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Supplemental information

Early systems change necessary for catalyzing long-term sustainability in a post-2030 agenda

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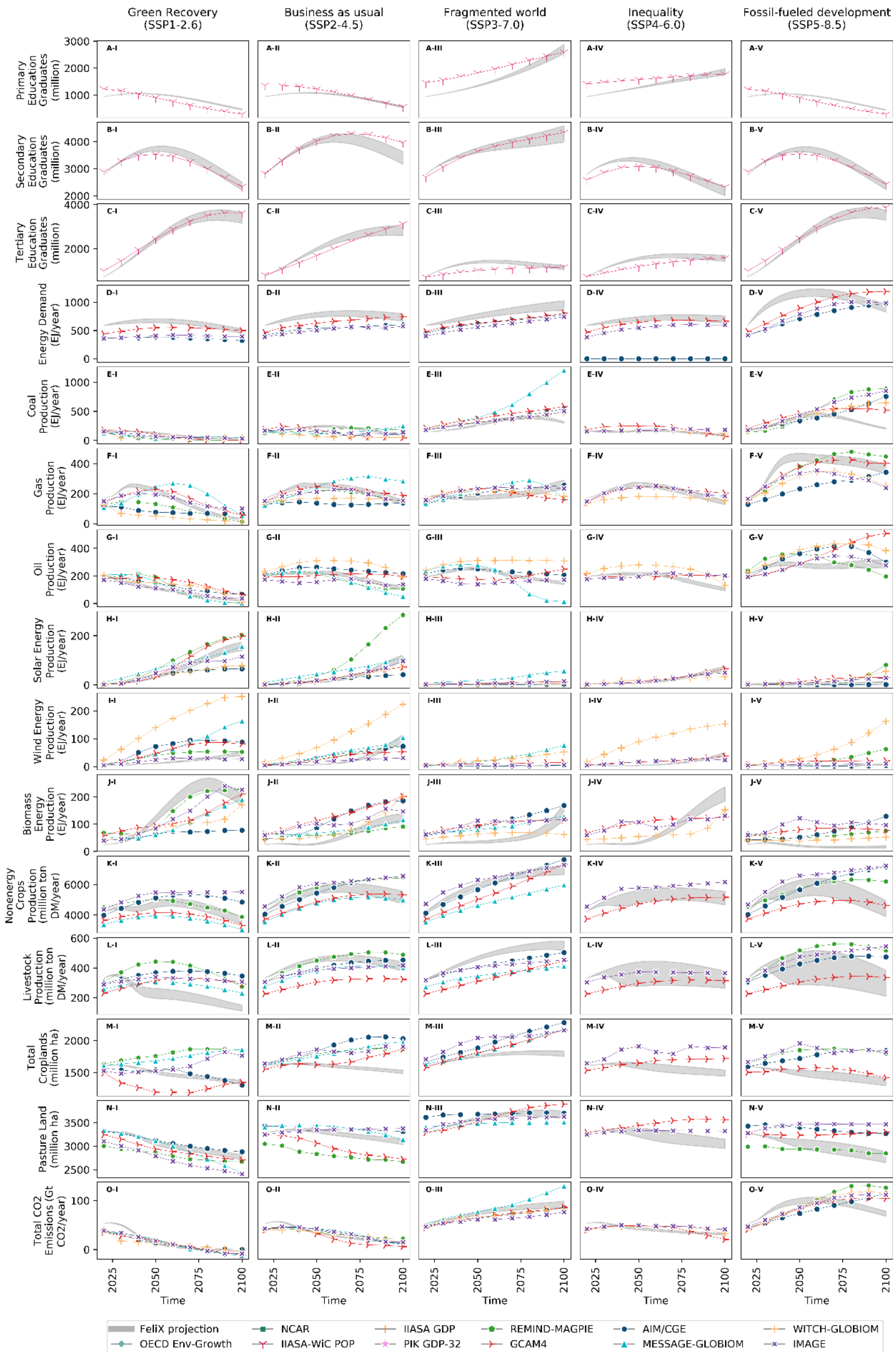


Fig. S1. Pathway simulation results against a suite of socioeconomic and environmental model outputs and comparison against similar simulation outputs of major models[1].

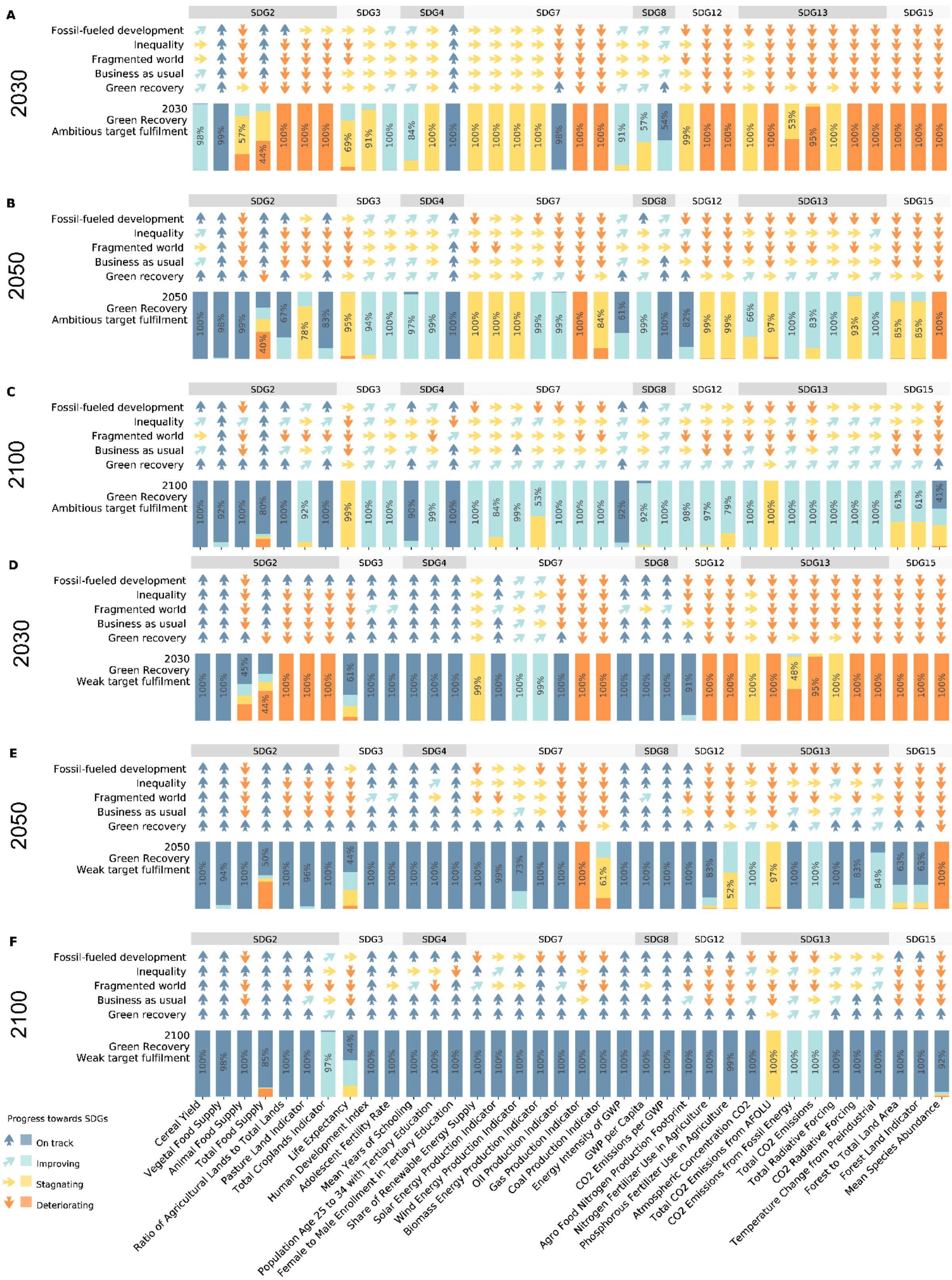
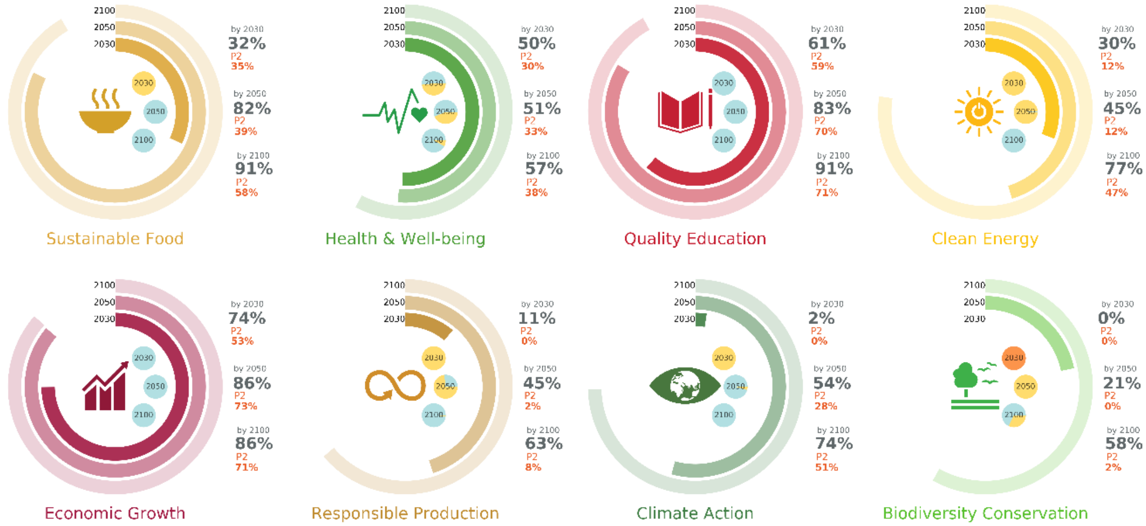
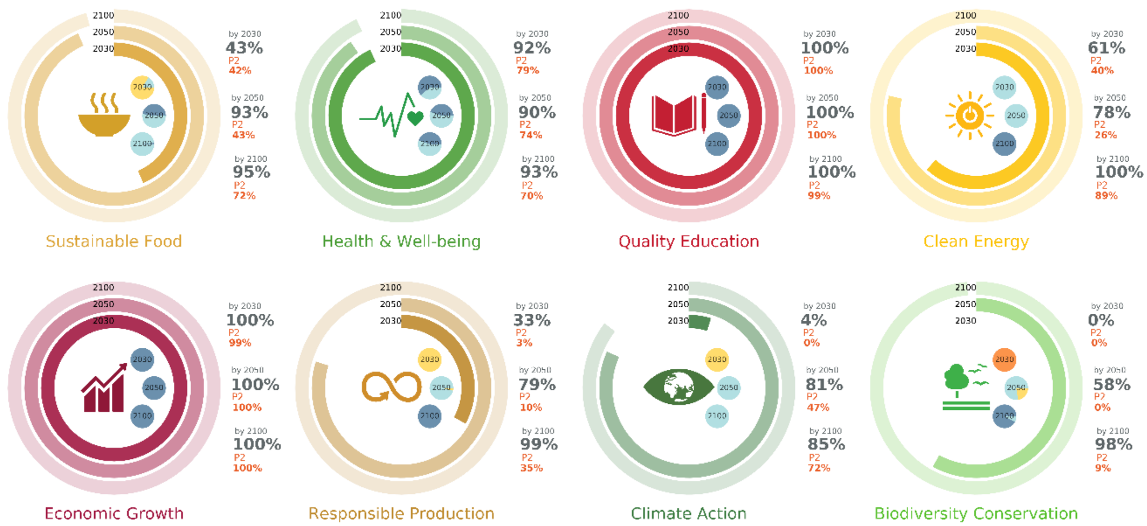


Fig. S2. Progress towards *ambitious* and *weak* targets on indicators by 2030, 2050, and 2100 under five modelled pathways. A, B, and C are towards ambitious targets and D, E, and F are towards weak targets. Each column represents one indicator. Related indicators are grouped under SDG labels. Progress levels (i.e., wrong direction, stagnating, improving, on track) at each indicator are coloured coded and also represented with arrows for all five pathways (Experimental Procedures). The arrows show the most likely progress of each pathway from 10,000 pathway realisations. The stacked bar charts focus only on Green Recovery as the most sustainable pathway. Annotated percentage inside each bar represents the share of 10,000 Green Recovery realisations for the corresponding progress level.

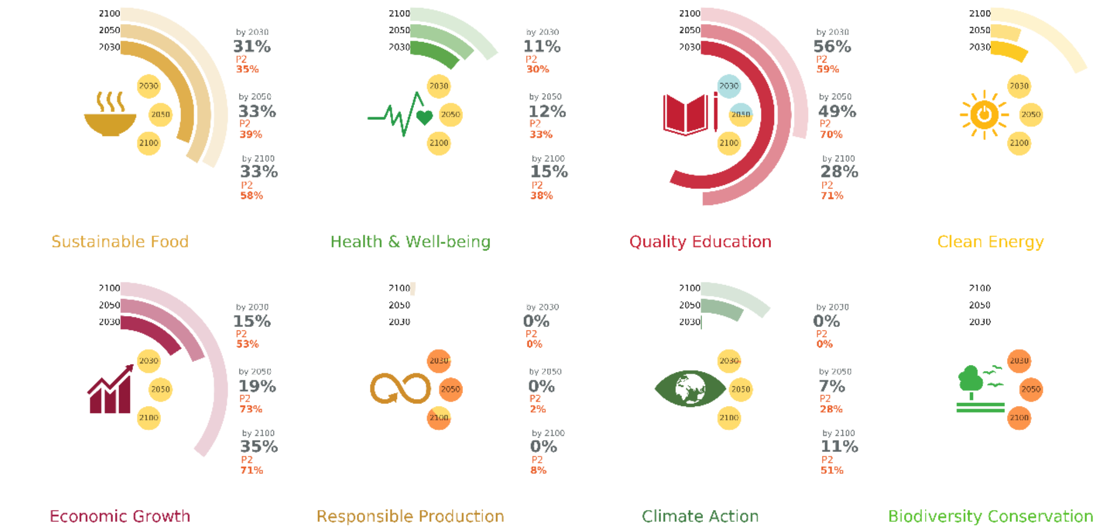


A

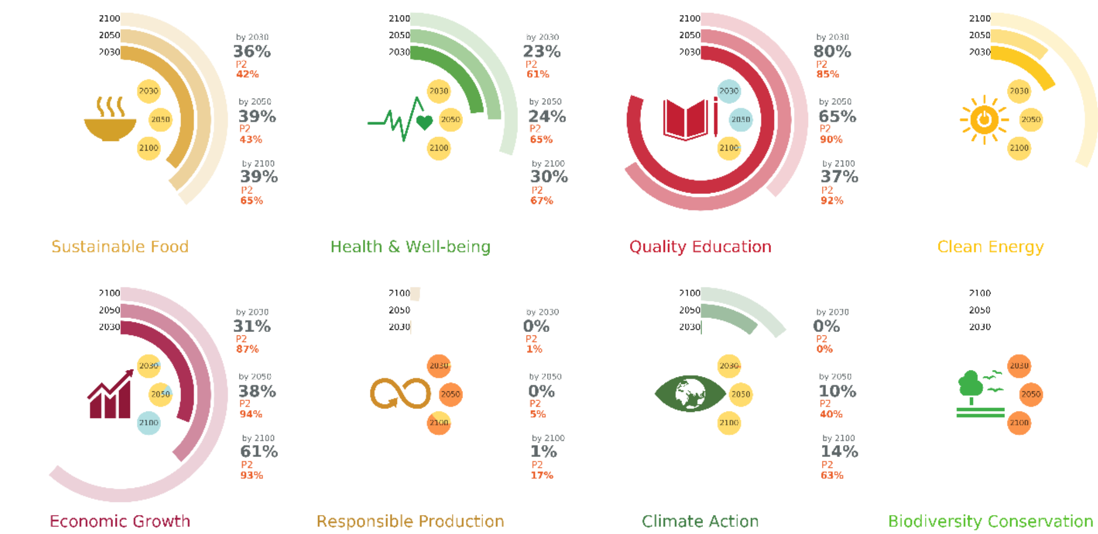


B

Fig. S3. Global progress towards eight modelled SDGs under Green Recovery. A and B show progress towards *ambitious* and *weak* targets, respectively.



A



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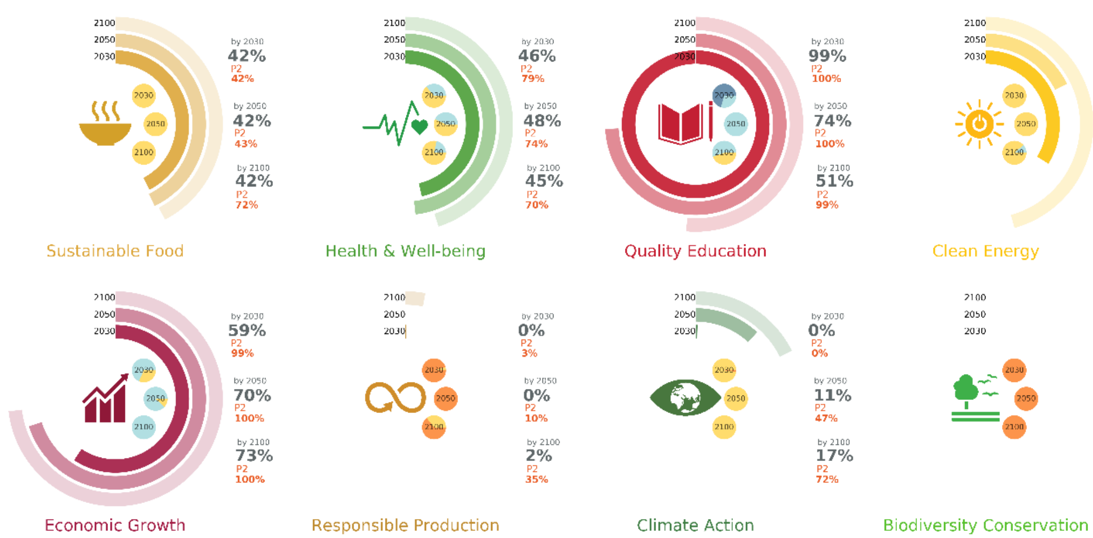
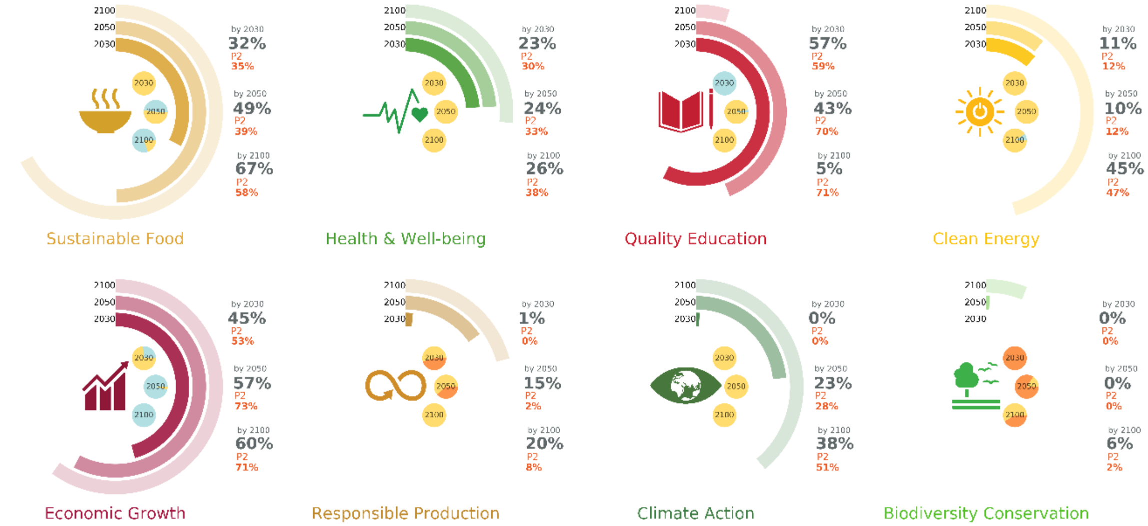
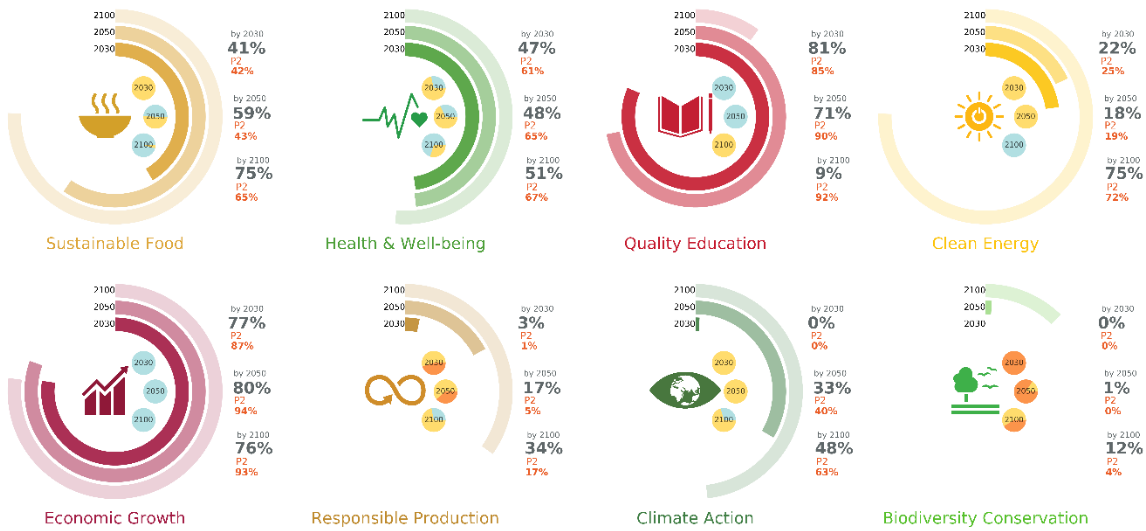


C

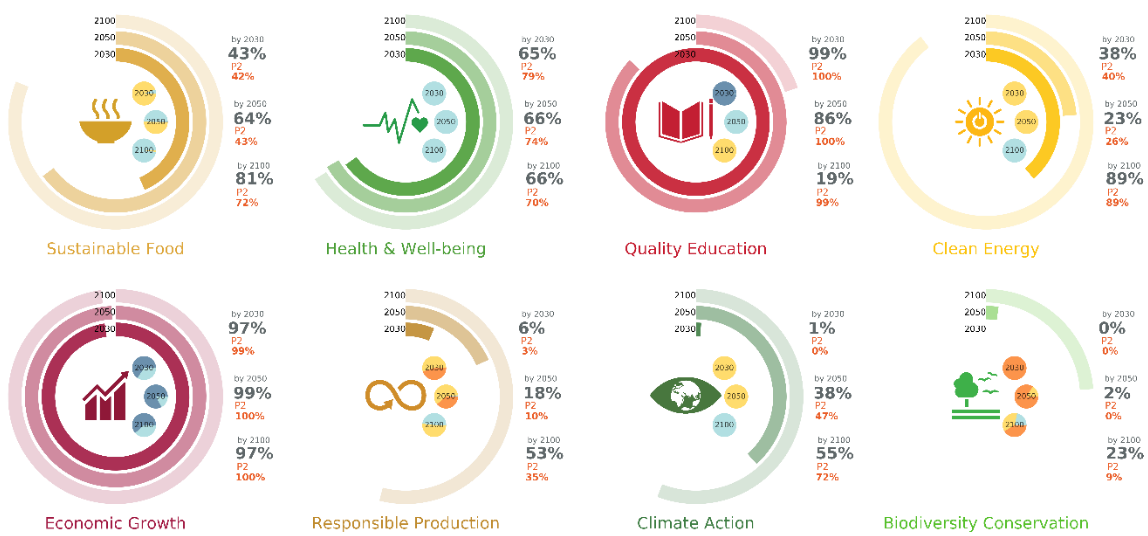
Fig. S4. Global progress towards eight modelled SDGs under Fragmented World. A, B, and C show progress towards *ambitious*, *moderate*, and *weak* targets, respectively.



A



B



C

Fig. S5. Global progress towards eight modelled SDGs under Inequality. A, B, and C show progress towards *ambitious*, *moderate*, and *weak* targets, respectively.

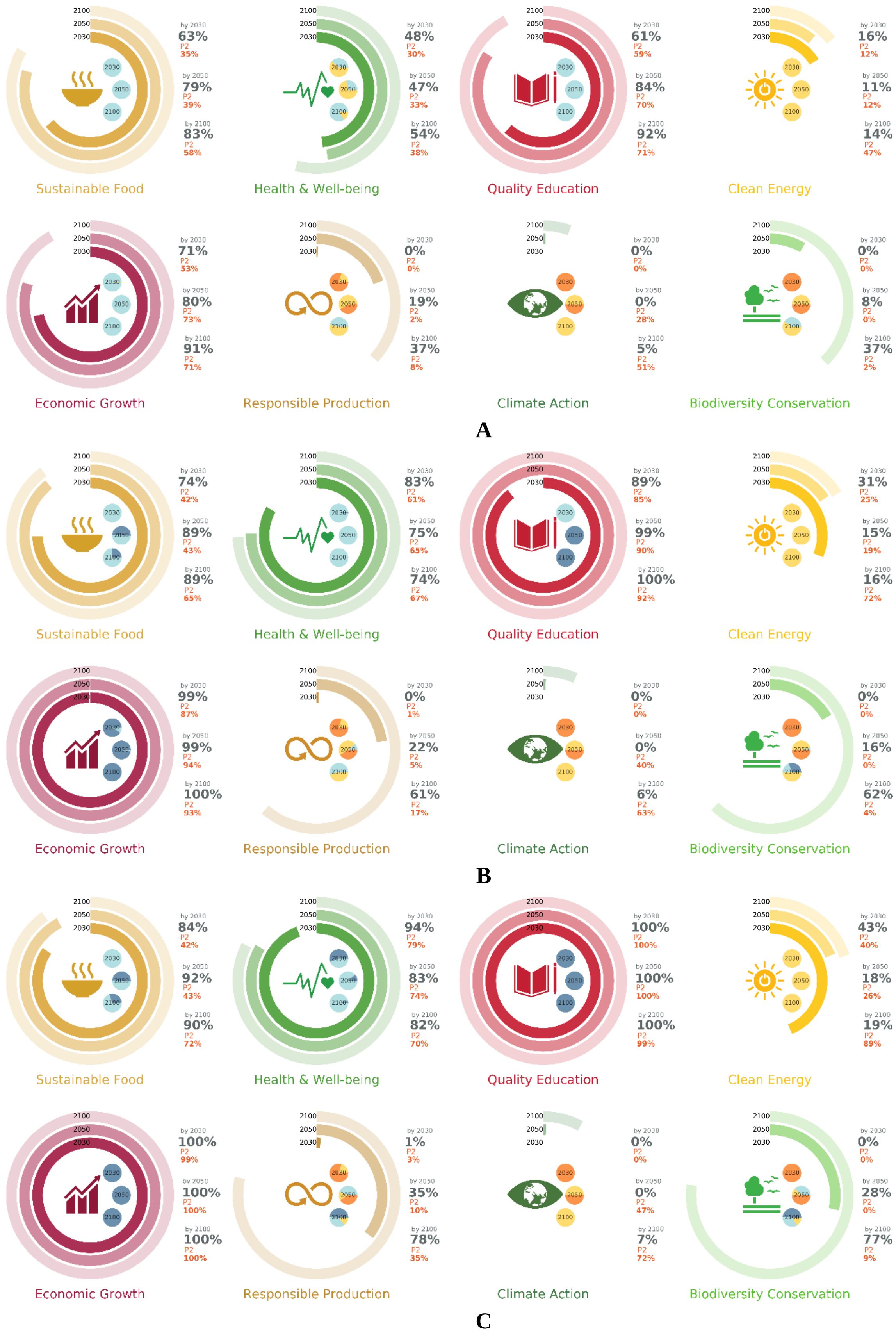
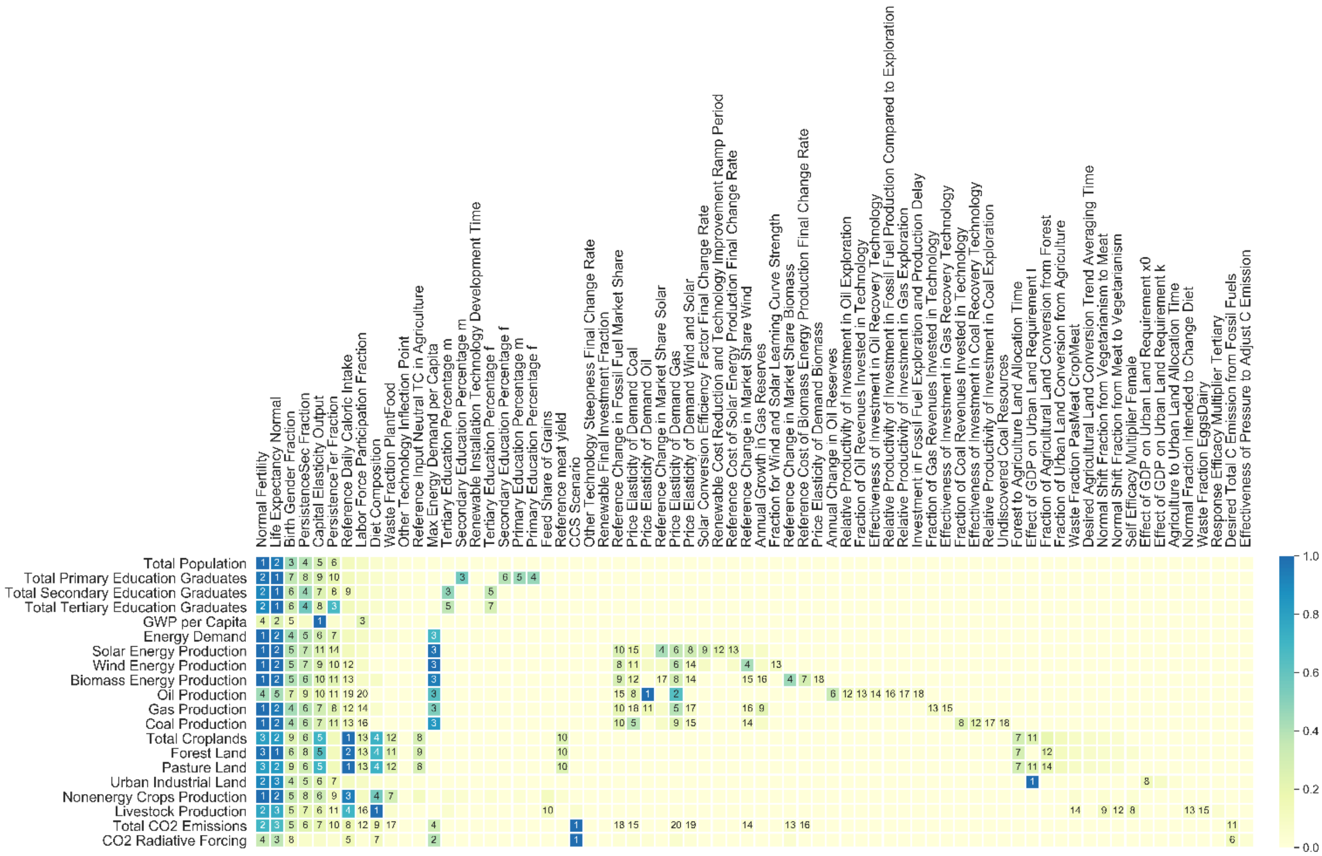


Fig. S6. Global progress towards eight modelled SDGs under Fossil Fuelled Development. A, B, and C show progress towards *ambitious*, *moderate*, and *weak* targets, respectively.



A

Entry point	Influential pathway drivers, associated system, and output variable	Business As Usual trends	Green Recovery trends
Human well-being and capabilities	**Education | Population with no/incomplete education (ratio)**		
	Educational attainment (8 parameters)	▸	▲
	Population | Total population (billion)		
	Population growth (3 parameters)	▸	▼
	Economic growth (2 parameters)	▸	▲
Sustainable food systems and healthy nutrition	**Land | Cropland and pasture area (billion ha)**		
	Deforestation (4 parameters)	▸	▼
	Land productivity (2 parameters)	▸	▲
	Food and diet change | Land-based animal caloric intake (kcal person^{-1} day^{-1})		
	Food waste (3 parameters)	▸	▼
	Food consumption (2 parameters)	▸	▼
	Sustainable diet change (5 parameters)	▸	▲
Energy transition and universal access	**Energy consumption | Energy demand (EJ year^{-1})**		
	Energy demand (1 parameter)	▸	▼
	Energy production | Fossil energy production (EJ year^{-1})		
	Market share of fossil energy consumption (9 parameters)	▸	▼
	Fossil fuels technology development (3 parameters)	▸	▼
	Investment in fossil fuels (8 parameters)	▸	▼
	Fossil fuel resource availability (3 parameters)	▸	▼
	Renewable energy investment and efficiency (3 parameters)	▸	▲
	Renewable energy production costs (2 parameters)	▸	▼
Sustainable economy decoupled from environmental impacts	**Economy | GWP per capita ($10,000 person^{-1} year^{-1})**		
	Economic growth (2 parameters)	▸	▲
	Climate | Atmospheric CO_2 emissions (ppm)		
	Use of carbon capture and storage (1 parameter)	▸	▲
	Limit on emissions from fossil fuels (1 parameter)	▸	▲

B

Fig. S7. The sensitivity of model parameters across FeliX's output variables in year 2100 and systems change in relation to the entry points. Sensitivity (A) is the normalised values of Morris index μ^* between 0 and 1. For each output variable, the most influential parameters are annotated with their importance rank. The number of most influential parameters can vary depending on the output variable. In characterising systems change (B), the first column shows four entry points. In the second column, influential model parameters (grey text) for change identified from sensitivity analysis (A) are categorised under their associated system change (the first black bold text) with one variable to measure the scale of that system change (the second black bold text). The value in parentheses in front of each influential model parameter shows the number of parameters used to model the specified driver in FeliX. The third and fourth columns represent the direction of change in each driver qualitatively under business-as-usual and Green Recovery. The signs ▲ represents an increase, ▶ is no change from business-as-usual, and ▼ is a decrease.

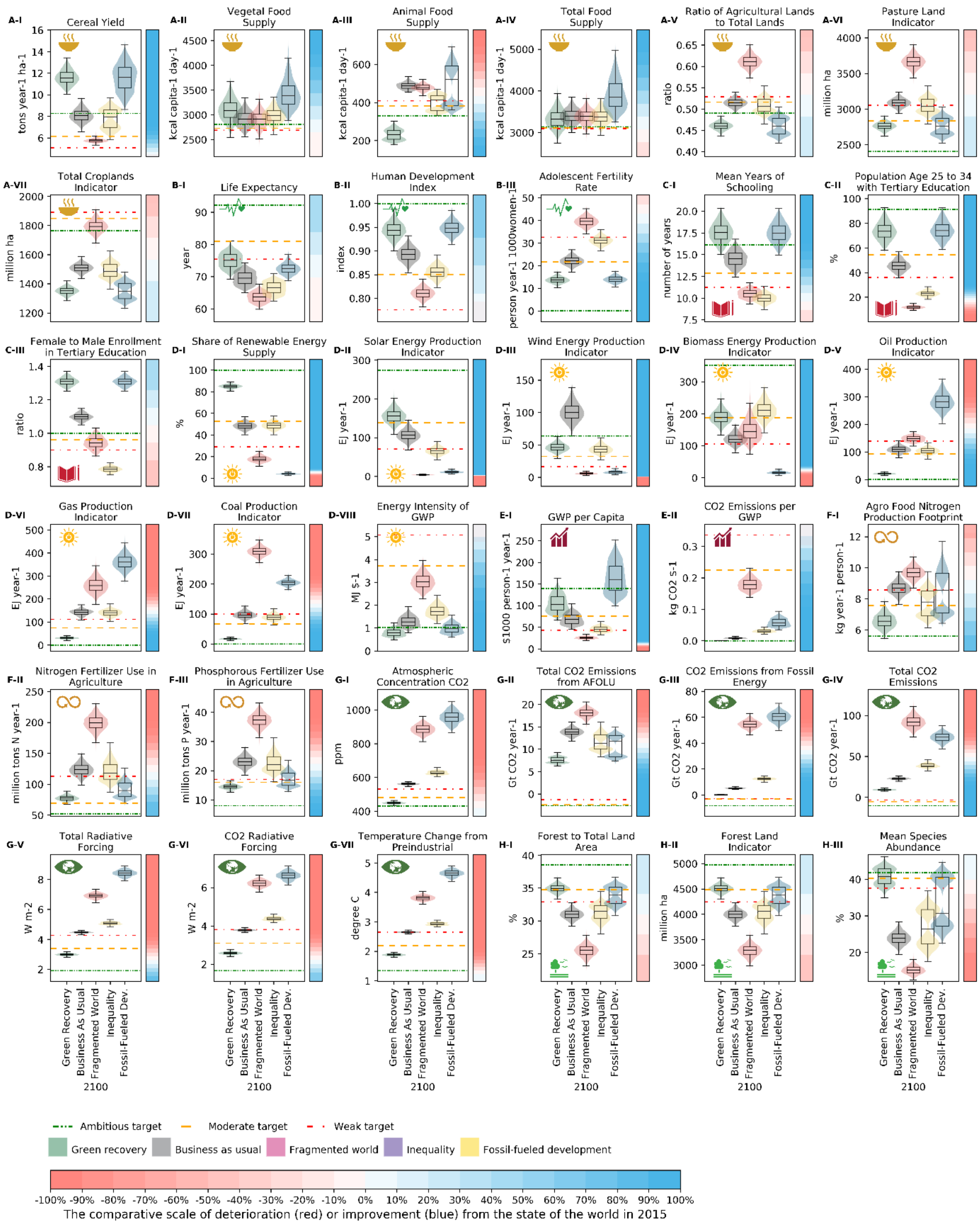


Fig. S8. Performance of global pathways towards SDG targets in 2100 under five SSP-compliant pathways. The violin shows the distribution of pathway's performance across 10,000 simulated realisations of each pathway. The box shows the inter-quartile range (centre line is median) of these simulated realisations while the whiskers extend to show the rest of the distribution, except for points that are identified as outliers. The lines mark weak, moderate, and ambitious targets in 2100 (Tables S3, S4). The red and blue colour bars specify the percentage that the pathway's performance is deteriorating or improving from the state of the world in 2015. They also show the progress direction and can be used to understand how ambitious the target levels are in comparison the 2015 state of the world.

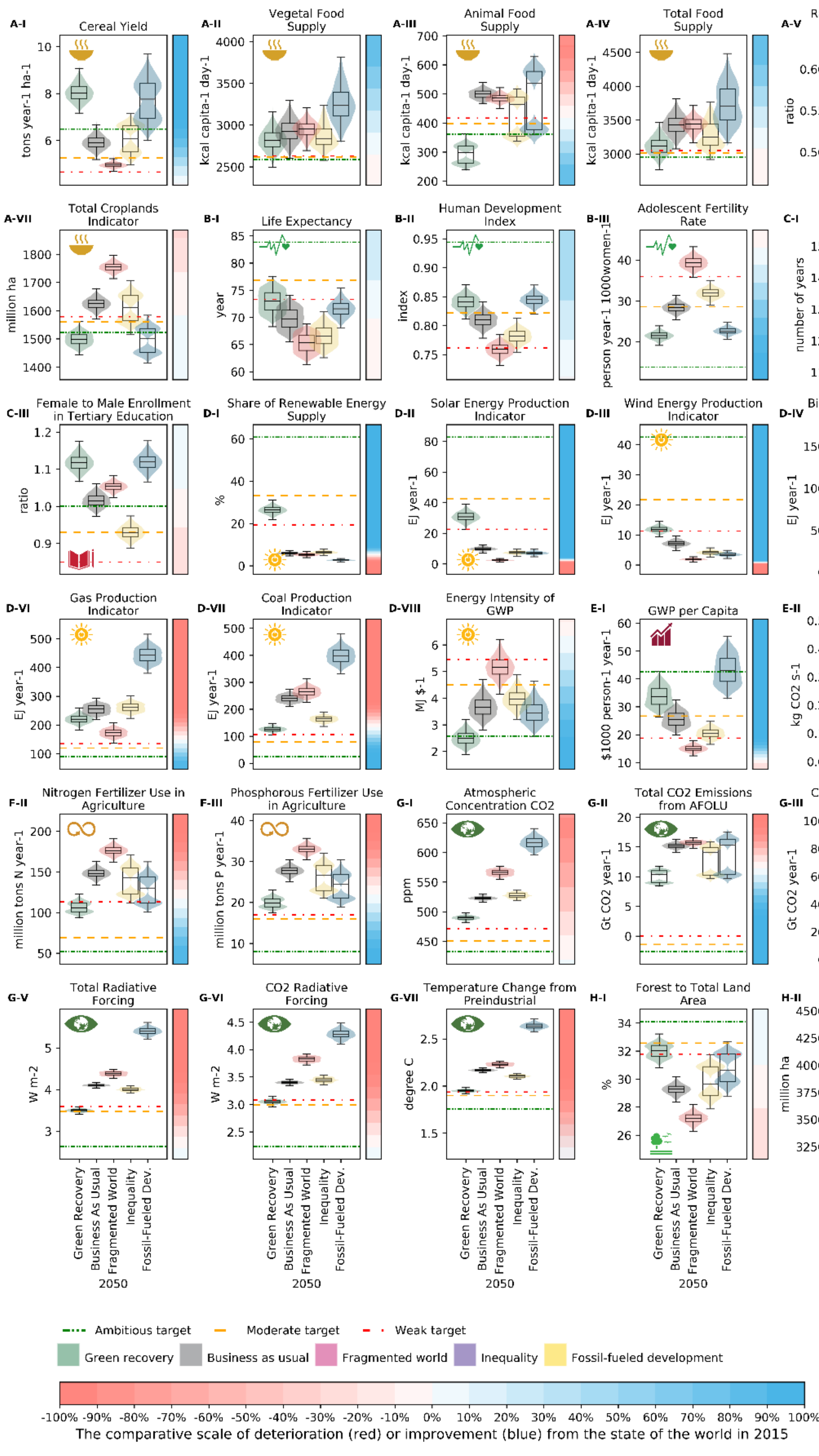


Fig. S9. Performance of global pathways towards SDG targets in 2050 under five SSP-compliant pathways.

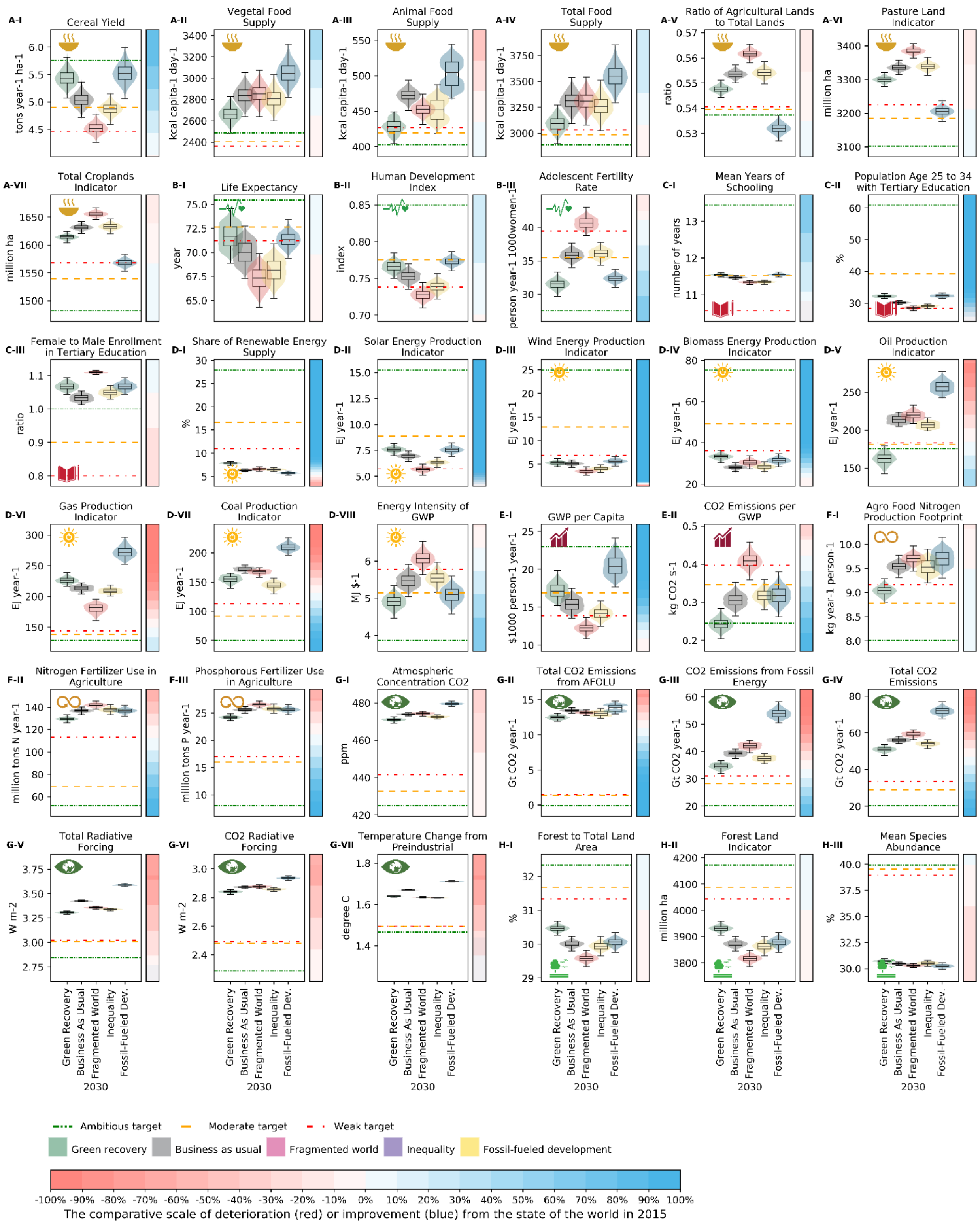


Fig. S10. Performance of global pathways towards SDG targets in 2030 under five SSP-compliant pathways.

Table S1. The narratives of future pathways framed by the five SSPs-RCPs. The narratives were used to guide qualitative and quantitative assumptions to the FeliX model.

Green Recovery	Business As Usual	Fragmented World	Inequality	Fossil-Fuelled Development
Population growth				
Trend				
Low fertility rate and long life expectancy.	Moderate fertility rate and moderate life expectancy.	High fertility rate and low life expectancy.	Moderate fertility rate and moderate life expectancy.	Low fertility rate and long life expectancy.
Narrative				
Investments in human capital and education levels along with fast technological progress facilitate a demographic transition in currently high fertility rate countries towards a relatively low population. At the same time, the prosperous economic condition and healthy lifestyle increase the average life expectancy of the population, especially in low-income, developing countries.	Population growth is generally at a moderate level, with a faster growth in low-income countries, slowing population growth in middle-income countries, and very limited or aging population growth in more developed, high-income countries.	Limited education opportunities and a very slow economy induce a fast population growth, especially in developing countries when the socioeconomic conditions are worsening. At the same time, life expectancy in developing countries is short which to some extent can balance the effect of high fertility rate, but it is not large enough to slow down the population growth.	A general economic uncertainty in developed countries results in relatively low fertility and low population growth, and a moderate life expectancy. The low-income countries, however, experience high population growth due to the limited education and low life expectancy due to poor socioeconomic conditions.	Global population peaks and declines due to slowing of fertility rate in developing countries resulted from investment in education, health, and economic prosperity. In high-income countries, fertility can be above replacement due to optimistic economic futures. The life expectancy is also high.
Educational attainment				
Trend				
High and balanced number of male and female population in their related maturation age who are enrolling in the tertiary education.	Moderate number of tertiary graduates.	Low and unbalanced number of male and female population in their related maturation age who are enrolling in the tertiary education.	Moderate and balanced number of male and female population in their related maturation age who are enrolling in the tertiary education.	High and balanced number of male and female population in their related maturation age who are enrolling in the tertiary education.
Narrative				
Universal access to primary and secondary and promoting higher education levels are achieved across all countries, especially in low-income countries, leading to poverty reduction and improvement of gender inequality.	Some progress towards universal education is achieved, but the investments are not high enough to reduce the population growth in low-income countries.	Very limited investments in education, especially in tertiary education, leads to poor populations in low-income countries with limited economic opportunities, working as a vicious cycle worsening gender inequality and increasing the population growth.	Investment on education in developing countries focusing on developing human capital based on small, highly educated elite at the expense of the broader public education.	Education and consequently poverty are significantly improved with the support of development policies that eventually aim to accelerate human capital development.
Economic development				
Trend				
Relatively high economic growth.	Moderate economic growth.	Low economic growth.	Relatively low economic growth.	High economic growth.
Narrative				
Fast economic growth is experienced across all countries (especially developing countries), although the economic development is tempered over time by achieving a balanced growth among well-being, equity, and sustainability.	Economic growth is moderate in general, following its historical patterns, with emerging economies experiencing a fast and a slowdown progress as their economies mature, low-income countries experiencing a relatively high growth, and high-income countries continuing to progress moderately	Limited international cooperation, low investments in education (and therefore limited training of skilled labour force) and in technology R&D result in a very slow economic growth with high inequalities across and within countries where the wealth is distributed unevenly.	The economy within and across countries works based on a high-tech, knowledge-based sector for highly educated labour force, and a low-tech, labour-intensive sector for a major part of the global population. This results in high- to middle-income (developed) countries to experience a moderate economic growth while low-income developing countries lag behind.	The globalised economies supported by a high level of international trade and cooperation result in a fast economic growth among countries. However, the growth is so much focused on consumerism and resource-intensive consumption.

Continued.

Energy demand and lifestyle change

Trend				
Low energy demand. High, relatively high, and moderate market share for solar, biomass, and wind. Low market share for all fossil energies.	Relatively high energy demand. Relatively high, low, and high market share for solar, biomass, and wind. Moderate, moderate, and high market share for coal, gas, and oil.	Moderate energy demand. Low, high, and low market share for solar, biomass, and wind. Relatively high, relatively low, and moderate market share for coal, gas, and oil.	Moderate energy demand. Moderate market share for solar, biomass, and wind. Relatively low, low, and moderate market share for coal, gas, and oil.	High energy demand. Relatively high, low, and relatively high market share for solar, biomass, and wind. Relatively high, high, and high market share for coal, gas, and oil.
Narrative				
Fast economic growth along with city development increases the overall energy use of the population. However, environmental consciousness and sustainable development goals along with the efficient end-use technologies lead to a transition to low energy intensity of services. This creates a high desire to adopt non-bio renewable energies (wind and solar) in response to their steeped cost reduction (high price elasticity) resulted from technological progress and low desire to respond to use fossil energy. The price elasticity of demand to biomass remains at a moderate level (less than wind and solar) due to concerns about its environmental impacts on land. A sustainable development with rapid economic growth and fast urbanisation across the world, especially in developing, low-income countries create political determinism / market interest to rapidly phase out fossil fuel use.	Service demand levels are between SSP 1 and SSP 5 on a per capita level and energy intensity of services is moderate across all end-use sectors. While significant progress with solving the energy access and moving away from fossil fuels is achieved, some issues persist which keep the traditional fuel use at its current trajectory.	Because of relatively poor economic development, the demand for energy services is not too high. However, because of low environmental standards, poorly performing public infrastructure, and ineffective regulation, the energy intensity of services is medium to high leading to a medium to high final demand, more desire to buy fossil fuel given that their price remains at an affordable level, and no desire for renewable given that their technology development and price reduction are very slow (except for biomass). Given the slow economic development and limited technology advancement, a continued reliance on traditional fuels especially in low-income with large rural communities is unavoidable. Fossil market share is higher than renewables as there is no other practical alternative for fossil fuels.	High-income countries show a modest per capita energy service demand because of a divided society in which the majority has modest income, but more importantly in response to strong regulation (energy taxes). The latter also lead to incentives for reaching low energy intensity of services fuelled by (non-biomass) renewable energies. In contrast, the desire for meeting the energy demand from (non-biomass) renewable sources is low in low-income countries while there is more preference for fossil energy and biomass. Similar to SSP3, poor economic development in low-income countries slightly lowers demand for energy services. However, inefficient technologies along with high population leads to moderate final energy demand. Countries with a large population of low-income communities remain highly dependent on fossil fuel, given the divided income distributions. However, developed, high-income countries have more interest and resource to transition from fossil fuels in their market.	The general preference for status consumption in urban sprawl in combination with prosperous economic development creates a lifestyle with high-energy service demand levels. Despite fast technological change, the market response to price change of renewable and fossil energies is relatively lower and higher than SSP 1. Despite fast economic development, the reliance on fossil fuel as the cheap source of energy remains much higher than SSP 1 in all countries (higher market share for fossil fuels).
Fossil energy production				
Trend				
Limited fossil energy (recovery and exploration) technology improvement, limited new investments.	Moderate fossil energy technology improvement, moderate new investments.	Slow fossil energy (recovery and exploration) technology improvement, moderate new investments.	Relatively slow fossil energy (recovery and exploration) technology improvement, moderate new investments.	Moderate fossil energy (recovery and exploration) technology improvement, high new investments.
Narrative				
The effectiveness of investments on fossil energy technologies is moderate due to strict environmental regulations. All fossil energy technologies experience low social acceptance leading to less investment of the revenue achieved from fossil energies in the improvement of same fossil sector and long delay for approving intended investment (due to environmental regulations).	All technologies develop at a moderate rate and along their past trajectories. The investment and social acceptability of energy technologies are at a moderate level.	With slow economic growth and low investments in technology R&D, technological changes of fossil are slow. Due to the dominance of local energy security goals and less concerns over global environmental issues, social acceptance for investment in fossil energy is relatively high. Technological progress for fossil energy technologies is limited and therefore the potential for low-cost recovery and exploration of fossil fuels remains limited too.	The effectiveness of investment in fossil fuels remains at a moderate level in all countries. Social acceptance regarding energy sector (fossil) investments is generally higher in low-income countries due to their poor energy access condition and vulnerability to resource scarcity. Medium- to high-income countries have a relatively low fossil energy social acceptance due to price competitive with renewable alternatives.	Fast technological development enhances the effectiveness and productivity of investment in fossil energy. Because of the strong preference for rapid conventional development, the world depends significantly on fossil energy and does not actively invest in alternative energy sources. This leads to high social acceptance for investment in fossil energy technologies.

Continued.

Clean energy technology advances				
Trend				

Fast renewable energy technology (efficiency and investment) improvement.	Moderate renewable energy technology (efficiency and investment) improvement.	Slow renewable energy technology (efficiency and investment) improvement.	Relatively slow renewable energy technology (efficiency and investment) improvement.	Moderate renewable energy technology (efficiency and investment) improvement.
Narrative				
In a world with rapid technological change toward environmentally friendly processes, wind and solar energy technologies improve rapidly. Renewable energies especially solar which is experiencing a rapid growth (and is not like wind, close to its maximum capacity) have a high social acceptability (e.g., more land availability for solar technologies installation). Fast technological development and the strong acceptability of renewable energies lead to low production cost for renewable energies.	All technologies develop at a moderate rate and along their past trajectories. The investment and social acceptability of energy technologies are at a moderate level too.	With slow economic growth and low investments in technology R&D, technological changes of renewable technologies are slow throughout the world. Renewable energies such as solar become less socially acceptable because of their limited costs reduction and technological advancement (e.g., facing more challenges in acquiring land for solar installation).	Renewable energy technologies are deployed at low costs throughout the world as multinational energy corporations co-invest in R&D and cost reduction as their hedging strategy against resource scarcity. Technological development is fast for wind and solar in high-income countries and slow in low-income regions due to slower economic growth.	There is modest but continued progress in wind and solar technologies due to the rapid economic growth and the expansion of renewable energy-related industries. Because of the strong preference for rapid conventional development, the world does not actively invest in renewable energy sources. This leads to low social acceptance for renewable energy.
Land-use change				
Trends				
Trend				
Low land cover built-up area. Deforestation at a slow rate and the expansion of cropland and pasture area at a slow rate.	Relatively low land cover built-up area. Deforestation at a moderate rate and the expansion of cropland and pasture area at a moderate rate too.	Low land cover built-up area. Deforestation at a high rate and the expansion of cropland and pasture area at a high rate too.	Relatively low land cover built-up area. Deforestation at a moderate rate and the expansion of cropland and pasture area at a moderate rate too.	High land cover built-up area. Deforestation at a relatively slow rate and the expansion of cropland and pasture area at a relatively slow rate too.
Narrative				
Along with economic development and increase in GDP across all countries, the rural population is attracted to urban centres. Urbanisation (shared/concentrated resources) also grows fast for environmental reasons. Thus, with cities as attractive destinations, the growth of GWP correlates with the acquisition of more lands for city expansion, while minimising the environmental impacts. Land use is strongly regulated. As a result, the deforestation rates are strongly reduced over time. This would be more in low-income, developing countries. The expansion of cropland and pasture also happens at a slow rate due to low population growth and a transition to sustainable diets.	All countries experience an extension of current trends in urbanisation, with the central urbanization pathway in various forms and patterns depending on their conditions and resources. While high-income countries continue their urban expansion trajectory, other medium- and low-income (developing) countries follow the historical urbanisation experiences of the more developed countries. Land use change is incompletely regulated. As a result, the deforestation continues, but with a gradual decline over time. Cropland and pasture growth at a moderate rate due to business-as-usual population growth and food consumption.	Slow GDP growth along with strict measures on international migration, and poor urban planning make cities unattractive. The rapid population growth along with slow socioeconomic development and environmental degradation also limit the mobility of the poor rural population. Thus, developments have limited impact on the expansion of cities and the acquisition of required lands for urban and industrial activities. With little regulation in place, there is continued deforestation because of rapid agricultural expansion driven by regional rivalry and domestic food security, and regional conflicts. Cropland and pasture expand fast to meet the increasing food demand in a world with a fast-growing population.	Cities in high-income countries with high living standards become attractive for global migration. However, the aging of the population in high-income countries limit internal rural-to-urban migration at a moderate level, contributing to a slow city expansion. Low-income countries with their rapidly growing rural populations, exposed by limited areas of arable land and job availability due to large-scale mechanised farming by international agricultural firms, experience a significant migration to urban areas in the hope of better opportunities. Land use is highly regulated in high- and middle-income countries, but deforestation still occurs in poor countries. Cropland and pasture expand to meet the global food demand, they have a moderate expansion rate.	Many large-scale engineering projects for the expansion of cities take place, supported by rapid technological progress and fast economic growth. However, the urban development is more in form of extensive man-made environments leading to urban sprawl with rather comfortable living conditions with high environmental footprints. Land use change is incompletely regulated. Thus, deforestation continues, but at a slowly declining rate over time. Low population and therefore less demand for food results in the expansion of cropland and pasture at a slower rate compared to business as usual (but higher than SSP 1)

Continued.

Land productivity				
Trend				
High crops and livestock yield.	Moderate crops and livestock yield.	Low crops and livestock yield.	Relatively low crops and livestock yield.	Relatively high crops and livestock yield.
Narrative				
Rapid improvement of the environmentally friendly technologies in the land sector results in high crops and livestock yield, especially in low- and medium-income countries, enabling them to catch up faster with high-income countries.	Crops and livestock yield declines slowly over time, but it gradually improves in low-income countries, enabling them to catch up with developed regions.	Limited international collaborations for technology transfer in low-income countries, slow economic growth and availability of resources and lack of required knowledge result in a strong decline in crops and livestock yield over time.	High-income countries supported by large-scale industrial farming can realise high crops and livestock yield whereas low-income countries with local and inefficient farming practices remain relatively unproductive in agriculture.	Crops and livestock yield id rapidly increasing due to advancement of technology and enhanced production systems.
Food waste, food consumption, diet change				
Trend				
Low waste, low animal calories consumption (sustainable diet).	Waste at the current level, the global diet follows the status quo (more meat, less vegetables).	Relatively high waste, the global diet follows the status quo (more meat, less vegetables).	Relatively low waste, the global diet follows may slightly to towards the less meat, more vegetables.	High waste, the global diet follows the status quo (more meat, less vegetables).
Narrative				
With a universal education and low population growth, healthy diets with low animal-calorie shares prevail and the food waste drops significantly, driven by environmental consciousness.	The consumption and animal calorie remains business-as-usual and food waste remains relatively unchanged.	With a great increase in population, poor economic development, and minimum access to education, unhealthy diets with high animal shares and high food waste prevail.	Food consumption and animal calorie share are similar to business-as-usual, while the shift to healthy diets is stronger in high-income countries because of higher education level and improved lifestyle.	High-income countries experience meat-rich and unhealthy diets and high waste resulted from rapid economic growth and high consumption.
Climate policy assumptions				
Trend				
RCP 2.6 - Low challenges to mitigation.	RCP 4.5 - Medium mitigation challenges.	RCP 7.0 Significant challenges to mitigation.	RCP 6.0 - Low challenges to mitigation.	RCP 8.5 - High mitigation challenges.
Narrative				
As an indicative scenario for low-range emissions with the highest potential for mitigation facilitated by technology advances and high level of global cooperation, we assumed carbon pricing for fossil fuel unit cost of production with a linearly increasing (global average) trajectory (reaching ~$450 per tCO_2 by 2100), high land-based mitigations; high adoption rate for carbon capture and storage for reducing emissions from fossil fuels and from bioenergy (BECCS). To model high global cooperation in adopting climate policies as early as possible, we activated all implemented measures by 2025. For other greenhouse gases that were not modelled endogenously in FeliX, we calibrated the model under the green recovery consistent with the lowest forcing level of 2.6 W $m^{-2,}$ with data from the IASA Scenario Database.	With medium mitigation challenges, we assumed slightly lower carbon price (reaching ~$300 per tCO_2 by 2100) compared to SSP1-2.6, lower adoption rate for carbon capture and storage for reducing emissions from fossil fuels and also from bioenergy (BECCS), and also lower land-based mitigations. To indicate less global cooperation in adopting climate policies, all measures were implemented by 2040, later than SSP1-2.6. For other gases, we calibrated the model consistent with 4.5 W m^{-2} forcing level, with data from the IASA Scenario Database.	With significant challenges to mitigation (and also with little global cooperation in the former), we assumed no effective climate policy regime for carbon emissions in FeliX. For other gases, we calibrated the model consistent with 7.0 W m^{-2} forcing level, with data from the IASA Scenario Database.	Similar to SSP2.4.5, with medium mitigation challenges, we assumed slightly lower carbon price (reaching ~$300 per tCO2 by 2100) compared to Green Recovery, lower adoption rate for carbon capture and storage for reducing emissions from fossil fuels and also from bioenergy (BECCS), and also lower land-based mitigations. For other gases, we calibrated the model consistent with 6.0 W m-2 forcing level, with data from the IASA Scenario Database.	With significant challenges to mitigation (and also with little global cooperation in the former), we assumed no effective climate policy regime for carbon emissions in FeliX. For other gases, we calibrated the model consistent with 8.5 W m^{-2} forcing level, with data from the IASA Scenario Database.

Table S3. The SDGs, indicators, and target levels implemented. The table also summarises the target description, the source of each indicator, and the method used for target setting with the source from which the target was extracted. See Experimental Procedures (main text) for the target setting process, Table S4 for the justification of the method used for target setting in each indicator and their scientific sources, and Equations S1 to S36 in Supplemental Experimental Procedures for the definition and methodology for calculating each indicator.

Target description	Indicator name, source, definition	Target setting method used, time-bound target levels	2030	2050	2100
Goal 2. End hunger, achieve food security and improved nutrition and promote sustainable agriculture					
Target 2.4. By 2030, ensure sustainable food production systems and implement resilient agricultural practices					
Improve the productivity of the croplands	*Cereal Yield (tonnes year^{-1} ha^{-1})* | SDSN, FAO The annual production rate per hectare of harvested croplands dedicated to cereal (pulses and grains) production.	Technical optimum			
		Ambitious	5.76	6.48	8.28
		Moderate	4.90	5.26	6.16
		Weak	4.47	4.65	5.10
Meet the increasing global demand for food with less meat consumption	*Vegetal Food supply (kcal capita^{-1} day^{-1})* | FAO The total annual production of pulses, grains, vegetable, fruits, roots, and other plant product (oil crops, sugar crops and nuts) per person per day.	Technical optimum			
		Ambitious	2484	2588	2809
		Moderate	2404	2617	2727
		Weak	2364	2631	2686
	Animal Food supply (kcal capita^{-1} day^{-1}) | FAO The total annual production of pasture-based meat (beef, sheep and goat) and crop-based meat (poultry and pork) - excluding seafoods - per person per day.	Technical optimum			
		Ambitious	403	361	331
		Moderate	419	398	383
		Weak	427	417	409
	Total Food Supply (kcal capita^{-1} day^{-1}) | FAO The total annual production of animal and vegetal foods per person per day.	Technical optimum			
		Ambitious	2887	2949	3139
		Moderate	2984	3015	3110
		Weak	3032	3047	3095
Reduce pressure on lands from food production and agricultural activities	*Ratio of Agricultural Lands to Total Lands (-)* | FAO The ratio of land allocated to agriculture (permanent crops, permanent meadows and pastures, arable lands) to total available lands (permanent crops, permanent meadows and pastures, arable lands, forest land, urban and industrial land).	Technical optimum			
		Ambitious	0.5372	0.5135	0.4899
		Moderate	0.5395	0.5276	0.5159
		Weak	0.5406	0.5347	0.5288
	Pasture Land Indicator (million ha) | IIASA Total available permanent pasture and meadow lands.	Technical optimum			
		Ambitious	3103	2787	2404
		Moderate	3184	3026	2835
		Weak	3225	3146	3050
	Total Croplands Indicator (million ha) | IIASA Total land allocated for energy and food (and feed) crops.	Technical optimum			
		Ambitious	1482	1523	1765
		Moderate	1540	1560	1849
		Weak	1568	1579	1807

Continued.

Goal 3. Ensure healthy lives and promote well-being for all at all ages						
Target 3.3. End the epidemics of communicable diseases Target 3.4. Reduce one third premature mortality from non-communicable disease						
Increase life expectancy and advance human wellbeing and richness of life	*Life Expectancy (year)* | SDSN, WHO, World Bank The average life expectancy of the population.	Leave no one behind		2030	2050	2100
			Ambitious	75	84	92
			Moderate	73	77	81
			Weak	71	73	75
	Human Development Index (-) | UNDP The UNDP Human Development Index as an average of three indexes of achievement (income, health, education) that impact most directly on human capabilities to produce and sustain well-being.	Leave no one behind		2030	2050	2100
			Ambitious	0.85	0.94	1.00
			Moderate	0.78	0.82	0.85
			Weak	0.74	0.76	0.78
Target 3.7. By 2030, ensure universal access to sexual and reproductive health-care services						
Reduce childbirth by adolescent girls with improved healthcare	*Adolescent Fertility Rate (person year^{-1} 1000women^{-1})* | SDSN, UNDP The number of births per 1,000 by women between the age of 15-19.	Leave no one behind		2030	2050	2100
			Ambitious	27.55	13.78	0.00
			Moderate	35.46	28.57	21.68
			Weak	39.41	35.97	32.52
Goal 4. Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all						
4.1 By 2030, ensure that all girls and boys complete free, equitable and quality primary and secondary education						
Increase the average years of schooling across population and all levels	*Mean Years of Schooling (number of years)* | UNESCO Average number of completed years of primary, secondary, and tertiary education (combined) of population.	Leave no one behind		2030	2050	2100
			Ambitious	13.44	14.78	16.13
			Moderate	11.52	12.19	12.86
			Weak	10.56	10.90	11.23
4.3 By 2030, ensure equal access for all women and men to affordable and quality technical, vocational and tertiary education						
Increase tertiary education coverage among young generations	*Population Age 25 to 34 with Tertiary Education (%)* | SDSN, OECD The percentage of the population, aged between 25-34 years old, who have completed tertiary education.	Leave no one behind		2030	2050	2100
			Ambitious	61	73	91
			Moderate	39	45	54
			Weak	28	31	36
Provide equal opportunities to access to tertiary education for both men and women	*Female to Male Enrolment in Tertiary Education (-)* | UNSC The percentage of the female to male graduation rate from tertiary education.	SDG absolute threshold		2030	2050	2100
			Ambitious	1	1	1
			Moderate	0.9	0.93	0.96
			Weak	0.8	0.85	0.9
Goal 7. Ensure access to affordable, reliable, sustainable and modern energy						
Target 7.2. By 2030, increase substantially the share of renewable energy in the global energy mix						
Increase the share of renewable energy in the total final energy supply	*Share of Renewable Energy Supply (%)* | UNSC, IPCC Percentage of renewable (solar, wind, biomass) energy supply share in total energy production.	Technical optimum		2030	2050	2100
			Ambitious	28	61	100
			Moderate	17	33	52
			Weak	11	19	29

Continued.

	Solar Energy Production Indicator (EJ $year^{-1}$) | IPCC Solar energy production limited by a maximum capacity and impacted by demand, market price, technology progress, GDP growth, amongst others.	Technical optimum	2030	2050	2100
		Ambitious	15.24	82.83	274.45
		Moderate	8.88	42.67	138.49
		Weak	5.70	22.60	70.50
	Wind Energy Production Indicator (EJ $year^{-1}$) | IPCC Wind energy production limited by a maximum capacity and impacted by demand, market price, technology progress, GDP growth, amongst others.	Technical optimum	2030	2050	2100
		Ambitious	24.93	42.48	63.71
		Moderate	12.89	21.66	32.28
		Weak	6.87	11.25	16.56
	Biomass Energy Production Indicator (EJ $year^{-1}$) | IPCC Biomass energy production limited by a maximum capacity and impacted by demand, market price, technology progress, GDP growth, amongst others.	Technical optimum	2030	2050	2100
		Ambitious	75.28	154.13	351.26
		Moderate	49.24	88.66	187.22
		Weak	36.21	55.93	105.21
Decrease fossil energy share in the total final energy supply	*Oil Production Indicator (EJ $year^{-1}$)* | IPCC Oil energy production limited by availability of resources and impacted by demand, market price, technology progress, GDP growth, amongst others.	Technical optimum	2030	2050	2100
		Ambitious	175.69	93.48	0.00
		Moderate	180.78	139.67	92.93
		Weak	183.32	162.77	139.40
	Gas Production Indicator (EJ $year^{-1}$) | IPCC Gas energy production limited by availability of resources and impacted by demand, market price, technology progress, GDP growth, amongst others.	Technical optimum	2030	2050	2100
		Ambitious	127.99	88.97	0.00
		Moderate	138.56	119.05	74.56
		Weak	143.84	134.09	111.84
	Coal Production Indicator (EJ $year^{-1}$) | IPCC Coal energy production limited by availability of resources and impacted by demand, market price, technology progress, GDP growth, amongst others.	Technical optimum	2030	2050	2100
		Ambitious	49.46	23.84	0.00
		Moderate	91.66	78.85	66.93
		Weak	112.76	106.35	100.39
Target 7.3. By 2030, double the global rate of improvement in energy efficiency					
Reduce the energy intensity measured in terms of GWP	*Energy Intensity of GWP (MJ $\$^{-1}$)* | UNSC, World Bank Energy consumption per unit of GWP production, as an indication of how much energy is used to produce one unit of economic output. Lower ratio indicates that less energy is used to produce one unit of output.	SDG absolute threshold	2030	2050	2100
		Ambitious	3.85	2.57	1.03
		Moderate	5.13	4.49	3.72
		Weak	5.78	5.46	5.07
Goal 8. Promote sustained, inclusive and sustainable economic growth for all					
Target 8.1. Sustain per capita economic growth, at least 7 per cent gross domestic product growth per annum					
Increase the GWP across countries	*GWP per Capita (\$1000 $person^{-1}$ $year^{-1}$)* | UNSC, World Bank The accumulation of the GDP of the countries, divided by the total GDP by combined population of these countries.	SDG absolute threshold	2030	2050	2100
		Ambitious	23	43	140
		Moderate	17	27	75
		Weak	14	19	43
Target 8.4. Improve progressively, through 2030, global resource efficiency in consumption and production					
Reduce carbon emissions on per unit of value added	*CO_2 Emissions per GWP (kg CO_2 $\$^{-1}$)* | World Bank, UNDP Human-originated carbon dioxide emissions stemming from emissions the burning of fossil fuels divided by the unit of the GDP.	Global improvement	2030	2050	2100
		Ambitious	0.24	0.10	0.00
		Moderate	0.35	0.27	0.22
		Weak	0.40	0.36	0.34

Continued.

Goal 12. Ensure sustainable consumption and production patterns

Target 12.2. By 2030, achieve the sustainable management and efficient use of natural resources					
Reduce environmental pressures (declining soil fertility) and the risk of polluting soil, water and air (nutrient surplus)	*Nitrogen Fertilizer Use in Agriculture (million tons N year^{-1})* | IFASTAT Commercial nitrogen fertilizer application in agriculture resulted from the effect of land availability, income, and technology on fertilizer use.	Technical optimum			
			2030	2050	2100
		Ambitious	52	52	52
		Moderate	69	69	69
		Weak	113	113	113
	Phosphorous Fertilizer Use in Agriculture (million tons P year^{-1}) | IFASTAT Commercial phosphorous fertilizer application in agriculture resulted from the effect of land availability, income, and technology on fertilizer use.	Technical optimum			
			2030	2050	2100
		Ambitious	8	8	8
		Moderate	16	16	16
		Weak	17	17	17
	Agro Food Nitrogen Production Footprint (kg year^{-1} person^{-1}) | SDSN Total reactive nitrogen per year per capita accumulated through commercial application in agriculture and application with manure. This corresponds to nitrogen emissions to the atmosphere, and leaching and runoff.	Technical optimum			
			2030	2050	2100
		Ambitious	8.00	7.20	5.60
		Moderate	8.78	8.38	7.58
		Weak	9.16	8.96	8.56
Goal 13. Take urgent action to combat climate change and its impacts					
Target 13.2. Integrate climate change measures into national policies, strategies and planning					
Reduce global CO_2 emissions across sectors	*Atmospheric Concentration CO_2 (ppm)* | IPCC Atmospheric CO_2 concentration per parts per million.	Technical optimum			
			2030	2050	2100
		Ambitious	425	433	430
		Moderate	433	451	480
		Weak	442	471	530
	Total CO_2 Emissions from AFOLU (Gt CO_2 year^{-1}) | FAO, IPCC Total CO_2 emissions from land-use change (such as deforestation), food and agriculture.	Technical optimum			
			2030	2050	2100
		Ambitious	-0.1	-2.6	-2.6
		Moderate	1.4	-1.4	-2.4
		Weak	1.5	0	-1.3
	CO_2 Emissions from Fossil Energy (Gt CO_2 year^{-1}) | IPCC Total CO_2 emissions from the fossil energy (oil, gas, coal) production.	Technical optimum			
			2030	2050	2100
		Ambitious	20.1	3	-8.3
		Moderate	28.2	11.8	-3.1
		Weak	31	17	-2.9
	Total CO_2 Emissions (Gt CO_2 year^{-1}) | IPCC Total CO_2 emissions from fossil fuels, renewable energies, land-use change (such as deforestation), food, and agriculture.	Technical optimum			
			2030	2050	2100
		Ambitious	20.3	-0.5	-10.2
		Moderate	28.9	9.9	-5.1
		Weak	33.5	17.9	-3.3
Limit global climate forcing	*CO_2 Radiative Forcing (W m^{-2})* | IPCC, IIASA The difference between insolation (sunlight) absorbed by the Earth and energy radiated back to space from CO_2.	Technical optimum			
			2030	2050	2100
		Ambitious	2.29	2.23	1.66
		Moderate	2.48	2.99	3.10
		Weak	2.49	3.08	3.80
	Total Radiative Forcing (W m^{-2}) | IPCC The difference between insolation (sunlight) absorbed by the Earth and energy radiated back to space from different greenhouse gases (CO_2, CH_4, N_2O, HFC, others).	Technical optimum			
			2030	2050	2100
		Ambitious	2.84	2.64	1.91
		Moderate	3.01	3.48	3.38
		Weak	3.02	3.60	4.27
Limit global temperature change from	*Temperature Change from Preindustrial (degree °C)* | IIASA	Technical optimum			
			2030	2050	2100
		Ambitious	1.47	1.76	1.35

preindustrial level	Global annual mean temperature change from the pre-industrial time calculated as atmosphere and upper ocean heat divided by their heat capacity.	Moderate	1.49	1.90	2.19
		Weak	1.50	1.94	2.65
Goal 15. Protect, restore and promote sustainable use of terrestrial ecosystems and forests					
Target 15.1. By 2020, ensure the conservation and restoration of terrestrial and inland freshwater ecosystems, in particular forests					
Stop deforestation and promote restoration of degraded forest lands to combat global warming and biodiversity loss	*Forest to Total Land Area (%)* | FAO, World Bank Percentage of forest to total (agricultural, urban and industrial, others) land areas.	Technical optimum			
			2030	2050	2100
		Ambitious	32.34	34.11	38.54
		Moderate	31.67	32.56	34.77
		Weak	31.34	31.78	32.89
	Forest Land Indicator (million ha) | IIASA Total area of forest lands.	Technical optimum			
			2030	2050	2100
		Ambitious	4173	4401	4973
		Moderate	4087	4201	4487
		Weak	4044	4101	4244
Target 15.5. Take urgent and significant action to reduce the degradation of natural habitats, halt the loss of biodiversity					
Stop biodiversity extinction from human activities and climate change	*Mean Species Abundance (%)* | CBD Mean abundance of measures the compositional intactness of local communities across all species relative to their abundance in undisturbed ecosystems. It varies between 100 (biodiversity as in undisturbed ecosystems) to 0 (population of zero for all original species).	Technical optimum			
			2030	2050	2100
		Ambitious	39.94	40.78	41.78
		Moderate	39.50	39.58	40.18
		Weak	38.95	38.19	37.59

Table S5. Main interactions among SDGs modelled in FeliX. In each cell, the indicator to the left of the arrow represents the SDG of the row where the cell is located and the indicator to the right represents the SDG of the column. Arrows show (in)direct interactions. For example, the interaction between SDG 2 and SDG 7 is reflected by SDG 2 - SDG 7 linkage (the impact of agricultural land-use change on forest biomass and energy crops production) and by SDG 7 - SDG 2 linkage (the impact of biomass energy demand on land-use change and the availability of non-energy agricultural commodities).

	SDG 2	SDG 3	SDG 7	SDG 8	SDG 12	SDG 13	SDG 15
SDG 2	-	Calorie supply → Life expectancy	Agricultural land expansion → Biomass production	-	Agricultural production → Fertiliser consumption	Agricultural production → C emission from land use	Agricultural production → Land-use change and biodiversity loss
SDG 3	Death rate, birth rate → Food consumption	-	Death rate, birth rate → Energy demand	Fertility rate, death rate → GWP	-	-	-
SDG 4	Education → Diet change and food consumption	Education → fertility rate	-	Education → Labour availability and GWP	-	-	-
SDG 7	Biomass demand → Agricultural production	-	-	Energy capital → GWP	-	Energy production → C emission	Biomass production → Land-use change and biodiversity loss
SDG 8	GWP → Food consumption, agricultural production	GWP → Life expectancy, fertility rate	GWP → Energy demand	-	GWP → Fertiliser consumption	-	-
SDG 12	Fertiliser consumption → Food yield	-	-	-	-	-	Fertiliser consumption → Biodiversity
SDG 13	Climate risks → Food yield	C concentration → Life expectancy	-	Climate risks → GWP	-	-	Climate risks → Biodiversity loss
SDG 15	Biodiversity → Land fertility	Biodiversity → Life expectancy	-	Biodiversity → GWP	-	-	-

Supplemental Experimental Procedures

Cereal Yield is computed as in Equation S1.

$$CY(t) = \frac{PR_{grains}(t) \times AH_{grains}(t)}{AH_{grains}(t)} \quad \text{Equation S1}$$

Where CY is the annual cereal production rate per hectare of harvested croplands dedicated to grains production (kg year^{-1}ha^{-1}), PR is crop yield per each category of crops (ton ha^{-1}year^{-1}), which is a function of the effects of fertiliser application, managerial practices, water withdrawal, and climate change on agriculture land fertility, and AH is the harvest area (ha).

Vegetal Food supply is computed as in Equation S2.

$$FS_{vegetal}(t) = \frac{\sum_{f \in PF} TFS_f(t) \times uc}{P(t) \times dy} \quad \text{Equation S2}$$

Where $FP_{vegetal}$ is the total annual production of plant products per person per day, $TFS_f(t)$ is the total supply of calories for food type f, PF is the plant food categories including pulses, grains, vegetable, fruits, roots, and other plant products (oil crops, sugar crops and nuts), $P(t)$ is the total population size at each year, uc denotes the unit conversion factor (Mkcal to kcal), and dy is the number of days in a year.

Animal Food supply is computed as in Equation S3.

$$FS_{animal}(t) = \frac{\sum_{f \in AF} TFS_f(t) \times uc}{P(t) \times dy} \quad \text{Equation S3}$$

Where FP_{animal} is the total annual production of animal food products (excluding seafoods) per person per day, $TFS_f(t)$ is the total supply of calories for food type f, AF is the animal-based food products including pasture-based meat (beef, sheep and goat) and crop-based meat (poultry and pork), eggs and dairy, $P(t)$ is the total population size at each year, uc denotes the unit conversion factor (Mkcal to kcal), and dy is the number of days in a year.

Total Food Supply is computed as in Equation S4.

$$FS_{total}(t) = FS_{vegetal}(t) + FS_{animal}(t) \quad \text{Equation S4}$$

Where FS_{total} is the total annual plant- and meat-based food production per person per day, $FS_{vegetal}$ is the total annual production of plant products per person per day, and FS_{animal} is the total annual production of animal food products (excluding seafoods) per person per day.

Ratio of Agricultural Lands to Total Lands is computed as in Equation S5.

$$RL_a(t) = \frac{LDR_a(t) + LC_{fa}(t) - LC_{au}(t) - LC_{af}(t) - LE_a(t)}{L_{total}(t)} \quad \text{Equation S5}$$

Where RL is the ratio of land allocated to a specific land-use to total available lands, a denotes agricultural land-use (i.e., permanent crops, permanent meadows and pastures, arable lands), and LDR_a is the agricultural land development rate, LC_{fa} is deforestation to agricultural land, LC_{au} is agricultural land conversion rate to urban land, LC_{af} is forestation from agricultural land, LE_a is agricultural land erosion rate, L_{total} is total area of land for a all types of land-uses (i.e., agricultural, forest, urban and industrial, and other land-uses).

Pasture Land Indicator is computed as in Equation S6.

$$L_p(t) = L_a(t) \times RAL_p \times uc \quad \text{Equation S6}$$

Where L_p is the area of land allocated to permanent pastures and meadows (million ha), L_a is total area of land for agricultural land-uses, RAL_p is the percentage of meadows and pastures in agriculture lands, and uc denotes the unit conversion factor (million ha ha^{-1}).

Total Croplands Indicator is computed as in Equation S7.

$$L_c(t) = L_a(t) \times (RAL_{pcrops} + RAL_{ararable}) \times uc \qquad \text{Equation S7}$$

Where L_c is the area of land allocated to for energy and food (and feed) crops (million ha), L_a is total area of land for agricultural land-uses, RAL_{pcrops} is the permanent crops percentage of agriculture land, RAL_{arable} is the arable percentage of agriculture land, and uc denotes the unit conversion factor (million ha ha^{-1}).

Life Expectancy is computed as in Equation S8.

$$LE(t) = LE_{ref} \times LM_{food}(t) \times LM_{health}(t) \times LM_{climate}(t) \qquad \text{Equation S8}$$

Where LE is the average life expectancy of the population (year), LE_{ref} is a referenced normal value for life expectancy and LMs are lifetime multiplier from food, health, and climate risk.

Adolescent Fertility Rate is computed as in Equation S9.

$$AFR(t) = \frac{AFF \times TF(t) \times 1000women}{RL} \qquad \text{Equation S9}$$

Where AFR is the number of births per 1,000 by women between the age of 15-19, AFF is the adolescent fertility fraction, $TF(t)$ is the total fertility which is a function of GDP and education, and RL is the adolescent reproductive lifetime.

Human Development Index is computed as in Equation S10.

$$HDI(t) = HI(t)^{-3} \times II(t)^{-3} \times EI(t)^{-3} \qquad \text{Equation S10}$$

Where HDI is the UNDP Human Development Index representing the achievement of income, health, education prosperity and its value represents human capabilities sustainable wellbeing (%), HI is the health index, II is the income index, and EI is the education index.

Mean Years of Schooling is computed as in Equation S11.

$$YS(t) = \frac{\sum_{e \in E} TY_e(t)}{\sum_{g \in G} \sum_{c \in C} P_{g,c}(t)} \qquad \text{Equation S11}$$

Where YS is the average number of completed years of primary, secondary, and tertiary education (combined) of population (year), $TY_e$is total duration in the e level of education (person year), E denotes the three primary, secondary, and tertiary levels of education, $P_{g,c}$ is the population size of gender g and age cohort c, G denotes both male and female genders, and C denotes age cohorts.

Population Age 25 to 34 with Tertiary Education is computed as in Equation S12.

$$PT(t) = \frac{\sum_{g \in G} \sum_{c \in C} TG_{g,c}(t)}{\sum_{g \in G} \sum_{c \in C} P_{g,c}(t)} \qquad \text{Equation S12}$$

Where PT is the percentage of the population, aged between 25-34 years old, who have completed tertiary education, $TG_{g,c}$ is the number tertiary education graduates for gender g and age cohort c, G denotes both male and female genders, and C denotes age cohorts between 25 and 34.

Female to Male Enrollment in Tertiary Education is computed as in Equation S13.

$$FM_{tertiary}(t) = \frac{ERT_{female}(t)}{ERT_{male}(t)} \quad \text{Equation S13}$$

Where $FM_{tertiary}$ is the percentage of the female to male graduation rate from tertiary education, ERT_{female} is the graduation rate of female population from tertiary education, and ERT_{male} is the graduation rate of male population from tertiary education.

Share of Renewable Energy Supply is computed as in Equation S14.

$$SES_{renewable}(t) = \frac{\sum_{e \in ER} EP_e(t)}{EP_{total}(t)} \times 100 \quad \text{Equation S14}$$

Where $SES_{renewable}$ is the percentage of renewable energy supply share in total energy production, EP_e is the energy production from source e, ER denotes the three biomass, solar, and wind renewable sources, and EP_{total} is total energy production from both fossil and renewable sources.

Solar Energy Production Indicator is computed as in Equation S15.

$$EP_{solar}(t) = min(\frac{PEP_{solar}(t)}{ED_{solar}(t)}) \times uc \quad \text{Equation S15}$$

Where EP_{solar} is the energy production from solar (EJ $year^{-1}$), that is limited by PEP_{solar} which is possible energy production from solar (maximum capacity) based on sun radiation, solar conversion efficiency factor, and available installed capacity, ED_{solar} which is energy demand for solar based on solar market share from total demand. uc is also the unit conversion factor (EJ $Mtoe^{-1}$).

Wind Energy Production Indicator is computed as in Equation S16.

$$EP_{wind}(t) = min(\frac{PEP_{wind}(t)}{ED_{wind}(t)}) \times uc \quad \text{Equation S16}$$

Where EP_{wind} is the energy production from wind (EJ $year^{-1}$), that is limited by PEP_{wind} which is possible energy production from wind (maximum capacity) based on average capacity per m2, a wind capacity factor multiplier, and wind installed capacity, ED_{wind} which is energy demand for wind based on its market share from total demand. uc is also the unit conversion factor (EJ $Mtoe^{-1}$).

Biomass Energy Production Indicator is computed as in Equation S17.

$$EP_{biomass}(t) = min(\frac{PEP_{biomass}(t)}{ED_{biomass}(t)}) \times uc \quad \text{Equation S17}$$

Where $EP_{biomass}$ is the energy production from biomass (EJ $year^{-1}$), that is limited by $PEP_{biomass}$ which is possible energy production from biomass (maximum capacity), $ED_{biomass}$ which is energy demand for biomass based on its market share from total demand. uc is also the unit conversion factor (EJ $Mtoe^{-1}$).

Oil Production Indicator is computed as in Equation S18.

$$EP_{oil}(t) = min(\frac{PEP_{oil}(t)}{ED_{oil}(t)}) \times uc \quad \text{Equation S18}$$

Where EP_{oil} the energy production from oil (EJ $year^{-1}$), that is limited by PEP_{oil} which is possible energy production from oil (maximum capacity) based on resource availability, investment, and technology improvement, ED_{oil} which is energy demand for oil based on its market share from total demand. uc is also the unit conversion factor (EJ $Mtoe^{-1}$).

Coal Production Indicator is computed as in Equation S19.

$$EP_{coal}(t) = min(\frac{PEP_{coal}(t)}{ED_{coal}(t)}) \times uc \quad \text{Equation S19}$$

Where EP_{coal} is the energy production from coal (EJ year^{-1}), that is limited by PEP_{coal} which is possible energy production from coal (maximum capacity) based on resource availability, investment, and technology improvement, ED_{coal} which is energy demand for coal based on its market share from total demand. uc is also the unit conversion factor (EJ Mtoe^{-1}).

Gas Production Indicator is computed as in Equation S20.

$$EP_{gas}(t) = min(\frac{PEP_{gas}(t)}{ED_{gas}(t)}) \times uc \quad \text{Equation S20}$$

Where EP_{gas} is the energy production from gas (EJ year^{-1}), that is limited by PEP_{gas} which is possible energy production from gas (maximum capacity) based on resource availability, investment, and technology improvement, ED_{gas} which is energy demand for gas based on its market share from total demand. uc is also the unit conversion factor (EJ Mtoe^{-1}).

Energy Intensity of GWP is computed as in Equation S21.

$$EI(t) = \frac{EP_{total}(t) \times uc}{GWP(t)} \quad \text{Equation S21}$$

Where EI is energy consumption per unit of GWP production (MJ \$$^{-1}$) indicating how much energy is used to produce one unit of economic output (lower ratio means that less energy is used to produce one unit of output), EP_{total} is the total energy production from both renewable and fossil resources, GWP is gross world product, and uc is the unit conversion factor (MJ Mtoe^{-1}).

GWP per Capita is computed as in Equation S22.

$$GWP(t) = REO(t) \times ME_{climate}(t) \times ME_{biodiversity}(t) \times uc \quad \text{Equation S22}$$

Where GWP is the gross world product (\$1000 person^{-1} year^{-1}), REO is the reference economy output based on change in technology and capital, $ME_{climate}$ is the net climate change impact on economy, $ME_{biodiversity}$ is the impact of biodiversity on economy, and uc is the unit conversion factor (\$1000).

CO2 Emissions per GWP is computed as in Equation S23.

$$EGWP(t) = \frac{CE_{fossil}(t) \times uc}{GWP(t)} \quad \text{Equation S23}$$

Where $EGWP$ is human-originated carbon dioxide emissions stemming from emissions the burning of fossil per GWP (kgCO2 \$$^{-1}$), CE_{fossil} is the total CO2 emissions from fossil energy, GWP is gross world product, and uc is the unit conversion factor (kg ton^{-1}).

Agro Food Nitrogen Production Footprint is computed as in Equation S24.

$$FEC_N(t) = \frac{(DR(t) + LR(t)) \times uc}{P(t)} \quad \text{Equation S24}$$

Where FEC_N is the Total reactive nitrogen per year per capita accumulated through commercial application in agriculture and application with manure (kg year^{-1} person^{-1}), DR is the denitrification rate, LR is the leaching and runoff rate, uc is the unit conversion factor (kg ton^{-1}), and P is the total population size.

Nitrogen Fertilizer Use in Agriculture is computed as in Equation S25.

$$FU_N(t) = FU_{ref} \times FUM_{income}(t) \times FUM_{technology}(t) \times FUM_{land}(t) \times uc \quad \text{Equation S25}$$

Where FU_N is commercial nitrogen fertilizer application in agriculture (1000ton year^{-1}), FU_{ref} is the reference nitrogen consumption in 2010, FUM_{income} is the effect of income on fertilizer use, $FUM_{technology}$ is the effect of technology on fertilizer consumption, FUM_{land} is the effect of land availability on fertilizer use, and uc is the unit conversion factor (1000ton ton^{-1}).

Phosphorous Fertilizer Use in Agriculture is computed as in Equation S26.

$$FU_P(t) = CP_{agriculture}(t) \times cf \times uc \qquad \text{Equation S26}$$

Where FU_P is commercial phosphorous fertilizer application in agriculture (1000ton year^{-1}), $CP_{agriculture}$ is the commercial P2O5 application for agriculture, cf is P2O5 to P conversion factor, and uc is the unit conversion factor (1000ton ton^{-1}).

Atmospheric Concentration CO2 is computed as in Equation S27.

$$AC(t) = \frac{C(t)}{cf \times uc} \qquad \text{Equation S27}$$

Where AC is atmospheric CO2 concentration (ppm), C is carbon in atmosphere computed based on flux biomass to atmosphere, flux humus to atmosphere, and a total carbon emission-flux atmosphere to biomass-flux atmosphere to ocean, cf and uc are unit conversion factors.

Total CO2 Emissions from AFOLU is computed as in Equation S28.

$$EC_{AFOLU}(t) = (C_{agriculture}(t) + C_{forest}(t)) \times uc \qquad \text{Equation S28}$$

Where EC_{AFOLU} is the total CO2 emissions from agriculture and land-use change (Gt CO2 year^{-1}), $C_{agriculture}$ is total carbon emissions from agriculture, C_{forest} is total carbon emissions from forest land-use change, and uc is the unit conversion factor.

CO2 Emissions from Fossil Energy is computed as in Equation S29.

$$EC_{fossil}(t) = C_{fossil}(t) \times uc \qquad \text{Equation S29}$$

Where EC_{fossil} is total CO2 emissions from fossil energy production (Gt CO2 year^{-1}), C_{fossil} is total carbon emissions from fossil energy, and uc is the unit conversion factor.

Total CO2 Emissions is computed as in Equation S30.

$$EC(t) = \frac{EC_{AFOLU}(t) + EC_{fossil}(t) + EC_{renewable}(t)}{P(t)} \qquad \text{Equation S30}$$

Where EC is total CO2 emissions, EC_{AFOLU} is the total CO2 emissions from agriculture and land-use change, EC_{fossil} is the total CO2 emissions from fossil energy, $EC_{renewable}$ is the total CO2 emissions from renewable energy, and P is total population size.

Total Radiative Forcing is computed as in Equation S31.

$$RF_{total}(t) = RF_{CO2}(t) + \sum_{g \in G} RF_g(t) \qquad \text{Equation S31}$$

Where RF_{total} the difference between insolation (sunlight) absorbed by the Earth and energy radiated back to space from all greenhouse gases (W m-2), RF_{CO2} is radiative forcing from CO2 which is computed endogenously in the model, RF_g is radiative forcing from greenhouse gas g which is read in the model from external database, and G indicates CH4, N2O, HFC, and ‘others’.

CO2 Radiative Forcing is computed as in Equation S32.

$$RF_{CO2}(t) = RF_{coefficient} \times \ln \frac{C_{atomosphere}(t)}{C_{atomosphere}(t_{preindustrial})} \quad \text{Equation S32}$$

Where RF_{CO2} is radiative forcing is resulted from CO2 emissions (W m-2), $RF_{coefficient}$ is CO2 radiative forcing coefficient, $C_{atomosphere}$ is carbon in atmosphere at any time, and $C_{atomosphere}(t_{preindustrial})$ is the preindustrial carbon in atmosphere.

Temperature Change from Preindustrial period is computed as in Equation S33.

$$TC(t) = \frac{H_{ao}(t)}{HC_{ao}(t)} \quad \text{Equation S33}$$

Where TC is the global annual mean temperature change from the pre-industrial time (degree C), H_{ao} is heat in atmosphere and upper ocean, and HC_{ao} is the atmospheric and upper ocean heat capacity.

Forest to Total Land Area is computed as in Equation S34.

$$RL_{forest}(t) = \frac{L_{forest}(t)}{L_{total}(t)} \times 100 \quad \text{Equation S34}$$

Where RL_{forest} is the percentage of forest to total land areas, L_{forest} is the size of forest land areas, and L_{total} is the size of total available lands.

Forest Land Indicator is computed as in Equation S35.

$$L_{forest}(t) = (LC_{af}(t) + LC_{of}(t) - LC_{fa}(t) - LC_{fu}(t)) \times uc \quad \text{Equation S35}$$

Where L_{forest} is the size of forest land areas (million ha), LC_{af} forestation from agricultural lands, LC_{of} is forestation from other lands, LC_{fa} is deforestation to agricultural lands, LC_{fu} deforestation to urban lands, and uc is a unit conversion factor (million ha ha^{-1}).

Mean Species Abundance is computed as in Equation S36.

$$MSA(t) = SR(t) - SE(t) \quad \text{Equation S36}$$

Where MSA is the mean abundance of original species relative to their abundance in undisturbed ecosystems (%), SR is species regeneration rate, and SE is species extinction rate.

Supplemental References

1. Riahi, K., van Vuuren, D.P., Kriegler, E., Edmonds, J., O'Neill, B.C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., et al. (2017). The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. Global Environ. Change *42*, 153-168. https://doi.org/10.1016/j.gloenvcha.2016.05.009.