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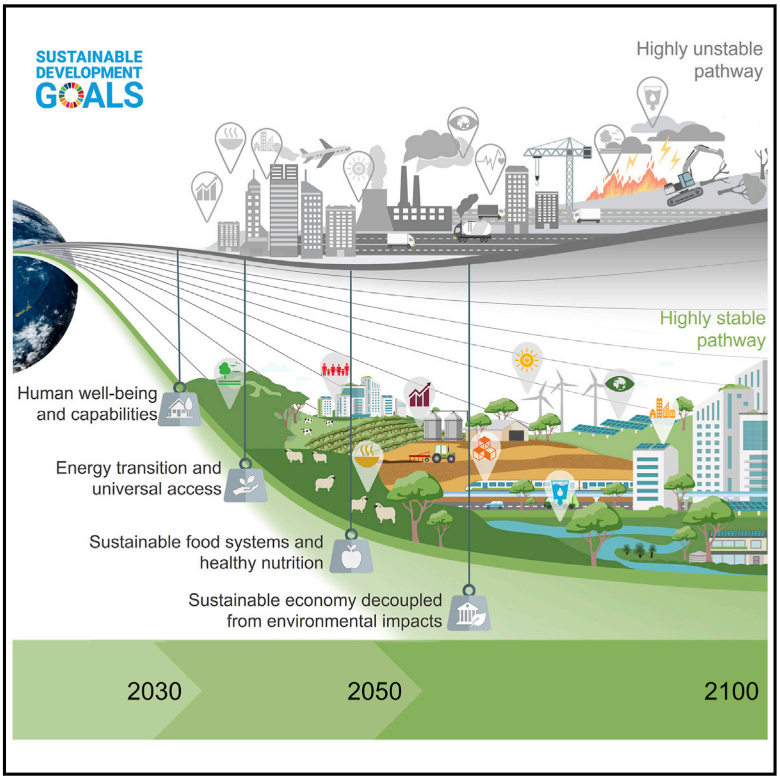
Early systems change necessary for catalyzing long-term sustainability in a post-2030 agenda

Graphical abstract



Highlights

- Sustainability progress to 2100 was analyzed using a system dynamics model
- Progress towards 2030 targets was limited across most pathways
- Early intervention is important for accelerating progress towards increasingly ambitious sustainability targets by 2050 and 2100

Authors

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In brief

Our model-based projection of progress toward the Sustainable Development Goals shows a limited chance of near-term success for achieving the 2030 Agenda. However, complex systemic interactions and feedbacks mean that early planning and action towards systems change can accelerate progress towards even more ambitious 2050 and 2100 targets than those for 2030. This longer-term analysis is important to improve the understanding of the conditions that appear to make a limited contribution to initial progress by the 2030 milestone but can become increasingly influential later in the century.

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Article

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

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SCIENCE FOR SOCIETY The world is subject to multiple global challenges, including climate change, environmental degradation, poverty, and inequality. The United Nations Sustainable Development Goals (SDGs) represent nations' collective ambition to overcome these challenges and achieve a more prosperous and sustainable future for all by 2030. However, with less than 8 years remaining, assessments have concluded that it is unlikely that the SDGs will be fully achieved by the end of the decade and that the slowing and reversal of negative trends in key challenges such as climate change is not likely to happen until after 2030. Despite long-term analyses of these component challenges, a deeper and more integrated understanding of the available opportunities to accelerate and achieve sustainability throughout the 21st century is now urgent. This new study, based on the simulated futures of the SDGs, characterizes the scale and feasibility of necessary systems change and provides a guide for long-term progress in sustainability.

SUMMARY

Progress to date toward the Sustainable Development Goals (SDGs) has fallen short of expectations and is unlikely to fully meet 2030 targets. Past assessments have mostly focused on short- and medium-term evaluations, thus limiting the ability to explore the longer-term effects of systemic interactions with time lags and delay. Here we undertake global systems modeling with a longer-term view than previous assessments in order to explore the drivers of sustainability progress and how they could play out by 2030, 2050, and 2100 under different development pathways and quantitative targets. We find that early planning for systems change to shift from business as usual to more sustainable pathways is important for accelerating progress toward increasingly ambitious targets by 2030, 2050, and 2100. These findings indicate the importance of adopting longer-term timeframes and pathways to ensure that the necessary pre-conditions are in place for sustainability beyond the current 2030 Agenda.

INTRODUCTION

The United Nations 2030 Agenda (also known as Sustainable Development Goals – SDGs) provides a framework for human development within planetary boundaries through a complementary set of goals (i.e., broad ambitions), targets (i.e., specific thresholds defining success), and indicators (i.e., metrics by which progress toward targets can be judged).[1] Progress to date toward the SDGs has been limited.[2,3] With less than 8 years to go, the scientific community has taken significant steps toward understanding and planning for the SDGs through different approaches, such as future pathway modeling,[4–7] science-based target setting,[8] and SDG interaction analysis.[9–11] SDGs have also been studied at global,[6,12] national,[13,14] and local scales.[10,15]

Despite important efforts, past SDG assessments have remained focused mostly on short-term (i.e., 2030) and medium-term (i.e., 2050) evaluations. Many of these assessments have found that (even the most ambitious) pathways are unlikely to fully achieve all SDGs by 2030[4,7,14] and, in some cases, not even by 2050.[12] Although such short/medium-term assessments can be justified in some cases (e.g., for SDGs related to peace, institution, and implementation with significant future uncertainties), they can limit the understanding of longer-term progress and overlook the role of delayed effects and non-linear behavior of slow sustainability trends, driven by systemic feedback interactions that emerge throughout to 2100. This knowledge gap has become increasingly important, given longer-term analyses in neighboring fields (e.g., conservation science,[16] climate change,[17] and demographic studies[18]) and the common finding that the slowing and eventual reversal of negative trends in key sustainability components (e.g., biodiversity loss, greenhouse gas emissions, and population growth) are likely to happen after 2030 and throughout the century.

Here we analyzed long-term global sustainability progress through the SDG lens by 2030, 2050, and 2100 across plausible socioeconomic and environmental development trajectories and through endogenous modeling of inter-connections in human-natural systems. Short-, medium-, and long-term timeframes were aligned with the 2030 Agenda, the Paris Agreement (2050), and the Intergovernmental Panel on Climate Change (IPCC) climate change milestone (2100), respectively. We used this longer-term analysis to show what lies beyond the 2030 Agenda in terms of non-linear progress toward increasingly ambitious targets over time and to identify systems change important for accelerating sustainability progress later in the century. Understanding the required systems change, the opportunities to initiate and sustain it, and the potential barriers to achieving it is prerequisite for future planning to enable missed 2030 targets to be met and exceeded later on and ensure that earlier achievements are not lost through complacency and despair.

RESULTS

Global system dynamics modeling for pathway simulation

Our analysis is underpinned by an established model, called Functional Enviro-economic Linkages Integrated Nexus (FeliX). It is developed based on the system dynamics methodology[19] and simulates global-scale social, economic, and environmental interactions and feedback[20] (Figure 1; Table S5; Experimental procedures). FeliX supports modeling of indicators representing eight SDGs related to sustainable food (SDG 2), health and well-being (SDG 3), quality education (SDG 4), clean energy (SDG 7), economic growth (SDG 8), responsible consumption and production (SDG 12), climate action (SDG 13), and life on land (SDG 15). With relatively simple but transparent structure and fast simulation runs, it can cover multiple sustainability dimensions in one integrated modeling framework, which is ideal to support simulation of evolving trade-offs and synergies between human activities (i.e., demography, economy, energy, land, and food) and environmental change (i.e., biodiversity, carbon cycle, and climate systems) over time. Among the few system dynamics models,[12,14,21] FeliX was selected for its transparency[20,22] and credibility in analyzing multiple sustainability dimensions such as emissions pathways,[23] sustainable diet shift,[24] and socio-environmental impacts in human and Earth systems[25] (see Discussion and conclusions for the model's strengths and limitations).

A wide range of long-term development pathways have been assessed, spanning different mitigation policies across systems and with different degrees of compatibility with the Paris Agreement and sustainable development.[7,26] We evaluated a set of five illustrative pathways, in line with the shared socioeconomic pathways (SSPs)[27] and representative concentration pathways (RCPs),[28] as benchmarks for long-term global development trajectories. The selected pathways were not meant to cover all possible futures but to demonstrate the effects of some of the future choices on socioeconomic and environmental development in our analysis. The five pathways are aligned with commonly used SSP-RCP combinations,[26] including Business As Usual (SSP2-4.5; the reference pathway), Green Recovery (SSP1-2.6), Fragmented World (SSP3-7.0), Inequality (SSP4-6.0), and Fossil-Fueled Development (SSP5-8.5) (see Discussion and conclusions for limitations and opportunities of the selected pathways).

We followed a "story and simulation" approach, where the SSP-RCP pathway narratives (Table S1) were used to specify the initial conditions of the model, and then used the model for simulating pathways in quantitative terms (Table S2). Using the FeliX model, we simulated 10,000 model evaluations (called pathway realizations) for each of the five pathways (50,000 pathway realizations in total) to take into account model parameter uncertainty (e.g., natural variability and error in quantification) and explore the variation around the five main pathways for more robust insights (Experimental procedures).

Of the five pathways assessed (Figures 2 and S1), Business As Usual as our reference pathway to 2100 used the continuation of the current trajectories as input assumptions, and therefore its socioeconomic and environmental behavior followed SSP2-4.5 projections. Compared with Business As Usual, Green Recovery had improving socioeconomic trajectories (driven by low population growth, growing economy, and better education access assumptions), fast transition to renewable energy (driven by lower production costs, higher investment, and technology improvement assumptions), and limited land use change (because of lower demand for food, lower meat consumption, and higher agricultural productivity assumptions). The environmental effects of these positive socioeconomic trends together with ambitious climate policies resulted in low deforestation and low-range greenhouse gas (GHG) emissions by 2100. Fragmented World projected declining socioeconomic prosperity (driven by increasing population and slower economic growth), large energy production from fossil fuels, high land use change, and significant environmental footprints (because of high deforestation and emissions levels) compared with Business As Usual. Inequality with slightly better trajectories resulted in moderately improved socioeconomic projections compared with Business As Usual and Fragmented World, relatively slow clean energy transitions, and relatively high food production and land use change trajectories. Fossil-Fueled Development projected an improving socioeconomic future (similar to Green Recovery) but at the cost of unsustainable environmental trajectories

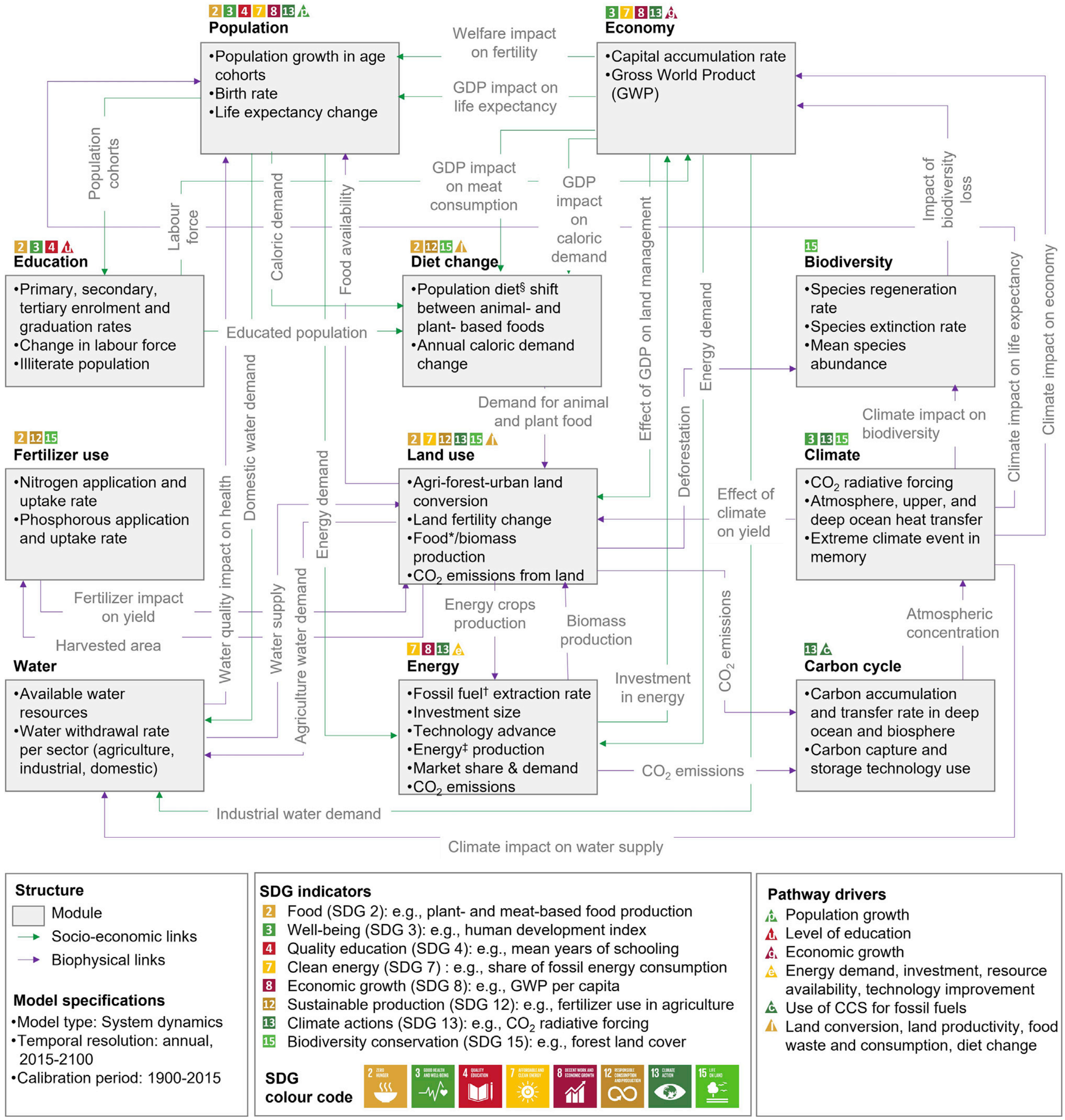

Figure 1. Overview of the FeliX model

Gray-shaded boxes represent different sectoral modules in FeliX. Square and triangle markers show where in the model the SDG indicators and pathway drivers were implemented. The marker colors are consistent with their corresponding SDG color, and their annotated numbers/letters correspond to the name of the SDGs and pathway drivers. *Food categories include animal products comprising crop-based meat (poultry and pork), pasture-based meat (beef, sheep, and goat), dairy, and eggs and the supply of plant-based products, including grains, pulses, oil crops, vegetables, roots, and fruits. †Fossil fuels include coal, gas, and oil. ‡Energy includes fossil and renewable (solar, wind, and biomass) energies. §Diet categories include five diet compositions of high to low meat and vegetable consumption. CCS, carbon captured and storage of fossil fuels. See Experimental procedures and Table S5 for more details about the model.

(e.g., slow clean energy transitions and high emissions) because of assumptions of fossil fuel dependency and resource-intensive development.

The results showed consistent behavior with input assumptions across systems in each pathway (Table S1) and also in harmony with the 2100 projections of other integrated assessment

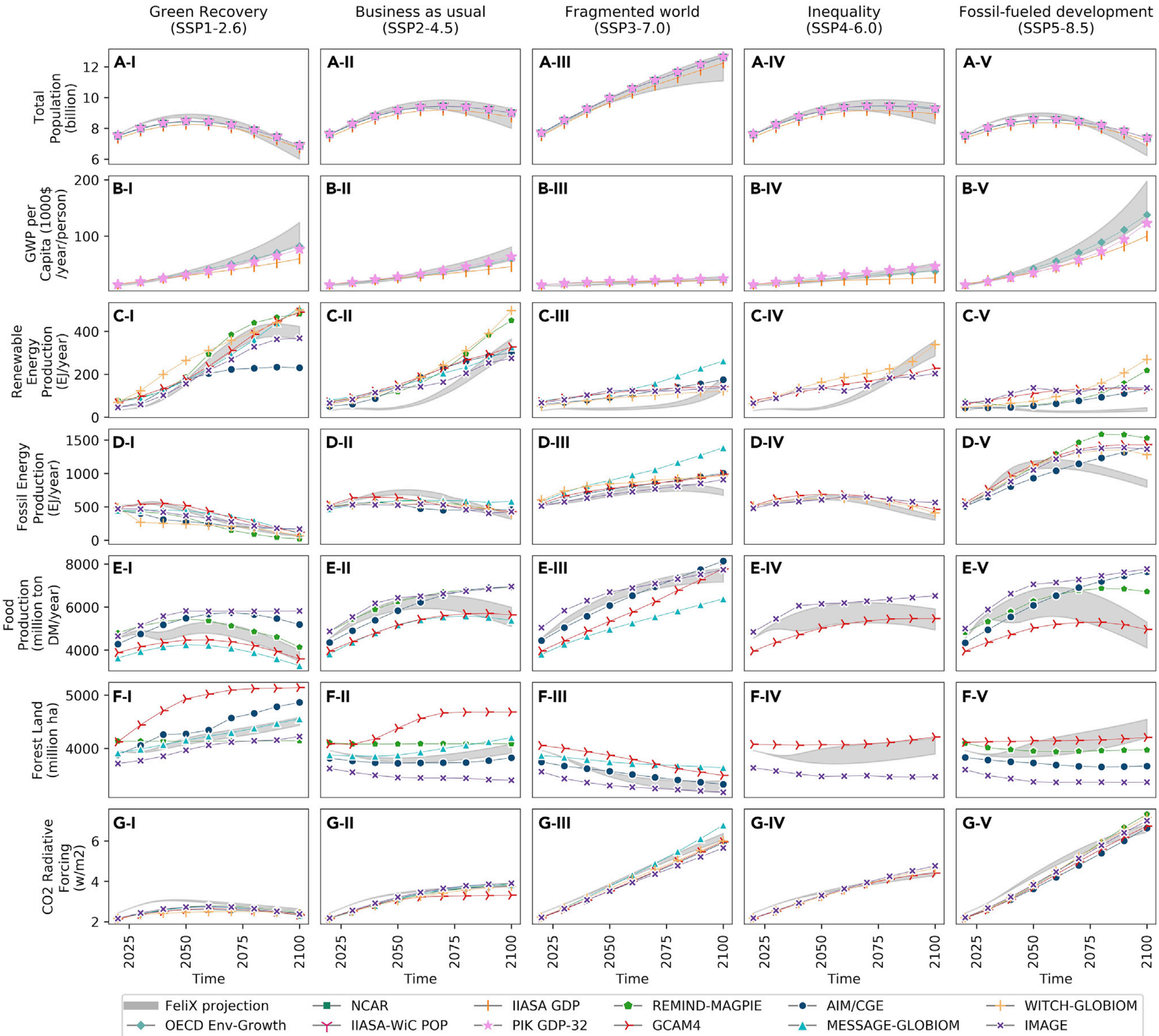

Figure 2. Pathway simulation results against a suite of seven socioeconomic and environmental model outputs and comparison against similar simulation outputs of major models

FeliX simulations cover the period 2015–2100 at an annual time step (Experimental procedures). The y axis in all panels represents control variables we used for cross-validating FeliX projections with those of other models. GWP, gross world product.

models.[29] However, because of the difference in FeliX's model structure and scenario parameter settings, pathways were often quantitatively different (and sometimes with different trajectory patterns) from the outputs of other models. FeliX is structurally different from most integrated assessment models because it is a descriptive model instead of prescribing cost-optimal choices, and it does not assume market equilibrium (see more in Discussion and conclusions). Similar variations in future projection have been observed among other models[29] (see other model projections in Figures 2 and S1), and this highlights the importance of diversifying models to obtain a broader variety of future possibilities for a robust assessment and better appreciation of the deep uncertainty in future projections.[30–32]

Our outputs differed from other models mostly in two main areas. First, FeliX projected a faster decline in fossil energy production (e.g., in Fossil-Fueled Development), which resulted from bolder assumptions about fossil fuel and renewable energy production costs. Second, lower livestock production and crop demand were projected in Green Recovery because of FeliX's endogenous diet change assumptions. More explicit assumptions about a shift toward sustainable diets in FeliX, driven by modeling of behavior change and consumption patterns, resulted in lower meat consumption and limited arable land expansion in some pathways compared with outputs from other models (Figures 2 and S1).

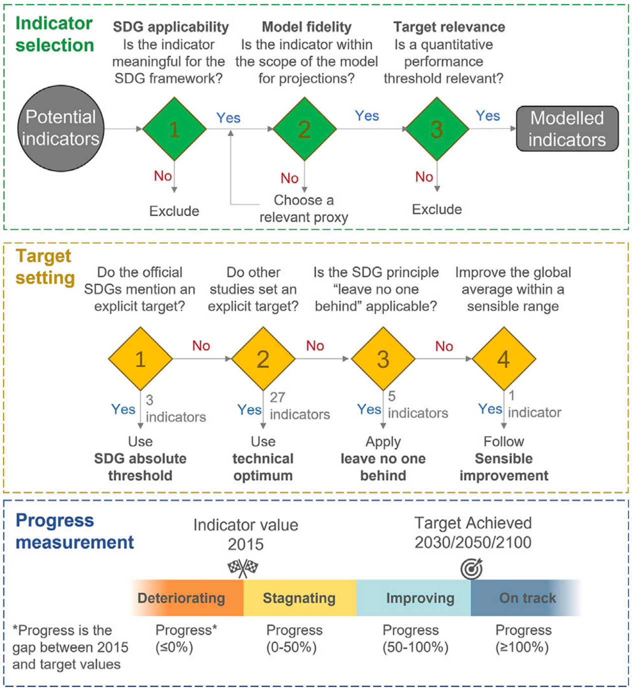

Figure 3. Indicator selection, target setting, and progress measurement processes

See Experimental procedures for further details.

Accelerating SDG progress

We specified a set of well-defined socioeconomic and environmental indicators and targets to measure long-term SDG progress in the projected pathways. Although the current 2030 Agenda has 169 targets and 232 indicators, many are complex, and some lack the specificity to support quantitative projections.[8] We therefore defined 36 complementary sustainability indicators and set quantitative targets related to eight SDGs that were within the scope of our modeling but were also diverse enough to cover most of the key areas of sustainable development related to people (SDGs 3 and 4), prosperity (SDG 8), sustainable resource management (SDGs 2, 7, and 12), and planet integrity (SDGs 13 and 15), as defined by van Vuuren et al.[8] (see Discussion and conclusions for strengths and limitations of selected SDGs).

Indicators were chosen based on a selection process that considers SDG suitability and measurement feasibility within our model (Figure 3; Experimental procedures). We set short-, medium-, and long-term measurable target values with an increasing ambition for 2030, 2050, and 2100 to indicate shifting performance thresholds for the selected indicators over time (Tables S3 and S4). The targets were set based on criteria that evaluate the suitability of alternative options in the current literature (Figure 3; Experimental procedures). Starting from the base year of 2015 (i.e., SDG initiation), progress toward the target for each indicator was measured in percentage terms, according to the standard SDG progress monitoring methodology and terminology,[33] in a range from 0% or less (indicating no or reverse progress; i.e., deteriorating), 0%–50% (i.e., stagnating), 50%–100% (improving), and 100% or greater (indicating that the target has been met or exceeded; i.e., on track).

Insufficient short-term progress

By 2030, although most SDG targets remained unachievable under the modeled pathways, the individual target achievement varied across pathways, with some resulting in slightly better progress than others but not enough to be on track to fully achieve the SDGs (Figures 4A and 5). To illustrate, we discuss some of the SDGs and pathways by 2030, with improving, stagnating, and deteriorating progress, respectively.

For the 2030 targets, health and wellbeing (SDG 3), quality education (SDG 4), and economic growth (SDG 8) had the highest progress in Green Recovery (82%, 89%, and 97%, respectively; Figure 5) and Fossil-Fueled Development (83%, 89%, and 99%, respectively; Figure S6B). In at least 50% of the realizations for each of these two pathways, progress under SDGs 3, 4, and 8 was either on-track (five targets) or improving (three targets) by 2030 (Figure 4A). A combination of assumptions on human capital investment and low population growth (Figures 2A-I, 2A-V, S1C-I, and S1C-V) put Green Recovery and Fossil-Fueled Development on track toward these targets by 2030. Fragmented World (and then Business As Usual and Inequality) had the slowest progress by 2030, stagnating and even deteriorating from 2015 for most socioeconomic targets under SDGs 3, 4, and 8 (Figures 4A, S4B, and S5B).

Sustainable food (SDG 2) and clean energy (SDG 7) were the two goals with relatively slow progress by 2030 across all pathways. For SDG 2, Fossil-Fueled Development outperformed other pathways by 74% progress, being on track or improving for six of seven 2030 food production and agricultural productivity targets (Figures S6B and 4A). Conversely, progress under Fragmented World was only 36%, being on track in achieving only three food-related targets by 2030 (Figures S4B and 4A). For SDG 7, the progress in Green Recovery is highest (47%), mostly because of economic growth with a higher adoption of efficient end-use technologies and a faster transition to renewable energy (Figure 2C-I). Fossil-Fueled Development and Fragmented World had the slowest progress of 31% and 17%, respectively (Figures S6B and S4B), because of heavy reliance on fossil fuels throughout the century (Figures S1E-V, S1F-V, and S1G-V).

The 2030 progress in biodiversity conservation (SDG 15), responsible production (SDG 11), and climate action (SDG 13) was the lowest in all pathways. By 2030, projected progress toward these targets was either stagnating or deteriorating in all pathways (Figure 4A). Green Recovery aside, this poor environmental performance was largely the result of increasing demand for food production, high meat consumption, and a growing energy-intensive economy in the model input assumptions for these pathways, which posed risks for environmental targets such as agricultural land expansion and nitrogen fertilizer use (Tables S1 and S2). In Green Recovery, despite model assumptions that were expected to counteract environmental damages, the low progress for SDGs 11, 13, and 15 was driven by the momentum of negative trends (e.g., ongoing ecosystem loss, deforestation, and global greenhouse gas emissions) and delayed sustainability improvements from systems change.

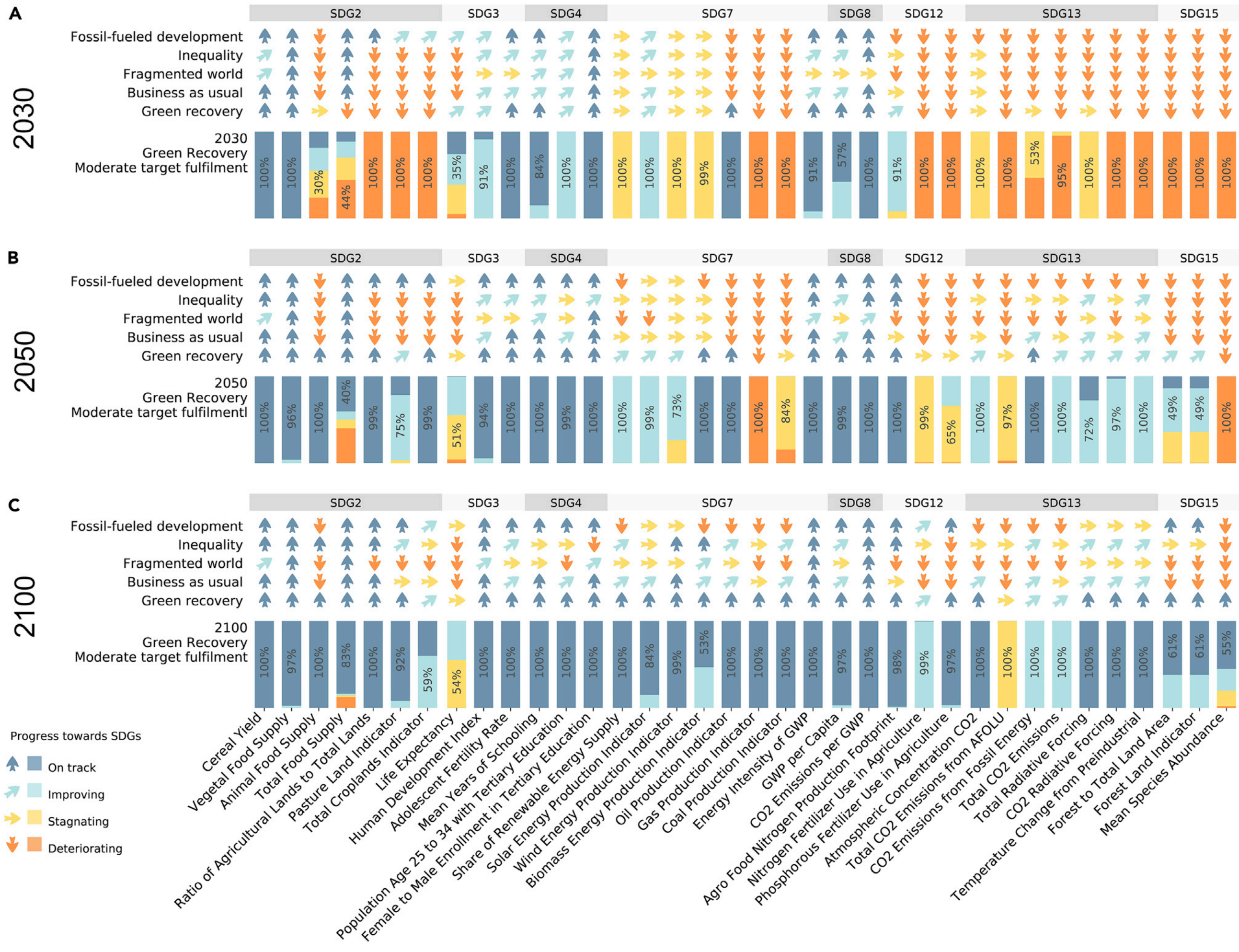

Figure 4. Projected progress toward moderate SDG targets over time and under five modeled pathways

(A–C) Progress by 2030 (A), 2050 (B), and 2100 (C). Each column represents one indicator. Related indicators are grouped under SDG headers. Progress levels (deteriorating, stagnating, improving, and on track) at each indicator are color-coded in the stacked bar charts and also represented by arrows for all five pathways (Experimental procedures). The arrows indicate the most likely progress of each pathway across its 10,000 realizations. The stacked bar chart focuses only on Green Recovery as the most sustainable pathway. The annotated percentage in each bar represents the share of 10,000 Green Recovery realizations for the corresponding progress level. For example, in (C), the bar for "Total Food Supply" shows that 83% of the 10,000 possible realizations of Green Recovery had on-track progress, whereas 17% of them had stagnating or deteriorating progress.

Post-2030 acceleration

Progress towards increasingly ambitious 2050 and 2100 targets accelerated beyond 2030 under all pathways. To illustrate, looking at Green Recovery as the pathway with highest long-term progress, the SDGs that had the worst outcome by 2030 experienced much faster progress toward new targets by 2050 and 2100 (Figures 4B, 4C, and 5).

By 2050 under Green Recovery, progress in responsible production (SDG 12), climate action (SDG 13), and biodiversity (SDG 15) increased to 54%, 74%, and 42%, respectively (Figure 5). Looking out to 2100 with even more ambitious targets than those in 2030 and 2050 (Tables S3 and S4), progress under Green Recovery in these three goals further increased to 94%, 84%, and 90%, respectively (Figure 5). Green Recovery's progress acceleration was less but still significant in other goals as well. For example, progress in food security (SDG 2) and clean energy (SDG 7) reached the highest level among all pathways, to 97% and 99% by 2100, respectively (Figure 5). Even in SDGs where Green Recovery did not seemingly progress much over time (e.g., Health and Well-being; Figure 5), the change in the absolute of value of the related indicators in 2100 is significant (Figures S8B-I to S8B-III). This can be explained by our methodology, which measures the post-2030 progress against shifting targets toward further 2050 and 2100 ambitions and not against the same 2030 target values (Experimental procedures).

Similar acceleration was also observed in Fossil-Fueled Development by 2100, but mostly across socioeconomic goals rather than environmental ones (e.g., SDGs 12, 13, and 15; Figure S6C). Other pathways, such as Fragmented World, also showed nonlinear long-term progress, but in the opposite direction, reversing their 2030 achievement and even deteriorating from their 2015

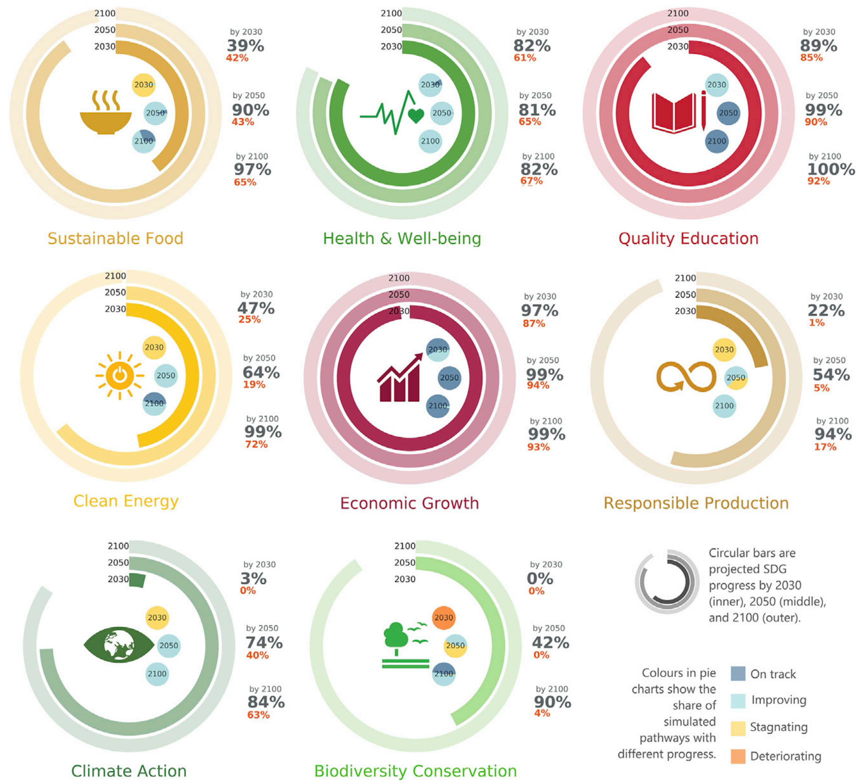

Figure 5. Global progress in Green Recovery toward eight modeled SDGs with moderate targets

The results for other pathways (i.e., Fragmented World, Inequality, and Fossil-Fueled Development) are shown in Figures S4–S6. Each panel shows the progress toward one SDG. The progress percentage in each SDG is the average progress of all indicators under that goal. In each panel, the three bars and the annotated gray text indicate progress towards 2030, 2050, and 2100 targets under Green Recovery. Targets in 2100 are more ambitious compared with 2050 targets and much more ambitious compared with those in 2030. The annotated red text is progress under Business As Usual to be used for comparison. The pie charts show the share of the four progress in 10,000 simulated pathway realizations of Green Recovery by 2030, 2050, and 2100.

status in socioeconomic and environmental SDGs (e.g., in SDGs 3, 4, 12, 13, and 15; Figure S4C).

The observed acceleration (or deceleration) of progress across pathways is driven by the non-linear systems behavior, leading to time lags and delay between pathway measures and their effects on SDG progress. To illustrate, under Green Recovery, population growth and fossil energy production peaked and then declined around 2050 (Figures 2A-I and 2D-I). Such non-linear behavior underpins the initially slow (by 2030) and later accelerated progress in several SDGs (by 2050 and 2100) that are related to demography and energy systems, such as SDG 7, where lower population and less fossil energy production can directly contribute to its progress.

The non-linear systems behavior characterized by delayed acceleration between pathways and their impacts is driven by a complex chain of system interactions that underlies the SDGs. An example is the initial (i.e., 2030) slow and later (i.e., 2100) accelerated progress in SDG 13 under Green Recovery (Figure 5). The reasons are mixed and manifold. Lower population growth (Figure 2A-I) combined with more sustainable lifestyles can attenuate the increase in energy demand (Figure S1D-I) and long-run impact on energy production, resulting in lower energy sector emissions. In a similar interaction, low population along with exponential growth in access to education over the century (Figure S1C-I) can gradually lead to more environmentally conscious consumption patterns and a higher uptake of healthier and more sustainable diets, as shown by Eker et al.[24] Over time, healthy plant-based diets and lower consumption of high animal-based foods (Figure S1L-I), as the key drivers of land-use and climate change,[34] can reduce the impact of agriculture on land (Figures S1M-I and S1N-I), decelerate or reverse forest loss (Figure 2F-I), and provide significant climate change mitigation (Figure S1O-I).

Systems change for long-term sustainability

The latest Global Sustainable Development Report suggested different entry points for long-term sustainability.[35] Achieving long-term progress acceleration through these entry points is complex and requires early planning for complementary systems change that cuts across multiple SDGs; changes that should be coherently pursued to transition[36] from currently established to emerging (and more sustainable) socioeconomic and environmental systems (Figure 6).[35] We characterizes systems change for long-term sustainability through the lens of four entry points: (1) human well-being and capabilities, (2) sustainable food systems and healthy nutrition, (3) energy transition and universal access, and (4) sustainable economy decoupled from environmental impacts (Experimental procedures). In each entry point, the scale of change across modeled systems is quantified based on the deviation from the continuation of current reference trajectories (i.e., Business As Usual) to the pathway of highest long-term progress (i.e., Green Recovery) at three timesteps of 2030, 2050, and 2100. With increasing attention to feasibility in modeling studies,[37] we also draw on recent studies to discuss some of the opportunities and challenges on the ground (e.g., new technologies, behavioral change, and grassroots support) and in the broader landscape (e.g., major socioeconomic change, power shift, and policy support) to deepen the understanding of what it would take to facilitate systems change and what could prevent an "idealized" implementation.[36]

Human well-being and capabilities

Improving education is an essential system change not only for advancing human material health and well-being but also for enhancing human capital in terms of knowledge, skills, and competencies to drive long-term sustainable development.[35] It was at the core of Green Recovery in our modeling as well, reflected

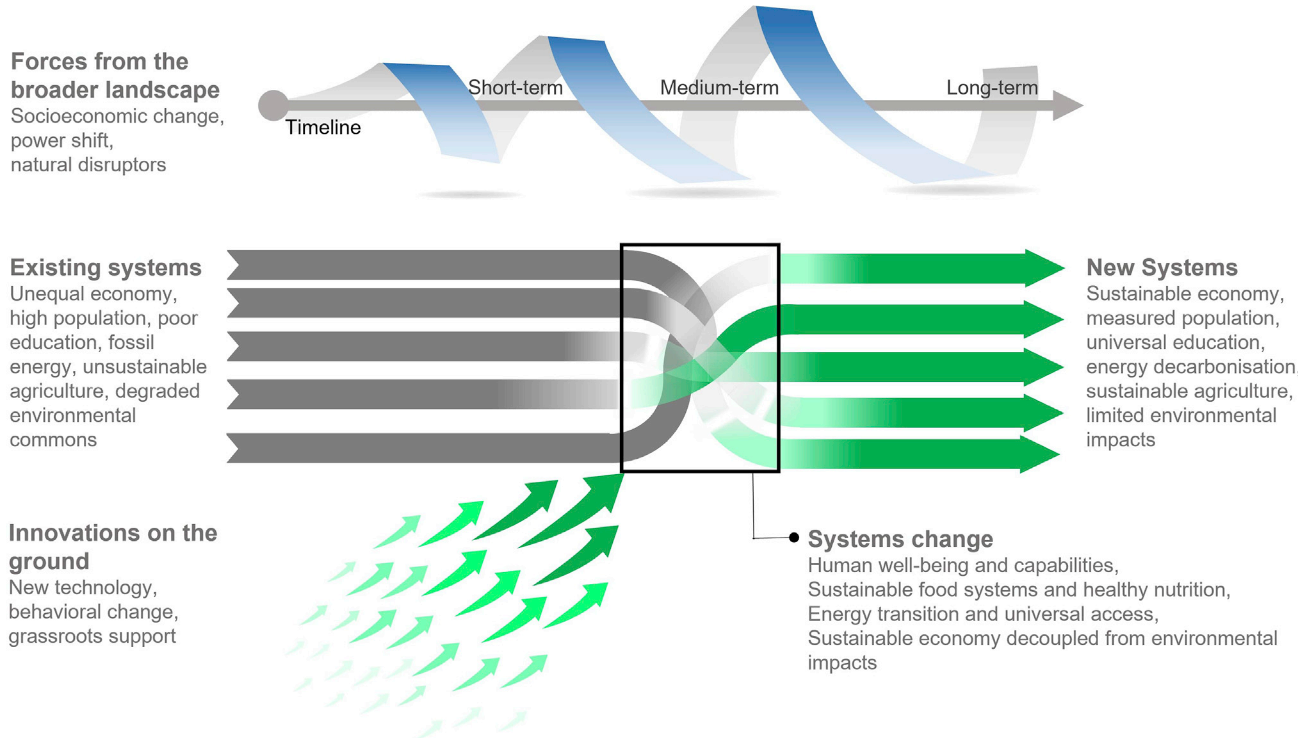

Figure 6. Conceptualization of long-term sustainability as transformation via complementary systems change

Systems change can be fostered or impeded by opportunities and challenges on the ground or in the broader landscape (adapted from Geels et al.[36]).

in improving access to quality education by 10% (one standard deviation range: 5%–14%) and 40% (23%–53%) compared with 2050 and 2100 Business As Usual trajectories (Figure 7).

Realizing system change in education cannot be easily achieved in all regions and requires significant technical and political support.[38] Among the support opportunities with proven effectiveness in different contexts are eliminating school fees for universal access to primary and secondary education, improving local access to schools and ending social and legal discrimination to ensure gender equality, and setting up systemic improvement through continuous learning evaluation and enhanced teacher training.[39] The long-term success of these measures rests on overcoming current challenges, such as establishing a stable education system that can allow gradual improvements and shifting mindsets around the role and benefits of inclusive education in less developed regions.[40]

Another important system change to contribute to human well-being and capabilities is related to demography and acting on rapid global population growth.[35] Under Green Recovery, this was represented by reducing population growth by 5% (3%–8%) and 26% (16%–35%) compared with 2050 and 2100 Business As Usual trajectories while improving life expectancy (Figure 7). Improved education with progress in social norms and adoption of bolder actions about family planning with positive impacts on fertility and mortality decline in developing regions are among opportunities for measured population growth.[41] Investment in effective healthcare and newborn health services are other rising opportunities for enhancing prosperity.[42] However, the success of such initiatives may be challenged by the geographic concentration of population growth in emerging economies with a growing middle class (estimated at ~5 billion by 2030) aspiring to lifestyles associated with increased consumption.[43] This highlights the important synergies between lower population growth rates and better redistribution of wealth and how policies addressing inequalities in income and gender could enhance long-term sustainability.[38]

Sustainable food systems and healthy nutrition

The business-as-usual trajectories and the continuation of current practices for the global food system cannot sustainably and equitably meet the needs of future populations, and the importance of a system change for sustainable food and healthy nutrition is undeniable.[44] One important aspect of this system change is related to land use and limiting agricultural land expansion (which also relates strongly to land as global environmental commons) through more efficient food production with higher yield and productivity. The scale of this change for Green Recovery was 7% (5%–10%) and 10% (7%–13%) reduction in cropland and pasture area, respectively, compared with 2050 and 2100 Business As Usual trajectories (Figure 8) while maintaining sufficient and higher-yield food production (Figures S8A-I and S8A-II). These types of changes can help limit deforestation and reverse biodiversity loss[16] (Figures S8H-II and S8H-III).

Diversified and emerging opportunities exist to control land use change from agricultural activities,[45] such as improvement in crop yields, more efficient use of inputs (e.g., water, nutrients, and pesticides) via automation and precision agriculture,[46] higher livestock productivity (e.g., through better feeding practices and supplements that reduce enteric fermentation),[47]

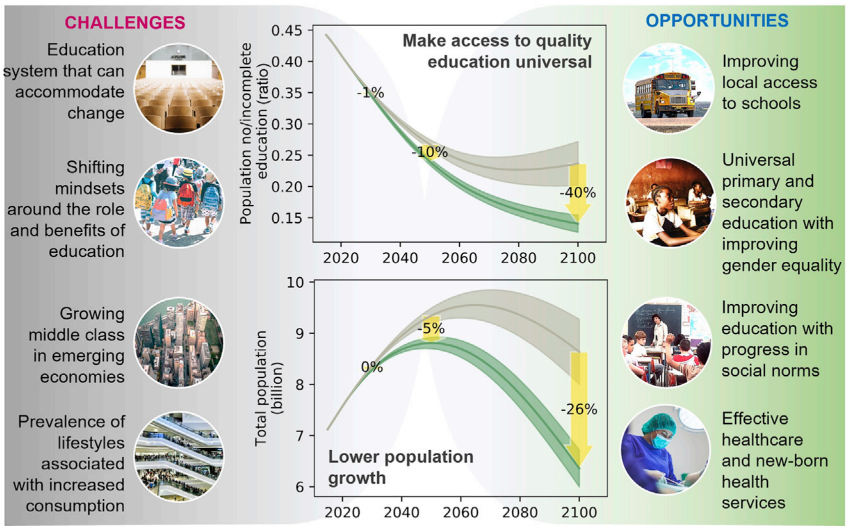

Figure 7. The underlying systems change in education and demography to shift from Business As Usual to Green Recovery

In the center plots, envelopes show one standard deviation bandwidth in the results. The middle line is the mean. Yellow arrows show the change percentage needed to deviate from the mean of the Business As Usual envelope to the mean of the Green Recovery envelope in 2030, 2050, and 2100. The mean estimate percentage of improvement (i.e., the distance between the mean value of the two envelopes) is annotated for 2030, 2050, and 2100. Challenges on the left illustrate two examples of potential barriers that can create lock-ins in Business As Usual and impede systems change. Opportunities on the right illustrate two examples of many potential actions that already exist, and their uptake can facilitate systems change.

reducing further demand for agricultural land expansion through controlling food waste via demand-side interventions (e.g., regulations and information/education campaigns),[48] and redesigning agricultural practices (e.g., intercropping and agroforestry).[49] These efforts to limit land use change can, however, face multiple challenges, such as institutional barriers for enabling smallholder farmers to access support and financial resources[50] and the concentration of land ownership in industrial farms, which could be more susceptible and less adaptive to external shocks.[35]

Another important aspect of a sustainable food system is consumption practices and collaborative action on food choices. In Green Recovery, this was translated into 39% (31%–46%) and 50% (43%–57%) reduction in land-based animal (i.e., ruminant meat and dairy) caloric intake in a healthy diet compared with 2050 and 2100 Business As Usual trajectories (Figure 8). More sustainable plant-based diets can improve the health and well-being of communities and also alleviate inequality by helping those affected by the distributional impacts on food supply chains.[51]

Technological innovations, economic incentives, and institutional changes are some of the emerging opportunities to promote healthy diets, among them investment in public health information, guided food choices through incentives, and educational guidelines to promote more nutritious foods.[44,52] Such opportunities, however, rely on significant and rapid behavioral change in the current eating habits of billions of consumers in diverse contexts.[53] This is extremely challenging, given the strong cultural and social norms around diets, such as strong associations between meat and aspects like wealth and masculinity.[54,55] Similarly, the success of many promising technological opportunities, such as novel alternative proteins (e.g., plant-based meats and milks or the prospect of cellular meat or microbial protein) fundamentally relies not only on development of palatable and affordable meat substitutes but also on creating public awareness and normalizing their consumption.[45] Demographic transition to a lower and more educated and prosperous population is among the key enabling factors for such a rapid shift in behavioral and social norms and changing people's attitudes around the potential impacts of their individual choices in the food system (e.g., fewer environmental impacts and lower health risk from less meat consumption).[24]

Energy transition and universal access

Energy transition is key to economic development and human and social well-being. It can also mitigate current alarming environmental trends, such as increasing emissions and rising temperatures.[17] In Green Recovery, this change was reflected by a decline of 36% (29%–42%) and 80% (75%–84%) in total fossil energy (i.e., coal, oil, and gas) production compared with 2050 and 2100 Business As Usual trajectories, respectively (Figure 9).

There are emerging opportunities that could pave the way for this system change.[56,57] Among them are efforts to increase the share of renewables through a global carbon price scheme with international burden sharing and strong progressive redistribution of revenues to avoid high mitigation costs and trade-offs with poverty,[53,58] financing innovation in renewable energy by private and public financial actors,[59] cheaper renewable energy technologies through subsidies, and a spatially optimized deployment of bioenergy with carbon capture and storage,[60] along with other measures for energy transition in buildings, transportation, and industry sectors.[57] Despite these opportunities, technology and policy and feasibility challenges persist, such as long-term storage of generated renewable electricity and smart grid network management, potential social and environmental trade-offs (e.g., the side effects of biomass and biofuel expansion on land use change), and disproportionate government support (e.g., subsidies) for fossil fuels compared with renewable energy.[35]

Changes in production systems need to be further supported by sustainable consumption practices to ensure reliable, cheap, and clean energy sources. This was reflected in Green Recovery through change in energy consumption patterns to 13% (3%–22%) and 32% (20%–43%) lower energy consumption compared with 2050 and 2100 Business As Usual trends, respectively (Figure 9). A number of key technological and consumption-related challenges need to be overcome to accelerate system change to the pace required. These include a huge stock of older buildings in need of retrofitting of heating and cooling

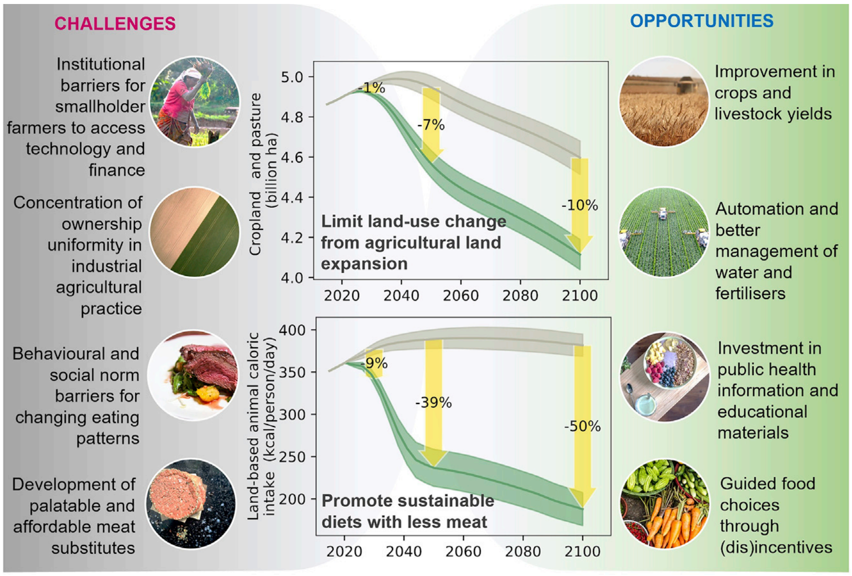

Figure 8. The underlying systems change in food production and consumption to shift from Business As Usual to Green Recovery

technologies based on renewables, both of which remain out of reach for most consumers in the absence of strong economic incentives.[61] Similarly, transforming energy-intensive, fossil fuel-dependent, and highly polluting industrial processes, increasingly manufactured in developing countries, is challenging too without strong economic incentives and international cooperation and coordination.[62] Key opportunities exist in consumer subsidies to improve dwelling characteristics and incentivize behavior toward larger household sizes with more densely constructed dwellings and energy-efficient appliances.[63] Opportunities also exist to realize low-energy consumption practices through innovations such as digital and artificial intelligence technologies for energy use and monitoring,[64] modern cities with energy-efficient public infrastructure, mobility systems, housing sectors, and smart grid management for long-distance power transmission and less energy loss.[56]

Sustainable economy decoupled from environmental impacts

A sustainable pathway needs its economic benefits to be decoupled from its environmental costs.[35,65] Advancing human well-being and capabilities, shifting to sustainable food systems and healthy nutrition, and energy transition with universal access together can organically lead to a system change in the broader economy toward sustainable growth with less environmental trade-offs. Under Green Recovery and in terms of economic development, this was represented by sustainable and decarbonized growth of at least 32% (7%–61%) and 52% (5%–118%) higher than Business As Usual by 2050 and 2100, respectively (Figure 10).

Boosting innovation and research can be a key contributor to economic growth. However, this growth can be deeply unequal and therefore unsustainable, resulting in further concentration of wealth and power and environmental exploitation because of overuse of natural resources in less developed regions resulting in a poverty-degradation spiral.[66] Sustainable economic growth needs to also encourage divestment in the current Business As Usual practices and promote innovations that can pave the way for long-term sustainability pathways (green growth) with improved human and environmental benefits.[67] A range of opportunities exists that can support such change, among them support of government science funding mechanisms to guide efforts effectively and with equal opportunities for all,[68] formation of innovation and entrepreneurship incubators to nurture and develop emerging ideas, and support of state investment banks[69] and public-private financing facilities for improved access to financial resources.[70] Among the challenges to realize these opportunities are the immaturity of policies, institutions, and sometimes technologies to promote economies with more efficient use of resources and also the engrained attitudes towards material- and status-related consumption associated with increased wealth.[71]

A sustainable economy with transitioning (food and energy) production and consumption systems can also minimize the environmental impacts, among them the degraded climate system from greenhouse gas emissions, which can have significant impacts on oceanic and terrestrial ecosystem health.[35] Under Green Recovery, the scale of climate change mitigation efforts, represented by the resulting atmospheric CO_2 concentration, was 6% (5%–7%) and 20% (18%–21%) lower compared with 2050 and 2100 Business As Usual trajectories, respectively (Figure 10). The climate system is deeply linked to previous systems change, and its emissions mitigation is the result of changes in demography, food, and energy systems. For example, carbon pricing, bioenergy with carbon capture and storage, reforestation, and reduced meat demand are among opportunities from other systems change that can also result in significant impacts and reverse the current climate trends. The emerging support for divestment in polluting industries, increasing green investments, and inclusion of climate change impacts in financial risk management are among important complimentary opportunities to support emissions reduction across all systems.[72] Beyond these, leveraging international governance and global partnerships through currently established frameworks (e.g., the Paris Agreement) and building on emerging public and political will to act on climate change are other opportunities to ensure implementation of systems change in a coordinated manner and effective management of efforts in conflicting contexts.[73]

Opportunities for highly ambitious emissions reduction can be, however, limited by challenges related to their technical feasibility and their significant trade-offs with other systems. For example, faster decarbonization (e.g., 1.5°C pathways[74]), which relies on very high deployment of negative emissions technologies, such as bioenergy with carbon capture and storage, raises concerns with respect to regional availability of geological storage, resource constraints (land or water), and/or securing the social license to

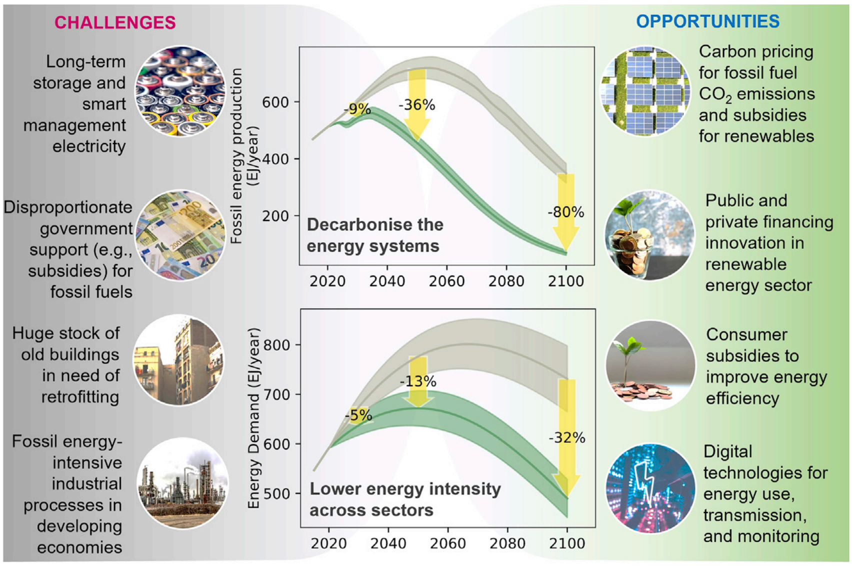

Figure 9. The underlying systems change in energy production and consumption to shift from Business As Usual to Green Recovery

support them.[53,75] Even given their feasibility in a context, some of the negative emissions technologies can compete with agricultural production and put food security and biodiversity at risk.[76] Ambitious emissions reduction opportunities therefore need to be further assessed for their policy costs, feasibility, and trade-offs with other non-environmental SDGs before implementation.[37,77]

DISCUSSION AND CONCLUSIONS

Longer-term assessment in SDG target space

The currently slow progress towards the SDGs poses challenges to the stability of human-natural systems.[78] Calls have been made to revise the SDGs and for new assessments to guide how to lead sustainable development for economic, social, and environmental prosperity.[79] In response, our study aimed to rethink options for the SDGs by adopting a new lens with a century-long timeframe. The longer timeframe (i.e., 2100) allowed simulation of effects of feedback interactions with delayed (post-2030) progress acceleration, which has not been previously discussed in the SDG context. This longer-term analysis is important because it can determine to what extent conditions that appear to make a limited contribution to initial progress by the 2030 milestone could become important later in the century. This long-term perspective can also help plan for the SDGs in an order of priority aligned with future possible trajectories of socioeconomic and environmental development, to better understand potential challenges and opportunities ahead well beyond the 2030 milestone, and to strongly maintain the progress against these challenges in time of diminishing faith and despair.

Any research focusing on a quantitative analysis of longer-term pathways also requires transparent and well-defined formulation of indicators and their desired targets to reveal the gaps and guide actions to fill the gaps.[8] Drawing on recent scientific data and consistent with the 2030 Agenda, our study was novel and complemented recent similar efforts[7,8] in systematically defining a balanced suite of socioeconomic and environmental indicators and setting explicit quantitative targets with increasing ambition levels throughout the 21st century. We used the targets for evaluating SDG progress over time. We also went beyond that by specifying the critical systems change important for accelerating long-term sustainability. This provided insights into what it would take to shift from Business As Usual to more sustainable pathways over the coming century and what challenges and opportunities could be faced ahead.

This longer-term analysis in SDG target space was, however, limited in some respects and therefore requires future development. First, the longer-term analysis (i.e., to 2100) is challenged by future deep uncertainties in all SDGs, in particular those with potential bigger changes in the future (e.g., related to peace, institution, and implementation). However, our aim was not to predict SDG-specific pathways to the 2100 world with any certainty. Rather, we wanted to constructively use and learn from previous pathway and scenario development, create illustrative pathways for the long-term future, and explore "what if" outcomes of these different pathways for the SDGs. To further advance the treatment of deep uncertainty, future research can use novel scenario discovery techniques[80,81] to obtain more robust insights into future pathways and their long-term impacts on the SDGs. Future research can also examine more systematically the delayed emergence of ambitious pathways to better understand different outcomes for sustainability progress in the medium and long term (e.g., food systems remain Business As Usual over the next few decades, but a major change occurs around mid-century).

Second, our study was also limited by the scope of our model. Although FeliX's global systems were diverse enough to cover most of the key areas of sustainable development[8] pertaining to 36 indicators, they did not cover all systems (e.g., transport, finance, and healthcare), did not span the entire list of 17 SDGs (e.g., those related to well-governed and peaceful societies, which are hard to quantify), or systems change in all possible entry points[35] (e.g., urban and peri-urban development and environmental aspects related to air, soil, and water pollution, which are not included in the FeliX model). Future research can extend the model scope to explicitly represent the missing sectors, better test the implications of sector-specific measures (e.g., subsidies and other incentives to accelerate energy transition), and explore their direct contribution to SDG progress.

System dynamics modeling for integrated assessment

We used the FeliX system dynamics model to analysis SDG interactions. System dynamics as an established methodology[19] has been used for modeling feedback interactions, delayed response, and non-linear behavior in a climate and sustainability context[23,24,82] and the SDGs in particular.[12,14,83,84] One useful feature of system dynamics models (including FeliX) for

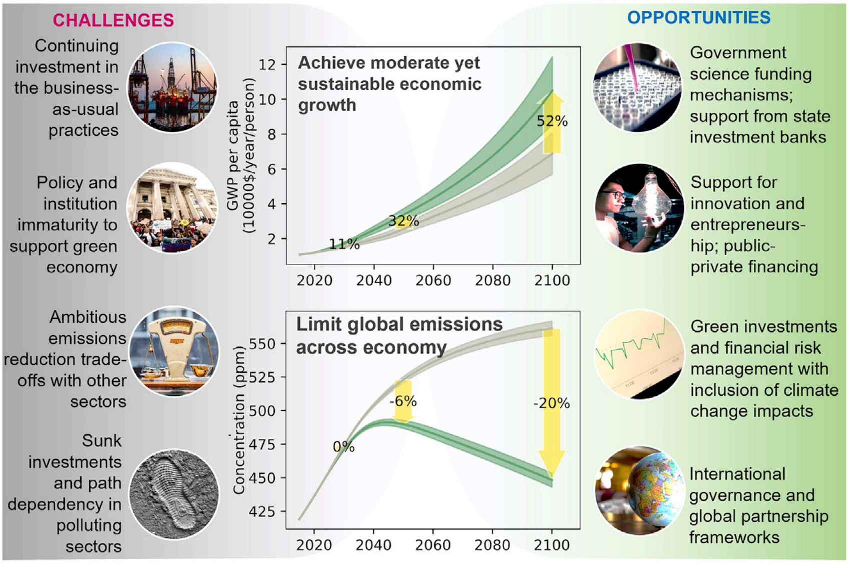

Figure 10. The underlying systems change in the broader economy and its environmental impacts on emissions reduction in shifting from Business As Usual to Green Recovery

sustainability studies is the development of relatively simple and transparent global models where relationships between observed outcomes and modeling assumptions are relatively easy to understand. This is important for SDG analysis in the light of one recent study[85] suggesting that policy-makers are less concerned about accuracy or precision and instead prioritize simplicity and ease of understanding in social and policy processes. Although this relative simplicity could limit predictive power, the link between model accuracy and sophistication remains tenuous.[86,87] Validation of our modeling against past trends[22] and against outputs from more sophisticated models (Figures 2 and S1) also showed a high degree of agreement.

Another strength of system dynamics models such as FeliX is the endogenous modeling of feedback interactions between social, economic, and environmental systems in one integrated framework (Figure 1; Experimental procedures). These models are ideally suited for capturing non-linearities in short- and long-term pathways, as highlighted in this study. The modeling of feedback interactions can help enhance the understanding of SDG inter-connections and complexities (e.g., non-linearity, tipping points, and delays).[12] Understanding complex interactions can lead to insights around SDG synergies and trade-offs by identifying underlying mechanisms of barriers or policy resistance and designing synergistic solutions that can translate to a more successful outcome for sustainable development.[88] Aggregate and descriptive system dynamics models can be used to complement the insights from other integrated assessment models (e.g., Earth systems and partial or general equilibrium) that focus more on a detailed view of biophysical and socioeconomic systems than feedback between systems.[89,90]

Although FeliX represents several key system elements and their feedback, it does not capture all important interactions. Future research can contribute to this by identifying and incorporating other feedback interactions currently not represented in existing integrated assessment models, including in FeliX. Examples can include modeling climate feedback interactions with other systems that are important in the context of sustainability, such as agriculture (e.g., CO_2 fertilization effects on natural vegetation and crop growth), land use (e.g., prolonged precipitation effects on land management decisions), energy (e.g., rising temperature effects on energy demand), and human behavior (perceived climate extreme event risks alter human emissions).[89,90]

Co-designing pathways for local contexts

Our modeling was focused at the global level. Global-scale studies[12,23,24] are important for their role in capturing interactions between systems, monitoring their aggregate outcomes, and guiding harmonized high-level interventions to ensure universal progress toward the 2030 Agenda and beyond.[91] Several of the environmental challenges addressed are common worldwide (e.g., temperature increase and biogeochemical flows), and management relies on an understanding of their aggregate effects and the globally connected systems that underpin them. Despite this global connection, different locations face unique, place-specific issues and have their own needs and sustainability priorities, creating strong geospatial ties for many of the SDGs.[92] For example, although unsustainable diets are a common challenge with an impact on global emissions shared by all, their effects on food demand, food production, and land use change vary between locations and depend on the unique socioeconomic and environmental characteristics of each region, including social norms, education level, resources, and dominant food systems of each community.[53] This necessitates future research to translate and downscale the global understanding of pathways and the SDGs at the local level to better acknowledge indigenous values, cultural differences, available resources and technologies, and local political and governance frameworks and also better understand the distributional effects and variations of progress across scales.[15]

However, there are often significant limits in modeling and translating the implications at the local scale, driven by the challenges of understanding heterogeneities on the ground[93] and resolving fundamental disagreements among stakeholders.[91] Previous studies have suggested frameworks for addressing these challenges through transdisciplinary approaches that can go beyond working with researchers and facilitate public community engagement in pathway development processes.[94,95] Although still a niche field, the growing application[96,97] of a variety of transdisciplinary approaches, such as knowledge co-production (including local, practical, and indigenous knowledge) and participatory processes with stakeholders (i.e., co-designing pathways, local priorities,[10] and plans[98]) have provided opportunities to advance the local-scale understanding of the SDGs.

Pathway development for bolder sustainability actions

Despite originally having been developed for climate projections,[26] the SSP-RCP compliant pathways and their variations have been widely used as benchmarks in broader sustainability science[5,7,14] and its related areas (e.g., water,[99] agriculture,[100] and biodiversity[101]). Their adaption in the current study was partly motivated by their extensive coverage of global-scale socioeconomic and environmental assumptions needed for an SDG analysis. SSP-RCP-compliant pathways also provided a basis for generating alternative plausible futures with fundamentally different sustainability outcomes, suitable for this study, where the emphasis was to demonstrate the range of alternative futures (spanning high to low progress) to the end of the century.

However, the five selected pathways in the current study were only used as illustrative archetypes to highlight specific variation across most commonly used combinations of SSP-RCP pathways[26] and were not intended to cover all future possibilities. For example, we did not include pathways of higher climate change mitigation[17] because of the trade-offs with other SDGs. Pathways from the SSP-RCP frameworks also do not include explicit driving forces related to some of the SDGs, such as gender inequality or partnerships that may impact projections because of missed synergies and trade-offs with other goals in FeliX. These issues would benefit from future research that goes beyond the current ambitions in SSP-RCP frameworks in building SDG-specific pathways for bolder actions not only for the 2030 Agenda[7] but also for longer-term timeframes (i.e., 2100) that can show acceleration toward sustainability later in the century.[53]

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

Further information and requests for resources and reagents should be directed to and will be fulfilled by E.A.M. (e.moallemi@deakin.edu.au)

Materials availability

All new materials generated are provided via links under "Data and code availability."

Data and code availability

The full code, results, and datasets used and generated are available at Zenodo: https://doi.org/10.5281/zenodo.6459874. Tables S2 and S4 in the supplemental information can be accessed at Zenodo: https://doi.org/10.5281/zenodo.6609917. FeliX, the simulation model used in this study, is available at Zenodo: https://doi.org/10.5281/zenodo.6459874 and from the IAMC website: https://www.iamconsortium.org/resources/model-resources/felix/.

The FeliX system dynamics model

FeliX is a system dynamics model that simulates complex interactions among 10 global systems: population, education, economy, energy, water, land, food (including diet change), carbon cycle, climate, and biodiversity. FeliX was originally developed for projecting socio-environmental impacts in human-natural systems[25] and was later advanced for exploring emissions pathways[23,102] and evaluating sustainable diet shift.[24] FeliX is one of the very few models of human-natural systems that covers the breadth of social, economic, and environmental aspects (and their feedback interactions) in one integrated framework suitable for SDG analysis. The model operates at an annual timescale and is designed to project global-scale future socioeconomic development and environmental conditions over the long term to 2100. It is implemented in the Vensim software and has been calibrated with historical data from 1900–2015 (see Rydzak et al.[22] for calibration results and graphs).

A key validation method in system dynamics and other modeling methodologies that project future pathways is based on comparing them with historical data (to show whether this model is at least reliable for reproducing the past) and with the future projection of other models, if available (to show the new model produces sensible results, also called cross-validation). FeliX has been validated in both ways. For validation with historical data, refer to the extended technical report for FeliX,[22] which includes detailed validation of each of FeliX's sub-models against historical data. For validation against other models, see Global systems modeling and Figures 2 and S1.

The use of system dynamics as a methodology has a long history. One of the first and most enduring applications of system dynamics was in The Limits to Growth's modeling of the environmental and social impacts of global industrialization in 1972,[103] pointing out that ecological and economic stability would not be out of reach if actions were taken early.[104] Since then, system dynamics has been used widely as an established methodology in sustainability science (for a review, see Moallemi et al.[83] and Allen et al.[105]). System dynamics models can be (and are often) developed based on a co-design process that enables interaction between researchers and stakeholders and supports synthesis of disciplinary and transdisciplinary knowledge.[106] This and other features mentioned in the main text were also highlighted in the review by Allen et al.[105] of modeling tools for the SDGs, suggesting that system dynamics models can be more transparent and legitimate compared with other modeling approaches.

Despite the methodological advantage, FeliX misses some sectors and requires future improvements. For instance, the primary energy demand in transport (∼15% of global GHG emissions in 2019[53]) is expected to increase by 25% by 2050 in a Business As Usual (BAU) scenario,[107] contributing to an increase of around 25% in global primary energy demand,[108] but an explicit modeling of the transport sector is missing in FeliX. Although our uncertainty exploration of energy demand projections (17%–33% increase in global primary energy demand by 2050 and compared with 2020 in Business As Usual; Figure 5) could cover the implications of transport system indirectly, a future improvement to model the transport sector (along with other missing sectors, such as governance) endogenously would be needed for better projections.

A summary of the sectoral modules in FeliX is available in Figure 1, and a detailed description is provided below. Important interactions among the eight SDGs modeled in FeliX are available in Table S5. Readers are also referred to the original FeliX documentation[22] and previous papers that have used FeliX[23,24] for an extended description and validation of the model with respect to historical data and cross-comparison with other scenarios. The model and its supporting data are publicly available online (Data and code availability). The equations underlying each SDG indicator in the model are available in the supplemental information. Information about the methodology for computing indicator values in the model is available in the supplemental experimental procedures.

Population and education

The population module describes population growth based on an aging chain and computes the male and female population size of 5-year age cohorts between the ages of 0 and 100+. The birth rate, driven by education and gross domestic product (GDP) per capita, is the main factor affecting population dynamics (either growth or decline), alongside the reproductive female population represented by gender and age-cohort segmentation in the model. The chain structure in the model represents the transition of newborns through the age cohorts as they age, meaning that each age cohort except the "0–5" cohort has one inflow (maturation of the previous cohort) and two outflows (maturation to the next cohort and mortality rate). In the population sector, gender differences are taken into account in two respects: the gender fraction of newborns, representing female infanticide, and educational enrollment and graduation differences. The population module also computes change in life expectancy with impacts for health services, food, and climate risk. Population is the core module in FeliX impacting, directly or indirectly, all other sectors, such as energy demand, water use, effects on fertilizer use, and food consumption. The population size at different age cohorts feeds into the education module to compute the population of primary, secondary, and tertiary education graduates through the feedback loops among the enrollment rate, graduation rate, and persistence to eventually reach the last grade of each education level. The accumulation of the educated population in all age cohorts between 15 and 64, multiplied by a labor force participation fraction, computes the labor force input for the economy module. Population and education are calibrated with the historical demographic data from the United Nations (UN) Department of Economic and Social Affairs.[109]

Economy

The economy module is modeled as a Cobb-Douglas production function, where total Gross World Product (GWP) is computed from labor input, total capital input from the energy and non-energy sectors, and total factor productivity from energy and non-energy technologies. FeliX further develops the Cobb-Douglas function to incorporate the impacts of changes in ecosystems and climate change on the economic outputs. Given that human development should include measures beyond economic advances, FeliX also computes an alternative measure, called human development index, which is an indicator of health (life expectancy), educational attainment, and income. The economy module is calibrated with historical statistics of world economy[110] and United Nations Development Programme (UNDP) data.[111]

Energy

The energy module models energy demand as a function of GDP per capita and population. Energy consumption is modeled through the market share of different energy sources by capturing the price-competitive mechanisms between three fossil (coal, oil, and gas) and three renewable (solar, wind, and biomass) sources. Energy production from each fossil source is modeled as a function of energy demand, the market share of energy source, the effect of investment on energy production, and the identified fossil energy resource. FeliX models the technological advancement in discovery of fossil resources and investment in exploration to account for undiscovered resources that can be identified in the future. FeliX also models the technological improvement for recovery of fossil resources. The basic model structure for renewable energy sources is similar to fossil fuels, determined by five key submodules of available renewable resources (e.g., average sun radiation and wind available area), the supply chain of installed capacity and their aging process, the unit cost of production (e.g., the impact of wind and solar technology learning curve), available investment, and technological efficiency and productivity (e.g., solar conversion efficiency and wind capacity factor). The energy module is calibrated with data from the International Energy Agency (IEA).[112]

Water

FeliX models the water sector through water scarcity; that is, the balance between water supply and withdrawal. Water supply is a function of available water resources, a drought rate for the impact of climate change, water withdrawal from different sectors, and the recovery of water used in those sectors. Water withdrawal is for agriculture, industrial, and domestic sectors. Agricultural water withdrawal depends on irrigated and rainfed agricultural lands, industrial water withdrawal depends on GWP (economic activities), and domestic water withdrawal depends on population and GWP. See The water module is calibrated with historical data from Intergovernmental Hydrological Programme (IHP), The United Nations Educational, Scientific and Cultural Organization (UNESCO).[113]

Land

The land sector in FeliX is distributed among four categories of land use: agricultural, forest, urban/industrial, and "other." Land use can be repurposed and switch between types depending on demand for more agricultural land. Demand for agricultural land is balanced by increasing crop yields via fertilization. Agricultural land is divided into arable land, permanent crops, and permanent meadows and pastures. Arable land and permanent crops can be harvested to produce food and feed as well as energy crops for biomass. Permanent meadows and pastures can only be used for feed production. The area of arable lands harvested is driven directly by food, feed, and energy crop production and indirectly through food demand and biomass energy demand. Crop and livestock yields are modeled as a function of input-neutral technological advancement, land management practices (impact of economy), water availability (impact of drought), nitrogen and phosphorus fertilizer use, and climate change (impact of carbon concentration). Nitrogen and phosphorus fertilizer use in agriculture, from commercial sources or produced with manure by pasture- and crop-based animals, is explicitly modeled in FeliX. However, potash fertilizer is not included because it constitutes the smallest fraction of global fertilizer use (~20%), and its environmental impacts are much lower compared with nitrogen and phosphorus because of high efficiency of uptake and low leakage rates.[114] Change in forest land cover is modeled through conversion with other land uses as well as harvested forest areas needed for biomass energy production. Forest land fertility is modeled endogenously as a function of the effect of biodiversity, land management practices, climate change, and CO_2 concentration. The land module in FeliX is calibrated with global scale historical data from Food and Agriculture Organization Statistics (FAOSTAT).[115]

Food and diet change

The food module in FeliX includes food demand and supply (including waste fraction) as well as diet shift in food consumption of the population. Food demand is a function of food and feed fraction in demand, each of which is determined based on the size of the population with animal-based and vegetable-based food diets. Food supply is the sum of the supply of animal-based products, including crop-based meat (poultry and pork), pasture-based meat (beef, sheep, and goat), dairy, eggs, and the supply of plant-based products, including grains, pulses, oil crops, vegetables, roots, and fruits. Food production (related to food supply) depends on the area of harvested lands (from agricultural lands) and the crop and livestock yields (already discussed in the land module). The food consumption (related to food demand) is determined by linking to a model that relates human behavior and dietary choices to different population segments (e.g., male and female, level of education). The diet change model[24] explains various environmental actions to move toward more sustainable (less meat) diets based on two feedback mechanisms: diet change because of social norms and diet change because of a threat and coping appraisal. The latter is linked to threats from climate events as an important feedback structure between physical and human systems. The food and diet change module is calibrated with historical data from FAOSTAT and Global Burden of Disease datasets.

Carbon cycle

FeliX models CO_2 emissions endogenously based on the accumulation of carbon emissions from the energy and land sectors in the atmosphere. CO_2 emissions from land include emissions from agricultural activities (i.e., food production and land use change to agricultural lands) as well as deforestation and forest conversion to managed forests and plantations. CO_2 emissions from the energy sector are computed explicitly based on the carbon intensity of energy production from fossil and renewable sources. Emissions from the energy sector also capture endogenously the effect of improvement in carbon capture and storage technology and a desired emissions level from fossil fuels. Carbon is cycled through terrestrial reservoirs, gradually absorbing into the biosphere, pedosphere, or oceans based on C-ROADS,[116] a climate model also used for climate impact analysis by The United Nations Framework Convention on Climate Change (UNFCCC). Carbon dissolution into the ocean is through the mixed ocean layer (depth, 0–100 m) and subsequently through four modeled deeper layers (100–400, 400–700, 700–2,000, and 2,000–2,800 m). See Walsh et al.[23] for modeled equations of carbon flux among different reservoirs. The carbon cycle module is calibrated with historical emissions data from the Carbon Dioxide Information Analysis Center.[117]

Climate

The climate module models CO_2 radiative forcing endogenously based on accumulated carbon (from land and energy) in the atmosphere compared with the pre-industrial level. Radiative forcing of other gases (CH_4, N_2O, and HFC) is modeled by linking FeliX to RCP scenarios and reading data from the projected forcing levels with the marker models of the SSPs (i.e., IMAGE, GCAM, AIM, and MESSAGE). The effect of total radiative forcing is associated with temperature anomalies as in the C-ROADS model. The surface temperature change is also affected by negative (cooling) feedback because of outbound longwave radiation as well as heat transfer from the atmosphere and mixed ocean layer to the four deep ocean layers.

Biodiversity

FeliX captures the effect of changes in land cover, land use, and climate impact on the species carrying capacity (global average). The biodiversity module uses this carrying capacity to compute the mean species abundance from the species regeneration and extinction rates. The biodiversity module was calibrated with historical data from the Secretariat of the Convention for Biological Diversity database.[118]

Pathway simulation

A complementary set of socioeconomic and environmental assumptions was identified from the current pathway projection literature to be used as FeliX inputs for future pathway projections. These assumptions were informed by the SSPs and the RCPs as widely used scientific frameworks for capturing a range of long-term uncertainties with a manageable number of alternative futures.[26] These frameworks have been also been used frequently in several previous sustainability assessments.[7,14,100,101]

Among various SSP-RCP combinations, we selected five benchmark pathways of SSP1-RCP2.6, SSP2-RCP4.5, SSP3-RCP7.0, SSP4-RCP6.0, and SSP5-RCP8.5 for projection with the FeliX model. The pathway assumption space included the global trends of different socioeconomic and environmental driving forces to 2100. They spanned socioeconomic (fertility, mortality, migration, educational attainment, and economic growth), energy and climate (energy demand, technology advances, fossil resource extraction, and production cost), land (land use change, crop and livestock yields, and land productivity), food and diet (waste, consumption, and diet change), emissions trajectories (1.9, 2.6, to 4.5, to 6.0, and to 8.5 W m^{-2} of global radiative forcing to 2100), and their associated climate policies (Table S1). The defined pathway assumption space was translated into relevant quantitative values for the FeliX's parameter settings (Table S2) using Vensim's built-in function (i.e., Powell) which is often used for quantifying system dynamics model parameters.

FeliX has many parameters, and therefore an evaluation of the impacts of uncertainty in parametric assumptions is necessary. To evaluate the effects of uncertainty, a global sensitivity analysis was performed to identify influential parameters whose uncertainty could have important impacts on pathway projections. Among the global sensitivity analysis methods, Morris elementary effects is ideal for integrated assessment models that have a large number of input parameters and require generation of reliable results with high computational efficiency[119] (Figure S7A). When the influential parameters were identified, to understand the full scale of variation in pathway performance in response to these uncertainties, a series of model runs was conducted using Latin hypercube sampling. Each run is a computational experiment, showing a realization of each pathway. We simulated 10,000 runs (realizations) of each pathway (50,000 total across all pathways).

The resulting projections and their uncertainty range were compared across socioeconomic and environmental output variables with the projections of other models, including IMAGE, MESSAGE-GLOBIOM, AIM, GCAM, and REMIND-MAGPIE[29] to assess the level of (dis)agreement with other models in pathway projections (Figures 2 and S1).

SDG progress measurement

The SDG framework includes 17 goals and 231 indicators to measure progress towards 169 targets, but they are too broad and complex to support quantitative assessment.[8] Therefore, we operationalized the SDGs in FeliX by selecting a subset of indicators, setting science-based targets for the selected indicators, and measuring progress toward targets as below.

Indicator selection

A list of 36 SDG-related indicators was selected from the United Nations Statistical Commission (UNSC) and other sources (e.g., Organisation for Economic Cooperation and Development [OECD], World Health Organization [WHO], United Nations Food and Agriculture Organization [FAO], and World Bank) based on three criteria (Figure 3). First, we looked at the global relevance of the potential indicators for measuring SDG progress (SDG applicability). Second, we assessed the ability of FeliX to quantify the SDG indicator (model fidelity). For indicators that were not present in FeliX, we either advanced the model structurally or chose proxies (i.e., a variable that is closest to the SDG indicator). For example, we did not include an official indicator for biodiversity conservation, such as the red list index, because the required data are not produced in FeliX. Instead, we presented mean species abundance as a proxy indicator for biodiversity.[16] Third, we ensured that the selected indicators are amenable to specification of quantitative performance thresholds for measuring progress toward the SDGs (target relevancy). All indicators that passed these three criteria were included in the analysis.

Target setting

Successful evaluation of progress toward the SDGs required a science-driven characterization of targets as quantitative thresholds on each indicator. We defined targets for each indicator using a four-step decision tree (Figure 3). First, we used available quantitative thresholds that were explicitly reflected in the official SDG framework to set targets (SDG absolute threshold; 3 indicators). For example, SDG 8 indicates "at least 7 per cent GDP growth," which can translate into a specific target for the growth rate of the "GDP per capita" indicator.

Second, if an explicit target was not mentioned in the SDG framework, then we used a technical optimum to set targets (technical optimum; 27 indicators). We used targets, wherever relevant, that were identified in other scientific journal articles, global reports,[33,120] and online databases.[121] For example, we used the IPCC's levels of radiative forcing for keeping the global temperature below 1.5°C as target levels for the "radiative forcing" indicator.

Third, wherever the SDG absolute threshold and technical optimum were not applicable, we followed the 2030 Agenda's principle of "leave no one behind" and set the targets based on the average state of the top performing countries in a base year using historical documented data (leave no one behind; 5 indicators). Here the global average as calculated by FeliX is expected to reach the levels of current top performing countries. In selecting the top performing countries, we removed the outliers from the list to reduce bias in our calculation. For example, a small country with limited arable land typically has very low levels of fertilizer application. Therefore, inclusion of this country as a top performer in calculating the target for the "food and agriculture phosphorous balance" indicator can be misleading for larger countries with a larger contribution to global food production. Where performance data were not available at the country level, we used regional data (e.g., OECD and continents).

Fourth, in the absence of any relevant targets, we nominally set a sensible improvement target in the indicator value from the world average in a base year guided by historical data (sensible improvement; 1 indicator). For example, "total CO_2 emissions from agriculture" is an indicator with no absolute threshold mentioned in the original SDGs or technical optimum in other studies. The value of this indicator is also sensitive to the size of a country's agricultural sector. Therefore, leaving no one behind and the average of the top performers did not lead to a meaningful target. In this case, we used a level of global improvement as a target for the indicator.

For each indicator, three target levels were set for selected indicators (weak, moderate, and ambitious) to acknowledge different levels of ambition in target setting and the high sensitivity of pathway performance to target specification. At each level, targets were set for 2030, 2050, and 2100 in alignment with the major global sustainability milestones. All results in the main text are based the moderate targets. The results for ambitious and weak targets are available in the supplemental information. The target values and their justification are available in Tables S3 and S4.

Progress quantification

To measure progress toward targets at each indicator, we normalized indicator values, each of which had different scales and units of measurement, to ensure comparability and consistent interpretation. For each target, we normalized indicator values to represent performance against target achievement, ranging between the 0% (no progress or divergence away from targets) and 100% (meeting or exceeding targets). The higher values denote a better performance, and the gap from 100 indicates the distance that needs to be taken to achieve the target. The scores below 0 and above 100 were interpreted as where the world is deteriorating from the status quo and exceeding target levels, respectively. The indicator values were normalized based on the rescaling formula in Equation 1,

$$Iij(x_i,\ w_i, t_i)\ =\ \frac{x_i\ -\ w_i}{t_i\ -\ w_i} \times 100 \qquad \text{(Equation 1)}$$

where $I_{i\,j}$ is the computed normalized value of indicator i under goal j, x_i is the model estimate of indicator i in a single projection, w_i is the base year (FeliX) value in 2015, and t_i is the indicator target level for a certain year. We then aggregated the normalized indicator values into an index score to represent global progress toward each SDG (Equation 2),

$$I'_j(N_j, I_{ij})\ =\ \sum_{i=1}^{N_j} \frac{I_{ij}}{N_j} \qquad \text{(Equation 2)}$$

where I'_J is the SDG and N_j is the number of modeled indicators under goal j. The index and its methodology were adopted from a similar index used in global monitoring of the SDG progress.[33] We used the arithmetic mean with a normative assumption of equal weight across each goal's indicators to align with the global efforts to treat all indicators equally and only prioritise indicators when progress is lagging. This also assumes that there is unlikely to be a consensus on SDG indicator priorities. Based on the normalized values at the indicator level and aggregated indices at the goal level, we measured world progress toward targets at four levels. "On track" indicates progress highly likely to achieve (or exceed) global sustainability targets (i.e., indicator and goal level target achievement $\geq$ 100%). "Improving" indicates positive trends toward the goal and indicator level targets but meeting them is unlikely, so challenges remain (i.e., target achievement between 50% and 100%). "Stagnating" indicates performance following current trends, little chance of target achievement, and significant challenges remain (i.e., target achievement between 0% and 50%). "Deteriorating" indicates a reversing trend (i.e., target achievement $\leq$ 0%).

Systems change characterization

We characterized the nature and scale of systems change required to ensure that the pre-conditions are in place for long-term SDG progress and discussed their challenges and opportunities ahead. We specified systems change in relation to four of the entry points that were within our model scope, originally discussed in the Global Sustainable Development Report:[35] (1) human well-being and capabilities, (2) sustainable food systems and healthy nutrition, (3) energy transition and universal access, and (4) sustainable economy decoupled from environmental impacts. To characterize systems change in each entry point, we first selected one variable from our model outputs that could best represent each system and its associated entry point. They included total population (billion) and population with no/incomplete education (ratio) for the first entry point, cropland and pasture area (billion ha) and land-based animal caloric intake (kcal person^{-1} day^{-1}) for the second entry point, energy demand (EJ year^{-1}) and fossil energy production (EJ year^{-1}) for the third entry point, and GWP per capita ($10,000 person^{-1} year^{-1}) and atmospheric CO_2 emissions (ppm) for the fourth entry point.

Second, we measured the scale of change in each selected output variable based on the distance between a reference pathway and Green Recovery in 2030, 2050, and 2100. Given future uncertainties, we measured a range including the mean and one standard deviation of this distance between the two pathways. It is worth noting that, across all output variables (i.e., systems change), depending on what the reference pathway is, the scale of change required to shift to Green Recovery can vary. The quantified scale of change here is based on deviation from the Business As Usual pathway (SSP2-4.5), whereas assuming other pathways as a reference (e.g., SSP3 and SSP5) can lead to much larger deviation.

To identify the drivers of systems change, we first identified high-impact model parameters that can drive change in population, education, economy, land, food, energy, and climate systems based on FeliX's sensitivity analysis results (as discussed for pathway projection and shown in Figure S7A). The goal was to find the combinations of high-impact parameters that can be most predictive of systems change. Those high-impact combinations (Figures S7A) were categorized according to influence in relation to the systems change under each entry point (Figure S7B). For each system change and in relation to its drivers, we discussed some of the challenges and opportunities qualitatively based on what has been identified previously in other studies. The goal was to enable a deeper understanding of the feasibility of our modeling.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.oneear.2022.06.003.

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AUTHOR CONTRIBUTIONS

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DECLARATION OF INTERESTS

The authors declare no competing interests.

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One Earth, Volume *5*

Supplemental information

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

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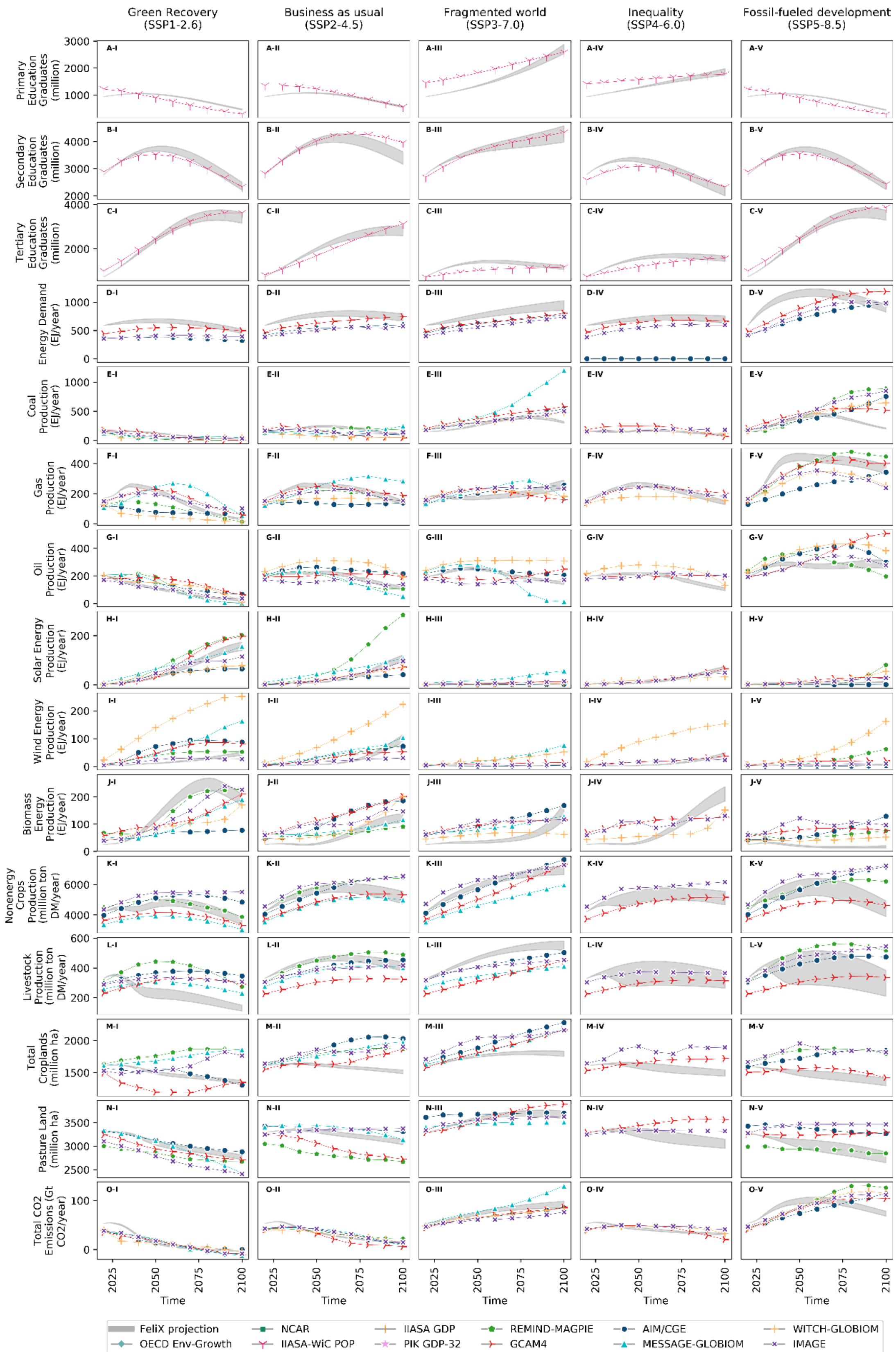


Fig. S1. Pathway simulation results against a suite of socioeconomic and environmental model outputs and comparison against similar simulation outputs of major models[1].

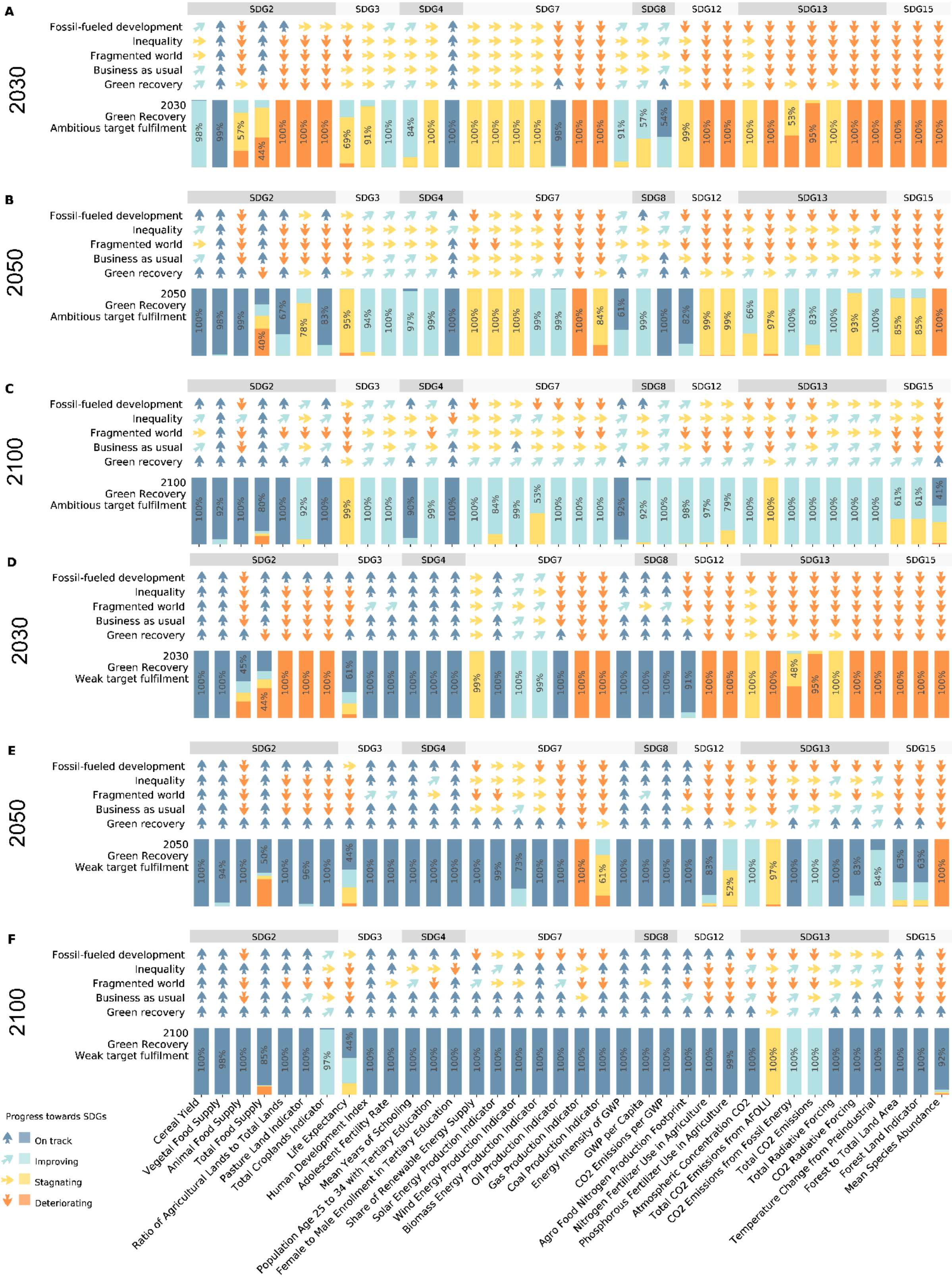
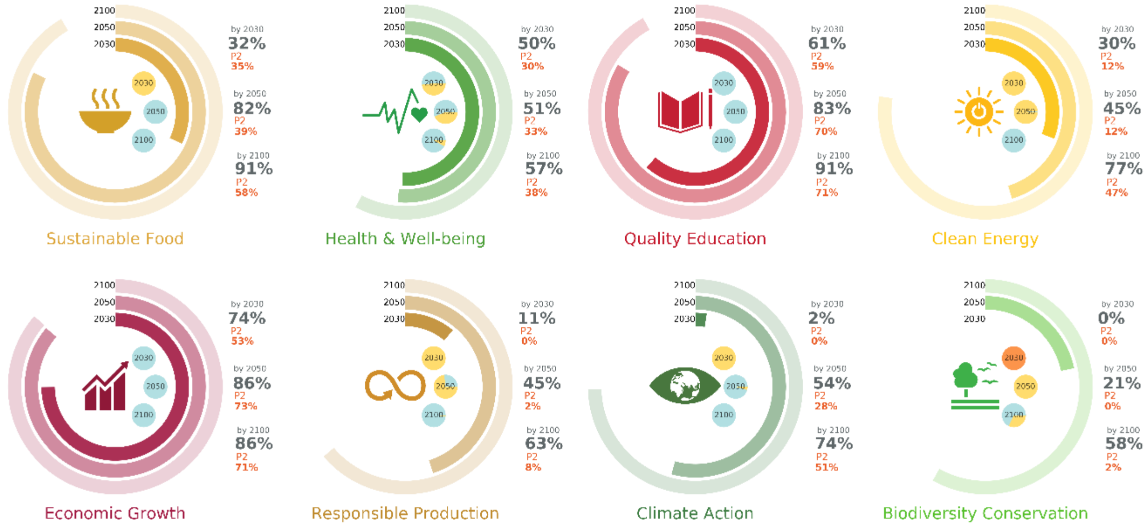
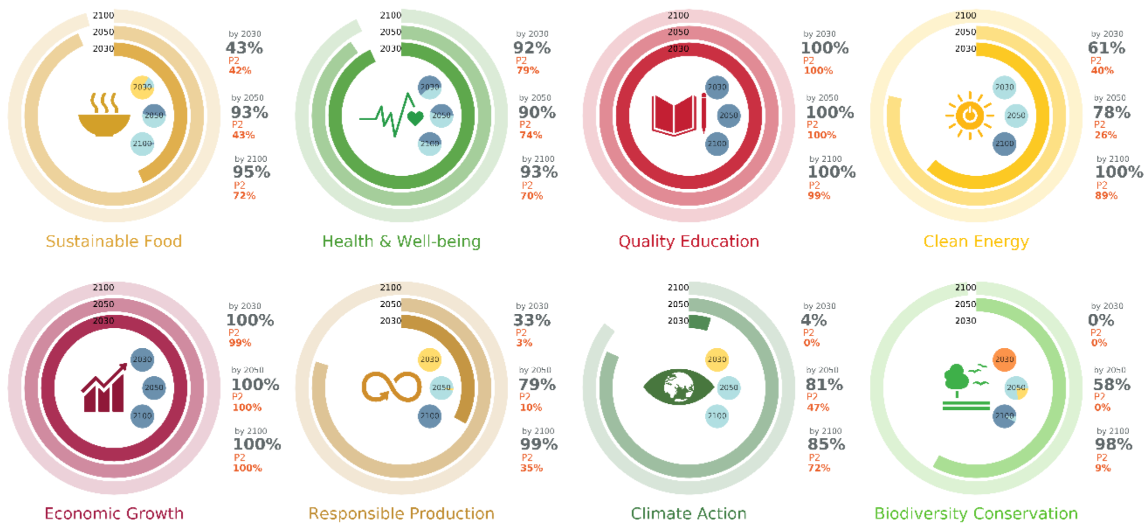


Fig. S2. Progress towards *ambitious* and *weak* targets on indicators by 2030, 2050, and 2100 under five modelled pathways. A, B, and C are towards ambitious targets and D, E, and F are towards weak targets. Each column represents one indicator. Related indicators are grouped under SDG labels. Progress 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.

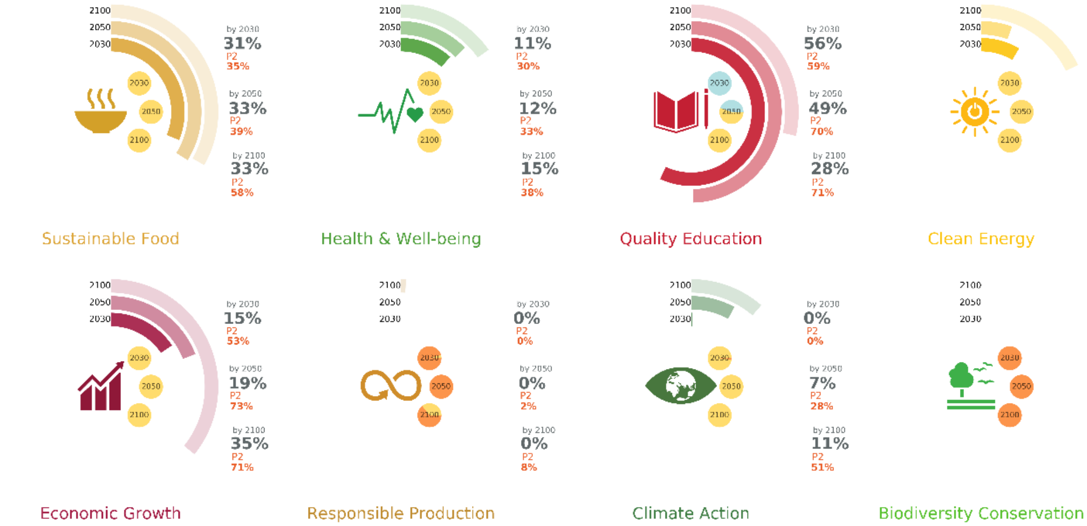


A

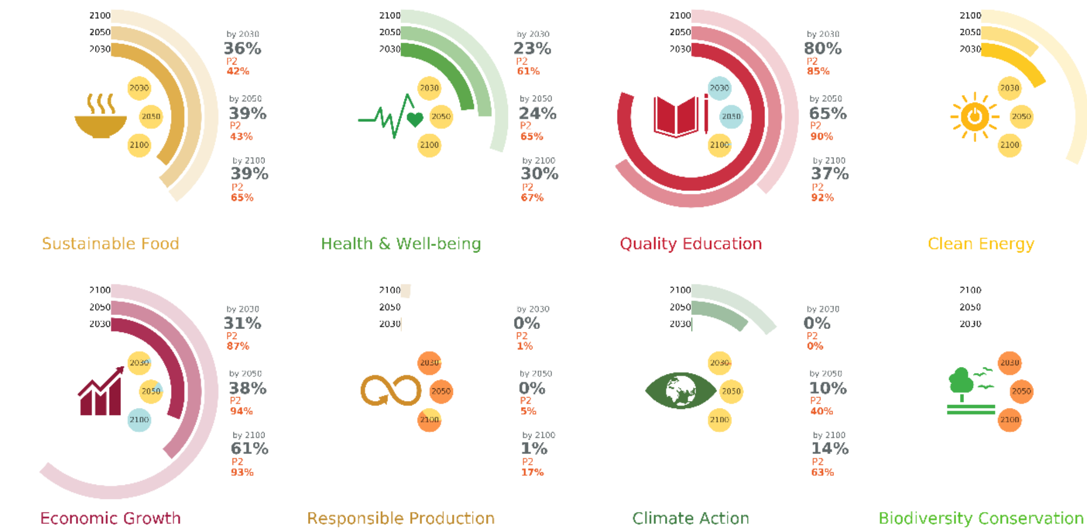


B

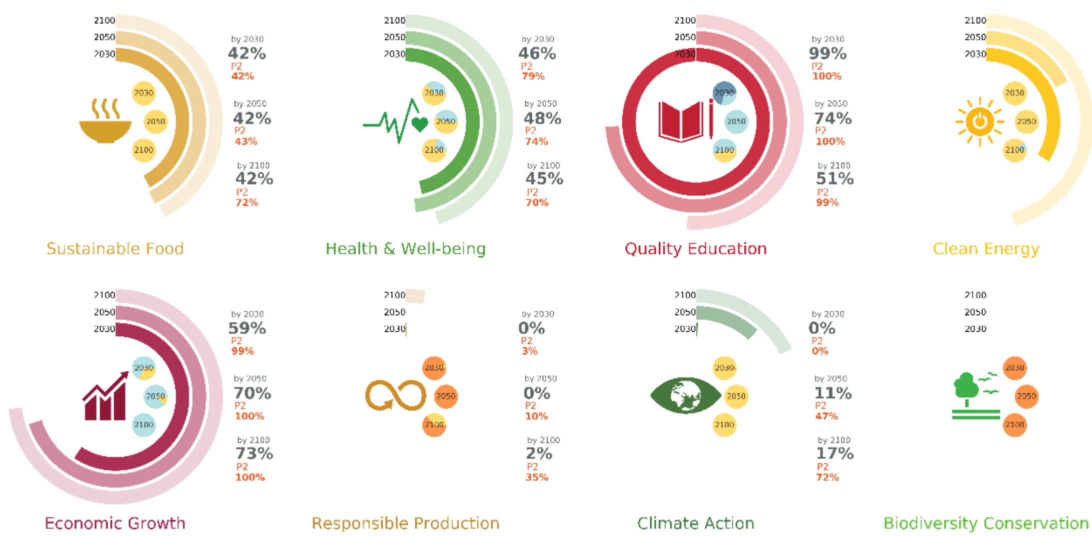
Fig. S3. Global progress towards eight modelled SDGs under Green Recovery. A and B show progress towards *ambitious* and *weak* targets, respectively.



A

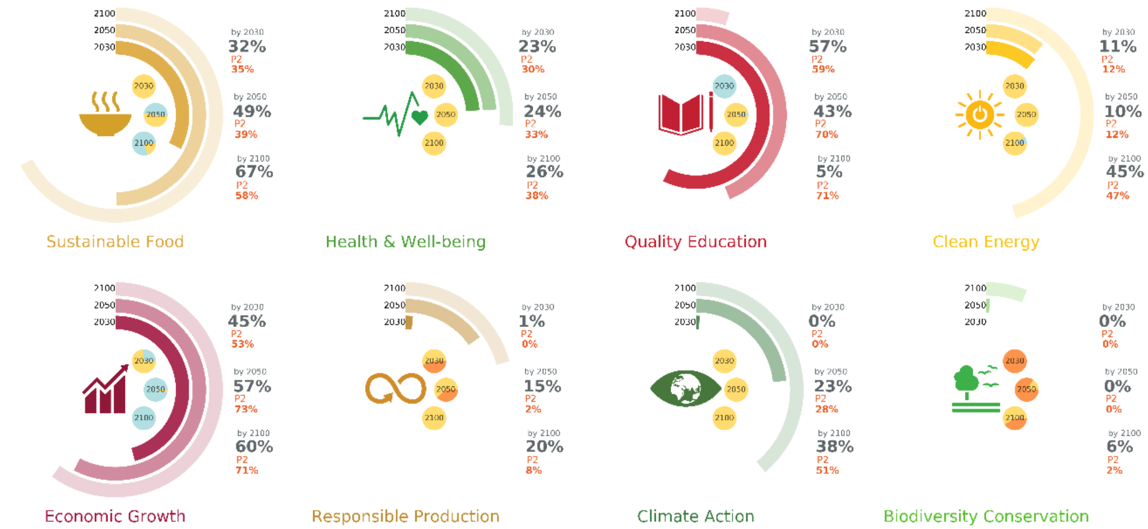


B

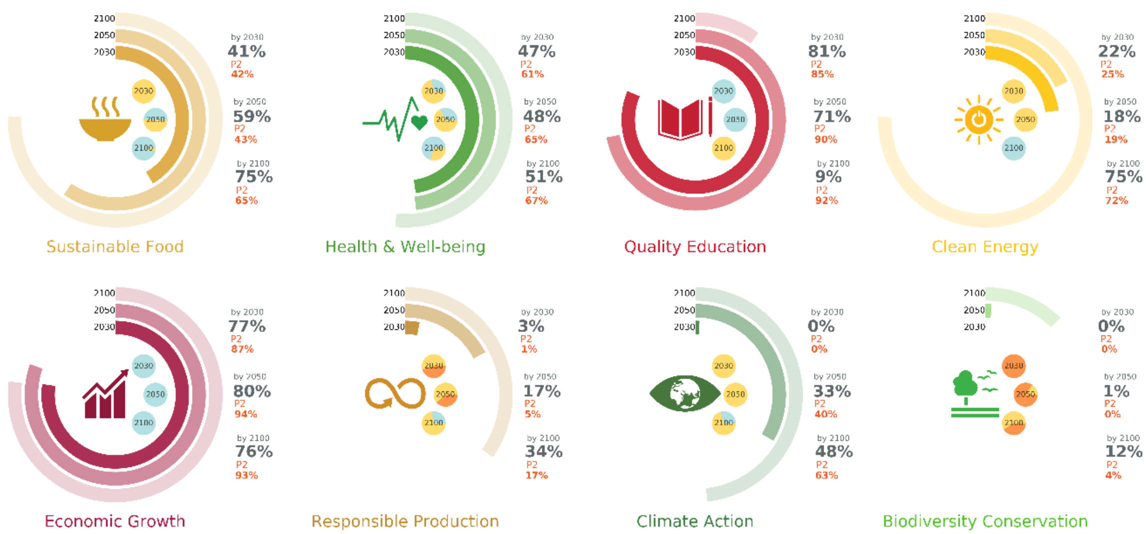


C

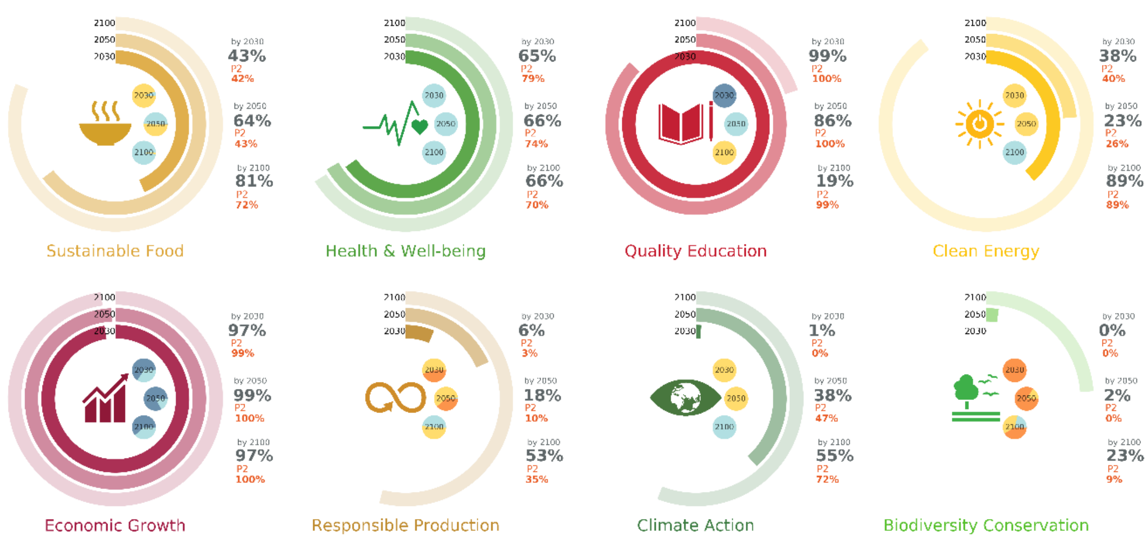
Fig. S4. Global progress towards eight modelled SDGs under Fragmented World. A, B, and C show progress towards *ambitious*, *moderate*, and *weak* targets, respectively.



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.

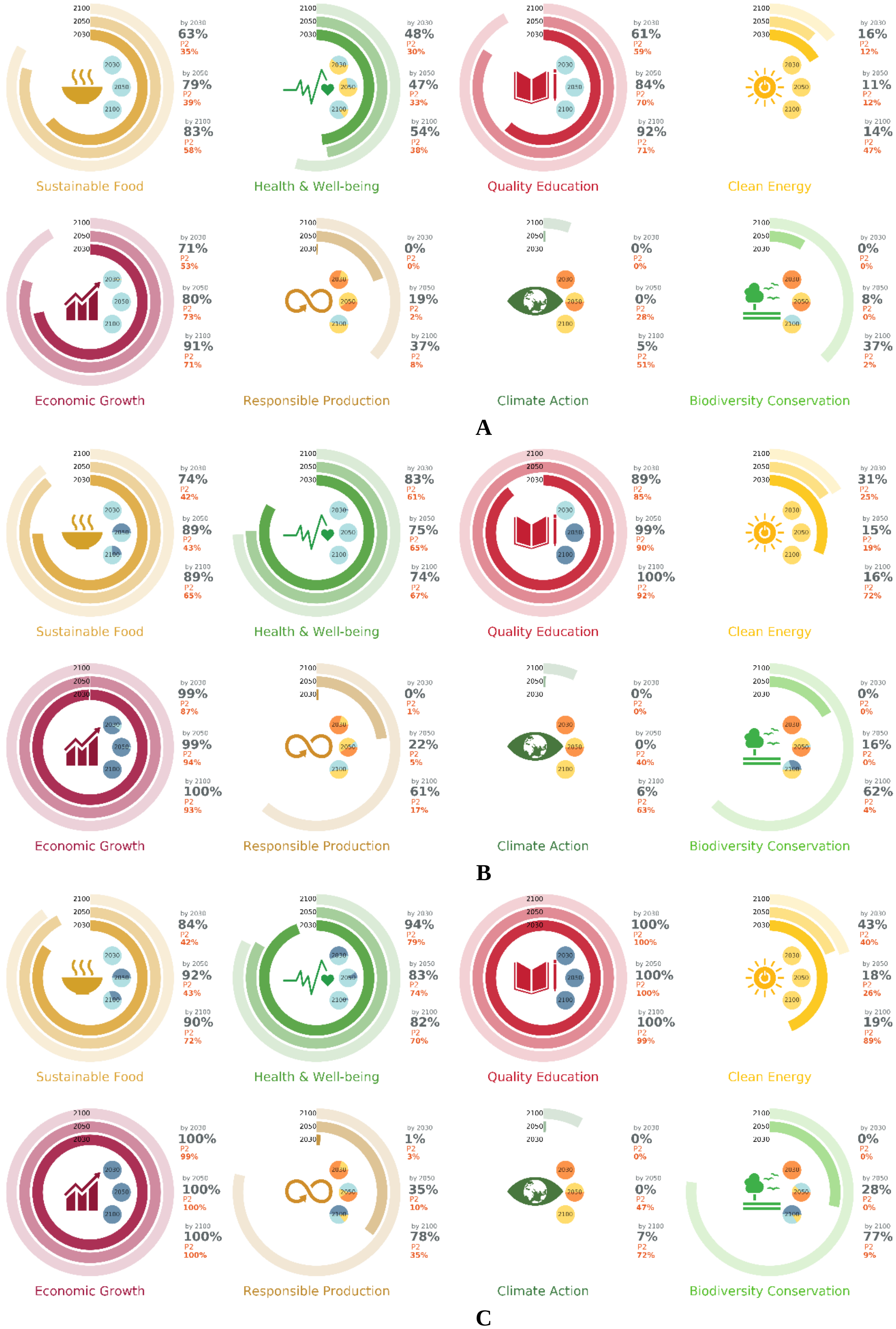
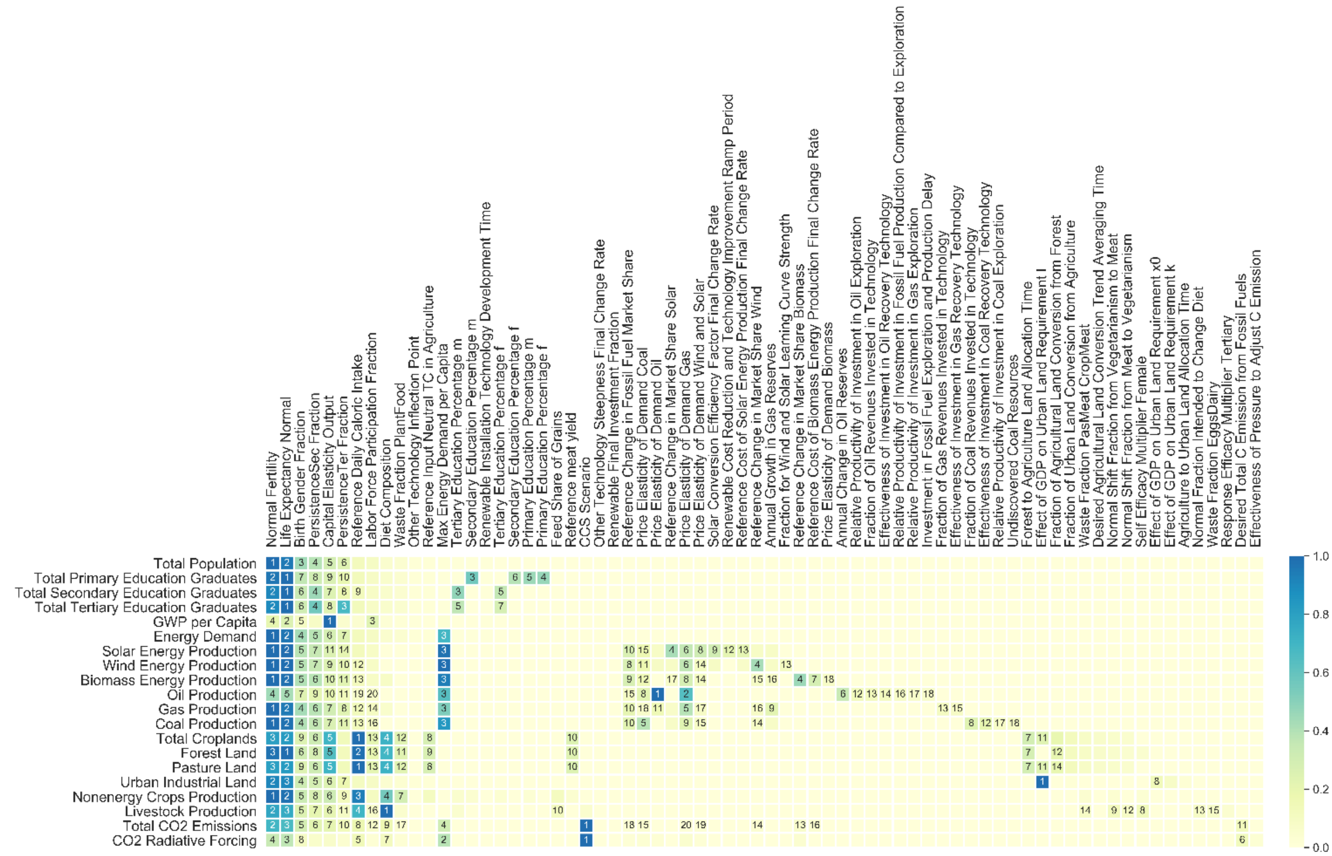


Fig. S6. Global progress towards eight modelled SDGs under Fossil Fuelled Development. A, B, and C show progress towards *ambitious*, *moderate*, and *weak* targets, respectively.



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.

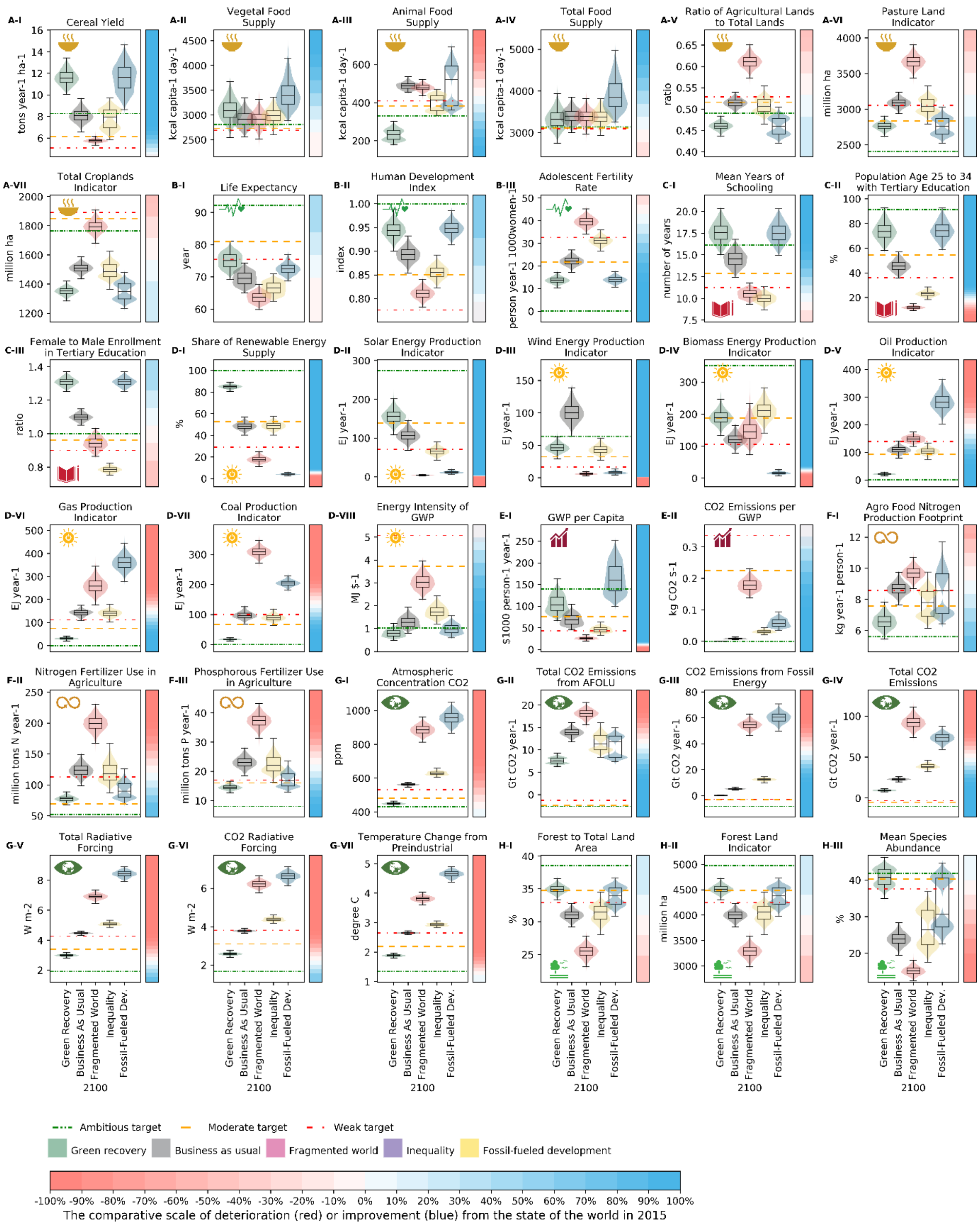


Fig. S8. Performance of global pathways towards SDG targets in 2100 under five SSP-compliant pathways. The violin shows the distribution of pathway's performance across 10,000 simulated realisations of each pathway. The box shows the inter-quartile range (centre line is median) of these simulated realisations 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.

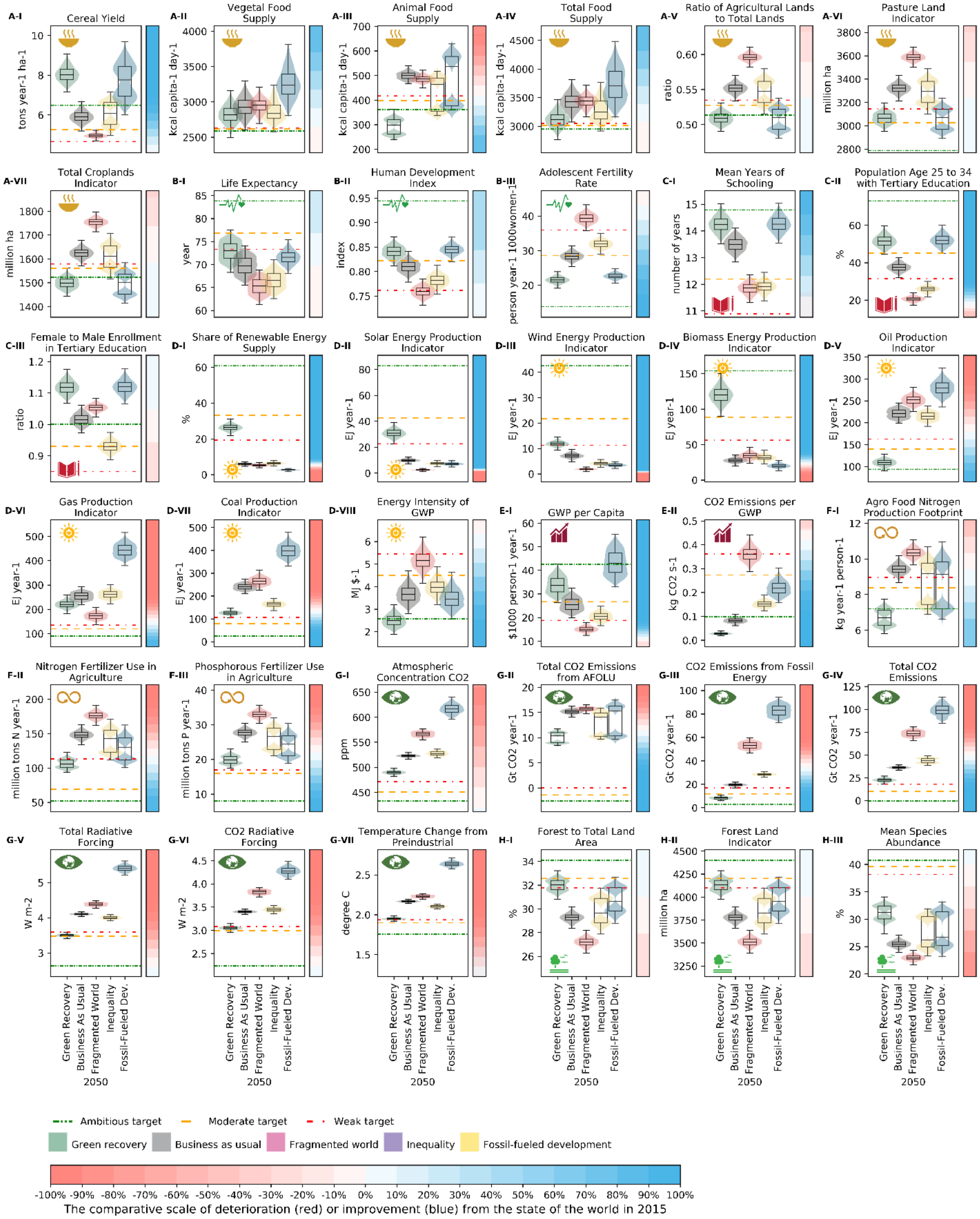


Fig. S9. Performance of global pathways towards SDG targets in 2050 under five SSP-compliant pathways.

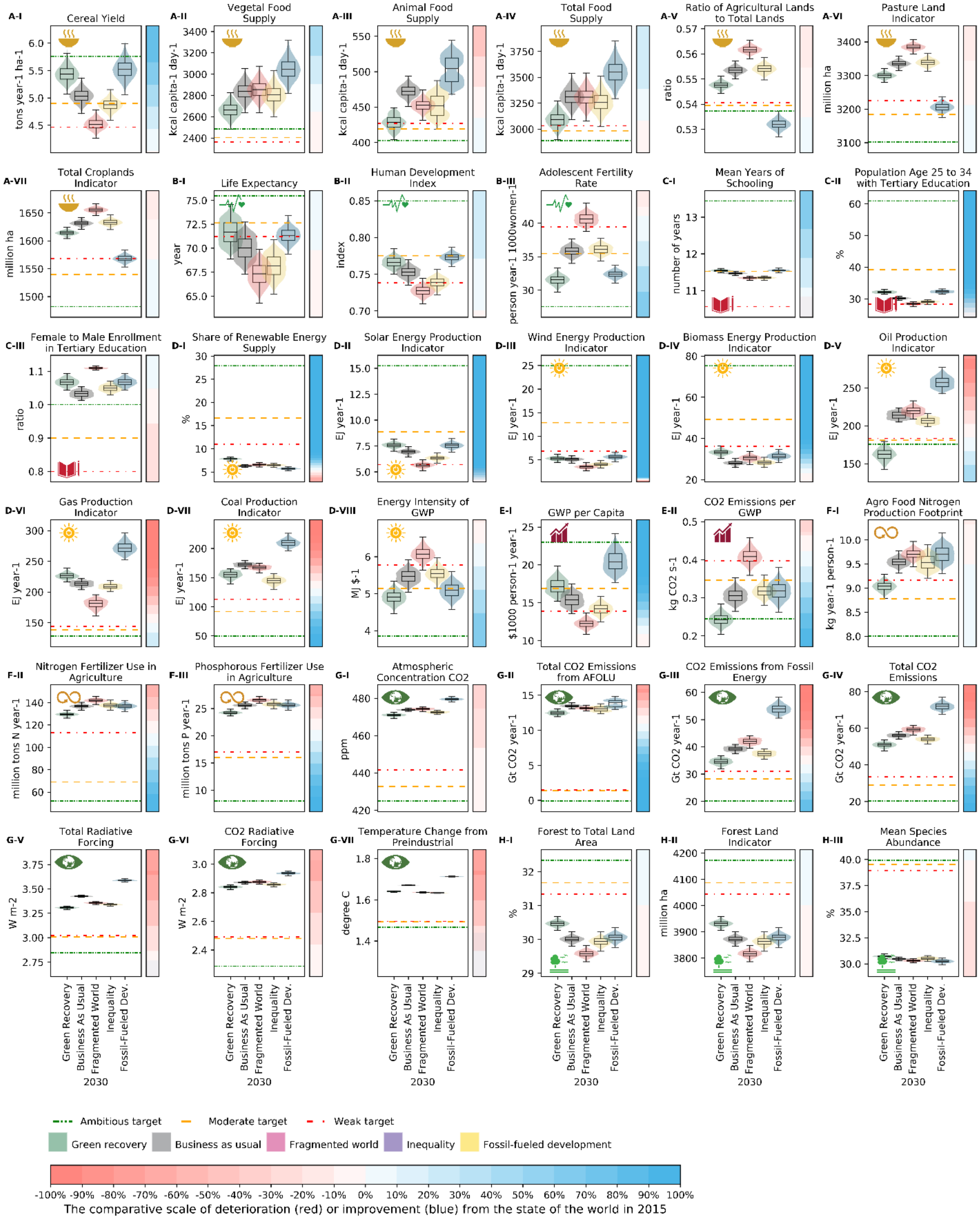


Fig. S10. Performance of global pathways towards SDG targets in 2030 under five SSP-compliant pathways.

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**			
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	2030	2050	2100
		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	2030	2050	2100
		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	2030	2050	2100
		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	2030	2050	2100
		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	2030	2050	2100
		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	2030	2050	2100
		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	2030	2050	2100
		Ambitious	1482	1523	1765
		Moderate	1540	1560	1849
		Weak	1568	1579	1807

Continued.

Objective	Indicator	Scenario	2030	2050	2100
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			
		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			
		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			
		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			
		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			
		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			
		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			
		Ambitious	28	61	100
		Moderate	17	33	52
		Weak	11	19	29

Continued.

			2030	2050	2100
	Solar Energy Production Indicator (EJ year^{-1}) | IPCC	Technical optimum			
	Solar energy production limited by a maximum capacity and impacted by demand, market price, technology progress, GDP growth, amongst others.	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	Technical optimum			
	Wind energy production limited by a maximum capacity and impacted by demand, market price, technology progress, GDP growth, amongst others.	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	Technical optimum			
	Biomass energy production limited by a maximum capacity and impacted by demand, market price, technology progress, GDP growth, amongst others.	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	Technical optimum			
	Oil energy production limited by availability of resources and impacted by demand, market price, technology progress, GDP growth, amongst others.	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	Technical optimum			
	Gas energy production limited by availability of resources and impacted by demand, market price, technology progress, GDP growth, amongst others.	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	Technical optimum			
	Coal energy production limited by availability of resources and impacted by demand, market price, technology progress, GDP growth, amongst others.	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}$)* | UNSC, World Bank	SDG absolute threshold			
	Energy consumption per unit of GWP production, as an indication of how much energy is used to produce one unit of economic output. Lower ratio indicates that less energy is used to produce one unit of output.	Ambitious	3.85	2.57	1.03
		Moderate	5.13	4.49	3.72
		Weak	5.78	5.46	5.07
Goal 8. Promote sustained, inclusive and sustainable economic growth for all					
Target 8.1. Sustain per capita economic growth, at least 7 per cent gross domestic product growth per annum					
Increase the GWP across countries	*GWP per Capita (\$1000 person^{-1} year^{-1})* | UNSC, World Bank	SDG absolute threshold			
	The accumulation of the GDP of the countries, divided by the total GDP by combined population of these countries.	Ambitious	23	43	140
		Moderate	17	27	75
		Weak	14	19	43
Target 8.4. Improve progressively, through 2030, global resource efficiency in consumption and production					
Reduce carbon emissions on per unit of value added	*CO_2 Emissions per GWP (kg CO_2 \$$^{-1}$)* | World Bank, UNDP	Global improvement			
	Human-originated carbon dioxide emissions stemming from emissions the burning of fossil fuels divided by the unit of the GDP.	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

Objective	Indicator	Technical optimum	2030	2050	2100
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.	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.	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.	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.	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.	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.	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.	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.	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).	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	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.

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

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.

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

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.

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

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.

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

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.

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

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.

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

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.

$$FM_{tertiary}(t) = \frac{ERT_{female}(t)}{ERT_{male}(t)}$$ 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.

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

$$EP_{solar}(t) = min(\frac{PEP_{solar}(t)}{ED_{solar}(t)}) \times uc$$ 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.

$$EP_{wind}(t) = min(\frac{PEP_{wind}(t)}{ED_{wind}(t)}) \times uc$$ 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.

$$EP_{biomass}(t) = min(\frac{PEP_{biomass}(t)}{ED_{biomass}(t)}) \times uc$$ 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.

$$EP_{oil}(t) = min(\frac{PEP_{oil}(t)}{ED_{oil}(t)}) \times uc$$ 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.

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

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.

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

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.

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

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.

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

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.

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

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.