Assumptions	Source
Nature-Based Solutions	4: A Healthy & Productive Ocean	800	**Bivalve Production** An additional 16 million metric tonnes is produced by 2030 at an average cost of $605 per metric tonne.	Rubino (2008)[18]
		2,500	**Finfish Aquaculture Expansion** An additional 4.5 million metric tonnes is produced by 2030, 20 percent from new intensive onshore and near shore farms at an average upfront cost of $20,000 per metric tonne, and 5 percent from offshore mariculture farms at an average upfront cost of $52,000 per metric tonne.	Robinson (2017)[19]; Interviews with experts and practitioners
		350	**Aquaculture Sustainable Intensification Training** 50 percent of 19 million aquaculture farmers receive training on sustainable production at an average cost of $450 per farmer.	FAO (2018)[20]; Interviews with experts and practitioners
		1,200	**Mangrove Restoration** 25 percent (4.25 million hectares) of total lost mangroves are restored by 2030 at an average cost of $3,379 per hectare.	TEEB (2009)[21]
		3,300	**R&D** Public and private R&D spending across food and land use system grows from 0.07 percent GDP (2018) to 0.1 percent of GDP by 2030. Total additional R&D spending 2018-2030 is $197 billion. 20 percent of the additional R&D spending is allocated to alternative fish feed, intensification impacts and scaling up of innovative production methods such as multitrophic aquaculture and offshore mariculture.	Pardey et al., (2016)[22]

Category	Critical Transition	Investment requirement (M$/yr) 2018-2030	Assumptions	Source
Wider Choice & Supply	5: Diversifying Protein Supply	1,800-7,500	**Plant-Based Meat** 14 percent of revenues from plant-based meat market is invested every year, starting from a $8.4 billion market in 2018, growing at a CAGR of 6.12 percent to 26.42 percent to 2030.	Research and Markets (2018)[23]; Barclays (2019)[24]; Beyond Meat (2019)[25]
		11,500-14,500	**Plant-Based Dairy** 33 percent of revenues from the plant-based dairy market is invested every year, starting from a $14 billion market in 2018, growing at a CAGR of 11.4 percent to 17 percent to 2030.	Research and Markets (2019a)[26]; Crunchbase (2019)[27]
		250-320	**Edible Insect Protein** Estimated market size in 2030 is expected to produce 730,000 million to 0.91 million tonnes at an average upfront cost of $4,273 per tonne.	Research and Markets (2019b)[28]; Interviews with experts and practitioners
		3,300	**R&D** Public and private R&D spending across food and land use grows from 0.07 percent GDP (2018) to 0.1 percent of GDP by 2030. Total additional R&D spending (2018-2030) is $197 billion. 20 percent of the additional R&D spending is allocated to alternative protein; cultured meat production; alternative feed for cows (e.g. algae); improvements in nutritional outcomes of plant-based meat and dairy.	Pardey et al., (2016)[29]
	6: Reducing Food Loss	680	**Demand Management in Developed Countries** A 30 percent reduction of consumer food waste (which is ~50 percent of food waste in developed countries) is targeted through consumer food waste reduction campaigns at an average cost of $43 per reduced tonne of food waste.	Lipinski et al., (2013)[30]; WRAP (2012)[31]

Category	Critical Transition	Investment requirement (M$/yr) 2018-2030	Assumptions	Source
Wider Choice & Supply	6: Reducing Food Loss	8,500	**Postharvest Waste in Developing Countries** Postharvest waste during storage and transportation is reduced for 30 percent of farming in developing countries at an average cost of $390 per hectare for perishables and $230 per hectare for non-perishables.	FAOSTAT (2016)[32]; McKinsey Global Institute (2011)[33]
		19,600	**Supply Chain Waste** Supply chain waste for 15 percent of farming in developing countries and 5 percent in developed countries is reduced through expanded and improved infrastructure (incl. cold chain supply) at an average cost of $920 to 1340 per hectare.	FAOSTAT (2016)[34]; McKinsey Global Institute (2011)[35]
	7: Local loops & Linkages	5,600	**Urban Farming** An additional 15 percent of urban-farmed vegetables and selected fruits consumed in cities (>100,000 people) are produced by vertical and greenhouse farming at an average cost of $4,500 per tonne.	Ellen MacArthur Foundation (2019)[36]; Proxy: Bright Farms (2018)[37], AeroFarms (2018)[38]
		2,900	**Composting of Inedible Foods** 10 percent of inedible food is composted via anaerobic digesters from current levels of 4 percent, requiring an additional 6 percent of inedible foods to be composted every year at an upfront cost of $154 per tonne.	Ellen MacArthur Foundation (2019)[39]; Proxy: World Biogas Association & C40 (2018)[40]
		1,700	**R&D** Public and private R&D spending grows from 0.07 percent GDP to 0.1 percent of GDP by 2030. Total additional R&D spending 2018-2030 is $197 billion. 10 percent of the additional R&D spending is allocated towards circular and resource efficient economies for indoor cultivation of diversified crops and fish; hydroponics, aquaponics and aeroponics production methods.	Pardey et al., (2016)[41]

Category	Critical Transition	Investment requirement (M$/yr) 2018-2030	Assumptions	Source
Opportunity for All	8: Digital Revolution	1,400-2,400	**Precision Agricultural Machinery** Advanced precision farming is implemented on 30 percent of farms in developed countries at an average cost of $100 to 178 per hectare.	McKinsey Global Institute (2011)[42]
		9,200	**Agtech Investment** Investments in agribusiness marketplaces, farm management software, sensing & IoT, farm robotics and midstream technologies increase by 150 percent by 2030 from current levels.	AgFunder (2018)[43]
		3,300	**R&D** Public and private R&D spending grows from 0.07 percent GDP to 0.1 percent of GDP by 2030. Total additional R&D spending 2018-2030 is $197 billion. 20 percent of the additional R&D spending is allocated towards digital technologies, to further develop and scale sensing, measurement and monitoring technologies and mapping and data systems for soil health, water and pests, precision technologies for irrigation and agro-chemical technologies, online marketplaces.	Pardey et al., (2016)[44]
	9: Stronger Rural Livelihoods	32,000-38,000	**Rural Infrastructure** Better rural infrastructure to facilitate market access is built for 30 percent of farms in developing countries at an average cost of $505 to 740 per hectare. Closing the clean energy access investment gap in rural areas requires $18.3 billion a year.	McKinsey Global Institute (2011)[45]; IEA (2018)[46]; SE4All & CPI (2018)[47]
		3,700	**Access to Clean Cooking** Closing the investment gap to achieve universal access to clean cooking in rural areas requires $3.6 billion a year.	IEA (2018)[48]; SE4ALL & CPI (2018)[49]
		6,500	**Irrigation Expansion** New irrigation infrastructure for 11 million hectares of cropland by 2030 at an average cost of $4,000 to $20,880 per hectare depending on geography.	Developing countries irrigation cost - IFPRI (2017)[50], USA - Maughn et al., (2017)[51]

Category	Critical Transition	Investment requirement (M$/yr) 2018-2030	Assumptions	Source
Opportunity for All	9: Stronger Rural Livelihoods	5,500	**Connectivity** 40 percent of 1.2 billion rural population without internet are connected to the internet at a rate of 40 million people per year at an average cost of $21 per person per year.	Our World in Data (2018)[52]; GSMA (2018)[53]; A4AI (2018)[54]
		8,300-17,000	**Training of Entrepreneurs** 100 million young agricultural entrepreneurs are trained with management and technical skills at an average cost of $1000 to 2000 per person.	Interviews with experts and practitioners
		16,500-18,300	**Financing Needs of Smallholder Farmers** Short-term yearly financing of $95 to 105 per farmer (for inputs, harvest, export) and long-term financing of $95 to 105 per farmer (for renovation and equipment) is provided to 161 million of non-commercial smallholders.	Goldman et al. (2016)[55]
		21,600	**Safety Nets for Rural Resilience** Safety nets to build more resilience into rural economies (e.g. payments to poor and vulnerable households, or cash and food payments for building local infrastructure or protecting the environment) are provided in low-income and lower-middle-income countries at an estimated cost 0.3 percent of GDP.	Economist (2018)[56]
	10: Gender & Demography	3,000	**Family Planning** Contraception is made available to 50 percent of female population (214 million women) with unmet needs in developing countries.	Darroch et al., (2017)[57]
		14,000	Girls' Education 130 million girls out of school (divided by age and years of education necessary to complete primary, lower secondary and upper secondary school) are provided with an education at an average price of $1.25 a day.	Global Partnership for Education (2019)[58]; UNESCO (2018)[59]

Technical Annex v) Methodological Note on "Business Opportunities"

This note explains the approach taken to estimate the projected value of major business opportunities created under the "Better Futures" food and land use systems scenario in 2030 via the ten critical transitions identified in the report. Business opportunities include both revenue streams generated from growing new markets and resources freed up due to efficiency gains or shrinking sectors that can be re-allocated elsewhere in the system (e.g. less land needed for food production, income gains from higher productivity, avoided food disposal costs via composting). Of course, capital which is "saved" will not automatically be redeployed into the Better Futures transitions – it is especially difficult to shift from capital intensive physical assets into recurring operational expenditure costs of human and natural capital development. This capital reallocation in the Better Futures scenario will require the right overall enabling environment to be in place – especially for regulations, subsidies, information, risk and innovation.

A full account of the methodology, data sources and assumptions used in the business opportunity calculations is provided below. Key variables from GLOBIOM (e.g. population numbers, areas reforested, new irrigated areas) have been used to tailor the assumptions to the Better Futures scenario. If estimates were not readily available, then they have been produced by the Blended Finance Taskforce at SYSTEMIQ using secondary sources.

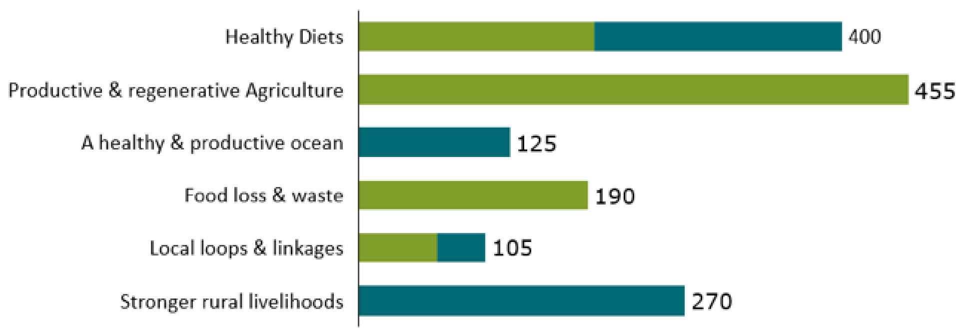
The estimates build on analysis from the Business & Sustainable Development Commission (BSDC)[1] which estimated that business opportunities from an SDG-aligned food and agricultural system were worth approximately $2.3 trillion per annum. Where possible, this analysis allocated the BSDC business opportunities to the ten critical transitions (see Exhibit C below). Two important modifications were introduced to align this opportunities analysis with the modelling efforts of the Global Consultation Report:

1. **Food loss and waste:** the assumption is a 15 percent reduction in food loss and waste by 2030 and a 25 percent reduction by 2050, compared to the 50 percent reduction by 2030 which was assumed in the BSDC report.

2. **Forest ecosystem services:** the current estimates for the Better Futures analysis focus on the portion of forest conservation and restoration projects that could, depending on countries' regulatory decisions, be carried out by the private sector, rather than estimating potential payments for ecosystem services generated by land use change more broadly.

Technical Annex Exhibit C: $1.5 trillion worth of business opportunities identified for "food and agriculture" in the BSDC report could be allocated across the ten critical transitions

USD billions (2017 prices)



Source: BSDC(2017), Valuing the SDG prize, unlocking business opportunities to accelerate sustainable and inclusive growth

After allocating the BSDC business opportunities to the critical transitions of the Better Futures scenario, estimates were generated for (a) revenues from new markets in a sustainable food and land use economy; and (b) freed up resources that can be re-allocated from assets in the old food and land use economy. These figures may be conservative in some instances, for example where market growth is still hard to predict (e.g. alternative proteins) or where markets do not yet exist or are in early stages of development (e.g. potential opportunities from new business models that derive value from standing natural forests such as wild honey or cosmetics from illipe nut butter). Estimates and related assumptions of the business opportunities are outlined in Table 5 below.

Technical Annex Table 5: Estimated yearly business opportunities and related assumptions in the Better Futures scenario in 2030 via ten critical transitions

Category	Critical Transition	Business Opportunities ($mn/yr) in 2030	Assumptions	Source
Nutritious Food	1: Healthy Diets	160,000	**Product Reformulation** Market size in 2030 grows by an additional 50 percent compared to estimates of 9 percent growth per annum from 2012.	SAM (2012)[2]
		100,000	**Additional Savings from Dietary Switch** Additional benefits from shifting to an ambitious meat reduction pathway (in line with the Better Futures scenario) resulting in further savings from pastureland valued at $500-740 per hectare.	WRI (2016)[3]
		600,000	**Fortified Food Markets** Market size in 2030 based on an estimated compound annual growth rate (CAGR) of 10.5 percent from a $57.7 billion market in 2015.	Research Nester (2019)[4]
		730,000	**Organic Food and Beverage Market** Market size in 2030 based on estimated CAGR of 14.56 percent from a $143 billion market in 2018.	Zion Research (2017)[5]
		45,000	**Feed Additives Market** Market size in 2030 based on an estimated CAGR of 4.54 percent from a $26 billion market in 2018.	Orbis Research (2018)[6]

Category	Critical Transition	Business Opportunities ($mn/yr) in 2030	Assumptions	Source
Nature-Based Solutions	2: Productive & Regenerative Agriculture	40,000	**Organic Fertiliser** Market size in 2030 based on an estimated CAGR of 14 percent from a $6.7 billion market in 2018).	Technavio (2018)[7]
		30,000	**Biopesticides** Market size in 2030 is based on an estimated CAGR of 17.4 percent from a $3.36 billion market in 2016.	Markets and Markets (2016)[8]
		5,000	**Biofertilisers** Market size in 2030 is based on an estimated CAGR of 14.08 percent from a $2.3 billion market in 2018.	Markets and Markets (2019c)[9]
	3: Protecting & Restoring Nature	200,000	**Forest Ecosystem Services** The private sector provides 10 percent of the estimated market opportunity of $50 billion needed for the REDD+ programme; 59 million hectares per year of reforestation activity is carried out privately at an estimated price of $3,000 per hectare; $20 billion is gained from providing other ecosystem services.	Rydge (2015)[10]
	4: A Healthy & Productive Ocean	40,000	**Sustainable Fisheries** 50 percent of $83 billion per year lost to unsustainable fisheries are recouped.	World Bank (2017)[11]
		130,000	**Sustainable Aquaculture** Market size for 2030 is based on an estimated CAGR of 5.2 percent from $170 billion in 2017, driven by increased aquaculture production.	Market Research (2018)[12]
		50,000	**Bivalves Production** Market size in 2030 based on a CAGR of 7.4 percent p.a. from a $21.4 billion market in 2018.	FAO (2016)[13]

Category	Critical Transition	Business Opportunities ($mn/yr) in 2030	Assumptions	Source
Wider Choice & Supply	5: Diversifying Protein Supply	140,000	**Plant-Based Meat** Market captures 10 per cent of the $1.4 trillion world meat market.	Barclays (2019)[14]
		90,000	**Plant-Based Dairy** Market size in 2030 is based on a CAGR of 17 percent from a $14 billion in 2018.	Grand View Research (2019)[15]; Research and Markets (2019a)[16]
		10,000	**Edible Insect Protein** Market size is based on a CAGR of 24.4 percent from a $0.4 billion market in 2019.	Expert interviews; Research and Markets (2019b)[17]
	6: Reducing Food Loss & Waste	120,000	**Reducing Consumer Food Waste in the Value Chain** 15 percent reduction of estimated 65 percent of $1.25 trillion worth of food wasted globally through the value chain in 2030.	Lipinski et al. (2013)[18]
		70,000	**Reducing Consumer Food Waste** 15 percent reduction of estimated 35 percent of $1.25 trillion worth of food wasted globally at consumption in 2030.	Lipinski et al. (2013)[19]
	7. Local Loops & Linkages	30,000	**Agricultural Waste for Biogas** Market size in 2030 is based on a CAGR of 6.5 percent from a $13 billion market in 2018.	Future Market Insights (2017)[20]
		60,000	**Greenhouse Horticulture** Market size in 2030 is based on a CAGR of 8 percent from a $24 billion market in 2018.	Adriot Market Research (2019)[21]

Category	Critical Transition	Business Opportunities ($mn/yr) in 2030	Assumptions	Source
Wider Choice & Supply	7. Local Loops & Linkages	40,000	**Vertical Farming** Market size in 2030 is based on a CAGR of 24.4 percent from a $1.8 billion market in 2017.	Allied Market Research (2017)[22]
		15,000	**Anaerobic Digestion** Market size in 2030 is based on CAGR 5.96 percent p.a. from $8.3bn in 2017 (assuming market size doubles from 2017 to 2030).	Vision Gain (2017)[23]
		30,000	**Composting/Avoiding Food to Landfill** Composting 230 million tonnes of inedible food between 2018- 2030 results in avoided costs of food waste disposal averaging $127 per tonne.	Ellen MacArthur Foundation (2019)[24]
Opportunity for All	8. Digital Revolution	25,000	**Precision Agriculture and Data** Market size in 2030 is based on an estimated CAGR of 14.9 percent from $4.5 billion market in 2018.	Allied Market Research (2016)[25]
		25,000	**Agricultural Drone Market** Market size in 2030 is based on an estimated CAGR of 31.4 percent from a $1.2 billion market in 2018.	Markets and Markets (2019a)[26]
		80,000	**Agricultural Robotic Market** Market size in 2030 is based on an estimated CAGR 25.34 percent from a $4.1 billion market in 2017. The agricultural robotic market includes: UAVS, milking roots, harvesting systems, driverless tractors.	Markets and Markets (2019a)[27]
		110,000	**Internet of Things for Agriculture** Market size in 2030 is based on an estimated CAGR of 14.5 percent from a $16.5 billion market in 2018. The IoT for agriculture includes: real time streaming analytics, security, monitoring, data management.	Acrognizance (2019)[28]

Category	Critical Transition	Business Opportunities ($mn/yr) in 2030	Assumptions	Source
Opportunity for All	9. Stronger Rural Livelihoods	40,000	**Electricity** An estimated 90 percent of poor people already spending approximately a total of $40 billion a year on kerosene lamps, candles, and disposable batteries to meet their lighting needs, which will be saved if the clean energy access gap is closed.	IFC (2012)[29]
		130,000	**Connectivity Income Gains** Internet connectivity allows 490 million people in rural areas to benefit from extension services, measuring and recording production and insurance payments via mobile phones increasing individual income by an average of $264 per year.	World Bank (2012)[30]; case studies

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Annex B:

Technical Annex

The
Food and Land Use
Coalition