This manuscript is a preprint and has been submitted for publication in Nature. Please note that, the manuscript’s status in the journal is currently ‘submitted’ for editorial assessment and a peer-review process. It has yet to be accepted for publication. Subsequent versions of this manuscript may have slightly different content. If accepted, the final version of this manuscript will be available via the ‘Peer-reviewed Publication DOI’ link on the right-hand side of this webpage. Please feel free to contact the corresponding author; we welcome feedback.
Global pathways to sustainable development to 2030 and beyond

Enayat A. Moallemi¹²³⁺⁺, Sibel Eker⁴, Lei Gao⁵, Michalis Hadjikakou¹, Jan Kwakkel⁶, Patrick M. Reed⁷, Michael Obersteiner⁸, and Brett A. Bryan¹

¹ Centre for Integrative Ecology, School of Life and Environmental Sciences, Deakin University, Melbourne, Australia.
² The 4TU Centre for Resilience Engineering, the Netherlands.
³ Monash Sustainable Development Institute, Monash University, Melbourne, Australia.
⁴ International Institute for Applied Systems Analysis, Laxenburg, Austria.
⁵ The Commonwealth Scientific and Industrial Research Organisation (CSIRO), Waite Campus, Urrbrae, SA 5064, Australia.
⁶ Faculty of Technology, Policy and Management, Delft University of Technology, the Netherlands.
⁷ Department of Civil and Environmental Engineering, Cornell University, Ithaca, NY, USA.
⁸ The Environmental Change Institute, University of Oxford, the UK.
⁺⁺ Corresponding author: e.moallemi@deakin.edu.au

Summary

Progress to-date towards the ambitious global 2030 agenda for sustainable development¹² has been limited³, and upheaval from the COVID-19 pandemic will further exacerbate the already significant challenges to Sustainable Development Goal (SDG) achievement⁴⁵. Here, we undertake a model-based global integrated assessment to characterise alternative pathways towards 36 time-bound, science-driven targets by 2030, 2050, and 2100. We show that it will be unlikely to jointly achieve socioeconomic and environmental targets by 2030, even under the most optimistic pathways and the least ambitious targets. Nonetheless, humanity can still avoid destabilisation of the Earth system⁶ and increase socioeconomic prosperity post-2030 via a ‘Green Recovery’ pathway. A Green Recovery by mid- and end of the century requires reducing global population by 5% and 26%, empowering sustainable economic development by 32% and 52%, increasing education availability by 10% and 40%, reducing the total global fossil energy production by 36% and 80%, reducing agricultural land area by 7% and 10%, and promoting healthy and sustainable lifestyles by lowering consumption of animal-based foods (i.e., meat and dairy) by 39% and 50%, compared to the business-as-usual trajectories for 2050 and 2100, respectively. Our results show that the combination of these changes together towards extended, more ambitious goals by 2050 and 2100 is central to the transformative change⁷ needed to ensure that both people and planet prosper in medium- and long-term futures.
Main text

Progress to-date towards the 17 Sustainable Development Goals (SDGs)\(^1\), which embody the shared aspirations of humanity to promote societal welfare within the planetary boundaries\(^8\), has been very limited\(^9,10\). With less than 10 years to go, much work is still to be done to reach these ambitious global goals. The global COVID-19 pandemic has also disrupted national social, health, and economic systems, and short-term recovery efforts will likely dominate the global agenda over the next decade, diverting investment and distracting nations from the longer-term multi-pronged focus required to meet the SDGs. But failing to achieve the global sustainability agenda is not an option, and calls have been made to reset it in light of the pandemic\(^4,5\).

A recent evaluation of the Convention of Biological Diversity 2020 Aichi targets has shown that none have been fully achieved\(^11\), which has necessitated rethinking the process, and a new round of revision and target-setting\(^12\). To avoid a similar outcome for the SDGs and subsequent loss of momentum in progress towards global sustainability, it is prudent to explore alternate pathways towards increasingly ambitious medium- and long-term goals to enable missed 2030 targets to be met later on, to ensure that earlier achievements are not lost through complacency, and to establish a long-term process of continuous improvement. Here, we use integrated assessment modelling to assess the performance of alternative pathways towards 36 sustainability targets under eight SDGs by 2030 (short-term) and their extensions to 2050 (medium-term) and 2100 (long-term) with increasing levels of ambition. Given current and future socioeconomic and environmental uncertainties, this assessment is timely to illuminate robust options for humanity to achieve global sustainability aspirations over the course of the 21\(^{st}\) century, even if we fail to fully achieve the United Nations (UN) 2030 Agenda.

The scientific community has attempted to inform policy discussion on the SDGs with model-based scenario assessments, but mostly with a focus on specific sectors such as land\(^13\), food\(^14,15\), energy\(^16,17\), and biodiversity conservation\(^18\) with a few notable exceptions of global nexus-type assessments such as food-energy-water\(^19\), land-food\(^20\), and land-food-biodiversity\(^21\). The few, more comprehensive, integrated assessments of global sustainability that do exist have either used relatively simple models that do not capture the interactions of complex systems\(^22\), or have not assessed progress towards explicit targets consistent with the SDGs\(^23\). This has impeded a comprehensive understanding of progress under the uncertainty of global change and precluded a detailed characterisation of the transformative change needed to reach the sustainability targets, especially over timeframes extending well beyond 2030.

We used the Functional Enviro-economic Linkages Integrated neXus (FeliX) model\(^17\), a global integrated assessment model based on system dynamics\(^24\), to evaluate how interlinked future drivers might unfold through the nexus of population, education, economy, energy, land, food, biodiversity, and climate systems (Extended Data Figure 1). We explored a set of five internally consistent descriptions of future pathways aligned with the Shared Socioeconomic Pathways (SSPs) scenarios\(^25,26\) which span a range of possibilities from continuation of current trends (business-as-usual) to implementation of very strong sustainability
interventions across the economic, education, food, and energy sectors (Extended Data Table 1 and Methods).

Our SSP-compliant pathways include ‘Green Recovery’ representing inclusive socioeconomic and environmental development (SSP1), ‘Business As Usual’ as the continuation of current global average trajectories (SSP2), ‘Fragmented World’ characterised by regional rivalry rather than global cooperation (SSP3), a world of high ‘Inequality’ in human and economic opportunities (SSP4), and ‘Fossil-Fuelled Development’ with prospering socioeconomic yet unsustainable environmental outlook (SSP5). Green Recovery and Fragmented World are indicative of an optimistic and pessimistic post-pandemic future. The former represents ‘a new world of opportunities’ where the world shows solidarity in a long-term, sustainable recovery from COVID-19 and emerges fairer, more inclusive, and more prosperous than before. The latter represents increasingly nationalistic attitudes amplifying perceived threats, failures, and a limited capacity to build resilience for coping with future global shocks. Given the deep uncertainties inherent in the characterisation of these five pathways, we used an exploratory ensemble modelling approach27,28 (50,000 model evaluations) to obtain more robust insights from many possible realisations of each pathway under socioeconomic and environmental uncertainties (Methods and Extended Data Figure 2). The characterisation of the five pathways and their associated realisations (Extended Data Figure 4 and Supplementary Figure 6) represents fundamentally different futures for human societies and facilitates the impact assessment of possible strategies towards the SDG agenda.

We selected 36 indicators within the scope of the model (Methods and Extended Data Figure 3) to evaluate eight sustainable development goals related to food and agriculture (SDG 2), health and well-being (SDG 3), quality education (SDG 4), clean energy (SDG 7), sustainable economic growth (SDG 8), climate action (SDG 13), and biodiversity conservation (SDG 15). We specified weak, moderate, and ambitious targets (Extended Data Figure 2 and Extended Data Table 2) for 2030, then increased the ambition and extended the timeframe of the targets to 2050 (consistent with the Paris Agreement timeframe29) and to 2100 (aligning with the IPCC assessment timeframe30).

**Joint target achievement requires a new post-2030 timeframe.** By 2030, across all pathways combined (stacked bar charts in Figure 1a), the world is on track (in >50% of 50,000 realisations) for only 5 out of the 36 moderate targets, mostly related to socioeconomic SDGs. Worse, the world is stagnating or even regressing compared to the 2015 state of the world (in >80% of 50,000 realisations) for more than two-thirds of the 36 moderate targets, mostly related to environmental SDGs.

To illustrate, for the 2030 moderate targets, quality education (SDG 4), economic growth (SDG 8), and health and wellbeing (SDG 3) have a progress of 85%, 78%, and 59%, respectively (Figure 2). Fossil-Fuelled Development and Green Recovery have the fastest progress to these goals. In at least 50% of realisations of each of these two pathways, moderate targets under SDGs 3, 4, and 8 are either on track (five targets) or improving (three targets) by 2030 (pie charts in Figure 1a). A combination of assumptions on accelerated human capital investment and low population growth (Supplementary Figure 6c-i, c-v and
Extended Data Figure 4a-i, a-v) makes Fossil-Fuelled Development and Green Recovery on track towards these targets by 2030. Among the modelled pathways, Fragmented World (and then Business As Usual and Inequality) have the slowest progress by 2030, stagnating (four targets) and even deteriorating from the 2015 state of the world (one target) for most moderate socioeconomic targets under SDGs 3, 4, and 8.

Figure 1. Projected progress towards the ‘moderate’ SDG targets by 2030 (a), 2050 (b), and 2100 (c) under five modelled pathways. Progress levels are coloured coded and defined according to Methods. The stacked bar charts represent the progress across 50,000 realisations of all future pathways combined. The highest percentage of the realisations at each progress level is indicated inside the bars. The arrows show the progress of the greatest number of realisations per each pathway. See Supplementary Figure 7 for progress towards ‘weak’ and ‘ambitious’ SDG targets.

Sustainable food (SDG 2) and clean energy (SDG 7) are the two goals with slower progress of 46% and 28% respectively (Figure 2). In SDG 2, Fossil-Fuelled Development outperforms other pathways by 74% progress with on track or improving trends towards six out of seven moderate 2030 targets on food production and agricultural productivity (Figure 1a). On the other hand, Fragmented World’s progress is only 36%, being on track in achieving only two food-related targets by 2030. For SDG 7, the sustainable economic development in Green Recovery leads to progress of 47% towards targets, mostly due to achieving economic growth with a higher adoption of efficient end-use technologies and a faster transition to renewable energy (Extended Data Figure 4c-i). However, Fossil-Fuelled Development and Fragmented World have the slowest progress and are on track in only one targets for clean energy (respectively) due to
heavy reliance on fossil energy (oil, gas, and then coal) production throughout the century (Supplementary Figure 6-e, f-v, g-v).

Inadequate progress by 2030 can be even worse with ≤0%, 5%, and 1% progress in biodiversity conservation (SDG 15), responsible production (SDG 11), and climate action (SDG 13), respectively. Projected progress in almost all 13 targets under these SDGs are either stagnating or deteriorating across the five modelled pathways by 2030. Poor environmental performance in all pathways except Green Recovery is largely the result of increasing demand for food production\(^{31}\), high meat consumption, and a growing energy-intensive economy which poses risks for environmental targets such as agricultural land expansion and intensive nitrogen fertiliser use (Extended Data Figure 4). The lowest achievements on these targets also translate into major consequences for ecosystem loss such as rapid decline in forest lands (in all pathways, 100% of realisations) and for destructive climate impacts such as faster global temperature increase (in all pathways, 99% of realisations), as raised in previous studies\(^{21,32,33}\) (Figure 1a).

**Figure 2.** Global progress towards achieving eight sustainable development goals. Each panel shows the progress towards one SDG. In each plot, the three bars indicate progress towards 2030, 2050, and 2100 targets. The bar indicates progress towards the moderate target and the error bar is the variation between progress towards ambitious (error bar bottom) and weak (error bar top) targets in across 50,000 simulated realisations of all future pathways combined. The annotated percentages are average progress across all pathways combined (grey text), the progress in the pathway with the worst performance (red text), and the progress in the pathway with the best performance (blue text), all percentages towards moderate targets by 2030, 2050, and 2100. The pie charts show the share of simulated realisations per each pathway (P1: Green Recovery, P2: Business As Usual, P3: Fragmented World, P4: Inequality, P5: Fossil-Fuelled Development). The pie chart colours show different progress levels (green: on track, yellow: improving, orange: stagnating, red: wrong direction) towards the moderate targets by 2100.

Overall, although individual target achievement varies between pathways and is sensitive to the uncertainty across different world realisations (Methods), the current UN agenda for sustainable development remains largely unmet by 2030, even in the most optimistic pathways (e.g., Green Recovery). This reflects tensions between socioeconomic and environmental goals\(^ {20,34}\) which lead to failure in concurrently achieving the 2030 targets.
Exploring pathways to reaching 2050 and 2100 targets. The short timeframe can have a complex effect on slow progress towards and tensions between the SDGs by 2030, and there is a higher chance of achieving more ambitious targets by 2050 and 2100. Looking at progress over the century (Figures 1 and 2), some SDGs such as biodiversity conservation and climate action could reverse their unsustainable trajectories in a post-2030 timeframe via immediate adoption of Green Recovery. Owing to investment in high-quality and well-functioning education (Supplementary Figure 6a-i, b-i, c-i) and a declining population growth (Extended Data Figure 4a-i), the trends under the Green Recovery pathway can achieve a high level of socioeconomic prosperity (Extended Data Figure 5b-i to b-iii; c-i to c-iii), but also with promising improvements to the major energy, climate, and ecological targets by 2050 and 2100. The Green Recovery pathway performs very well in the medium-term, with 42%, 54%, and 74% progress in biodiversity conservation, responsible production, and climate action by 2050, respectively (Figure 2). This means being on track or improving for 9 out of 13 targets by 2050 (compared to only one improving target by 2030) even with a higher level of target ambition (Figure 1a).

With a longer timeframe and even more ambitious targets, Green Recovery’s progress in biodiversity conservation, responsible production, and climate action will become greater by 2100 (90%, 94%, and 84% respectively), being on track or improving on 12 out 13 targets (Figure 1a). The cumulative effect of interventions (e.g., low carbon energy system, healthy diet with reduced meat consumption) incorporated in the Green Recovery pathway creates these promising long-term trajectories towards targets, which is central to turning the ‘tide of change’ post-2030 to higher achievements.

While the improvement in SDG achievement over the century is substantial in Green Recovery, this is not the case for other pathways where the environmental SDGs (i.e., 7, 12, 13, 15) remain largely unmet by 2050 and 2100. For example, the Fossil-Fuelled Development pathway results in the most rapid improvement in socioeconomic indicators, such as Gross World Product (GWP) per capita (Extended Data Figure 5e-i), achieving moderate (and sometimes even ambitious) targets by 2100. However, human and economic prosperity in Fossil-Fuelled Development also leads to the rapid growth in the share of fossil fuels in energy supply (Extended Data Figure 5d-v, d-vi) driven by increasing energy demand from high energy intensity of the industry and services (Supplementary Figure 6d-v). The reliance on fossil fuels translates into high climate impacts from energy-related CO₂ emissions (Extended Data Figure 5g-iii) by 2100 in almost all 10,000 realisations of the Fossil-Fuelled Development pathway. This jeopardises the achievement of even the weakest targets set for climate indicators by the IPCC in 2030 and beyond. Longer term target achievement is also challenged in Business As Usual, Fragmented World, and Inequality, where they fail to meet even the weakest socioeconomic, energy, climate, and ecological targets in most of pathway realisations.

Priorities for transformative change in a new post-2030 agenda. Humanity is at a crossroads in planning for a post-pandemic world. Our projections of progress towards the SDGs showed that the 2030 agenda faces significant challenges limiting the chances of near-term success. Based on this evidence, we call for
extending the current UN Agenda 2030’s timeframe, with increasing levels of ambition in targets over the course of the century. This maintains the imperative for and global focus on sustainable development\(^5\) over the long-term with a more radical approach\(^{18,21}\) that disrupts the status quo, accelerates actions for achieving the SDGs, and puts a safety net in place where achieving ambitious long-term sustainability aspirations are not threatened by a failure to achieve some short-term goals.

Figure 3. Socioeconomic and environmental transformative change needed in realising pathways to Green Recovery. The envelops show one standard deviation bandwidth in the results and the middle line is the mean. The arrows represent the change percentage needed to deviate from the mean of the business-as-usual envelop to the mean of the Green Recovery envelop in 2030, 2050, and 2100. The mean estimate percentage of improvement reported in the text and annotated is the distance between the mean value of the envelopes in 2030, 2050, and 2100. The confidence range reported in the text is the minimum and maximum distance between the upper-bound and lower-bound (one standard deviation) of the two envelopes in 2030, 2050, and 2100.

We showed (in Figures 1 and 2) that the Green Recovery pathway, over the medium- to long-term, can be a way forward for realising co-benefits between multiple goals\(^36\). As a step towards developing a more effective approach, we characterise the major transformative change needed across multiple sectors by analysing the distance to be bridged from current business-as-usual trajectories to the trajectories of a Green Recovery in a post-2030 timeframe (Figure 3 and Methods).

Compared to 2050 and 2100 business-as-usual, a Green Recovery primarily requires slowing population growth by 5% and 26%, along with a modest yet sustainable economic growth of 32% and 52%, and improving access to education by 10% and 40%, respectively. The demographic transition to a lower but more highly educated and prosperous population can lead to poverty reduction and gender equality. Higher educational levels also correlate with social norms and people’s beliefs in the adoption of bolder actions such as improved family planning\(^37\), consuming less meat\(^15\) and the appropriate attribution of extreme events to climate change\(^{18,39}\) to lower population, avoid further deforestation, and reduce GHG emissions, respectively. Concurrently achieving these long-term targets and goals strongly relies on harnessing synergies and minimising trade-offs through steady progress across key parameters such as education level.

These socioeconomic changes, however, need to be further supported by transformations in the current consumption and production practices in energy, land, and food systems to mitigate some of the currently alarming trends of emissions and increasing temperature\(^{16,40}\). Our energy systems need to be decarbonised
more rapidly compared to business-as-usual trajectories with a decline of at least 36% and 80% in fossil energy (i.e., coal, oil, gas) production by 2050 and 2100, respectively. This also needs to be coupled with changing the patterns of energy consumption through a transition to 13% and 32% lower energy intensity services (compared to the business-as-usual) by mid and end of the century.

Cropland and pasture land need to be reduced by 7% and 10% compared to business-as-usual by 2050 and 2100 while continuing to increase food production. This requires improvement in crops and livestock yields and reducing food waste along with strong regulations on land-use change to limit deforestation and reverse the currently alarming trends of biodiversity loss\textsuperscript{31}. These changes in the land sector should be facilitated by and intertwined with collaborative actions on food choices\textsuperscript{15} through 39% and 50% reduction in land-based animal (i.e., meat and dairy) caloric intake in a healthy diet and a drop of 49% and 67% in livestock production by 2050 and 2100, respectively (compared to business-as-usual). This can also help those worst affected by the distributional impacts on food supply chains in a post-pandemic world.

While realising such transformative changes may come across as wishful thinking given current trends and the myriad of technical and political challenges that beset it, a pathway to Green Recovery is not totally out of reach. There are currently promising endeavours across several key sectors that could pave the way for transition to Green Recovery. Universal education is projected to be nearly achieved in many developed and developing countries, with supporting measures such as eliminating school fees and improving local access to schools to ensure equality\textsuperscript{41}. In energy sector, there is already diverse global support for reducing energy intensity through digitalisation to transform energy efficiency and increase its value\textsuperscript{42}. Reduction in energy demand in various countries is also complemented by policies such as carbon pricing for GHG emissions to accelerate the decarbonisation process\textsuperscript{17,40}. Coordinated efforts in food and land sectors have also emerged to promote healthy diet and sustainable agriculture through strategies such as investment in public health information and intensifying food production of high-quality outcomes\textsuperscript{33,43}.

The global community needs to take additional steps to capitalise on these efforts in revising and extending the SDGs as an internationally agreed framework that works at the global, national, and local scale\textsuperscript{44} and that can unite all sectors and countries behind a resilient economy and build coherent policies for a healthy planet. A Green Recovery pathway can create a touchpoint for science and policy discussions about resetting the global sustainability agenda of the 21\textsuperscript{st} century in the light of sustainable futures that is central for recovering from the pandemic with a better future for people and planet.
Main references

1. UN. Transforming our world: the 2030 Agenda for Sustainable Development. (The United Nations (UN), 2015).
2. van Soest, H. L. et al. Analysing interactions among Sustainable Development Goals with Integrated Assessment Models. Global Transitions 1, 210-225, doi:https://doi.org/10.1016/j.glt.2019.10.004 (2019).
3. Sachs, J., Schmidt-Traub, G., Kroll, C., Lafortune, G. & Fuller, G. Sustainable Development Report 2019. (Bertelsmann Stiftung and Sustainable Development Solutions Network (SDSN), New York, 2019).
4. Naidoo, R. & Fisher, B. Reset Sustainable Development Goals for a pandemic world. Nature 583, 198-201, doi:10.1038/d41586-020-01999-x (2020).
5. Editorial. Time to revise the Sustainable Development Goals. Nature, 331-332, doi:10.1038/d41586-020-02002-3 (2020).
6. Steffen, W. et al. Planetary boundaries: Guiding human development on a changing planet. Science 347, 1259855, doi:10.1126/science.1259855 (2015).
7. TWI2050 - The World in 2050. Innovations for Sustainability. Pathways to an efficient and post-pandemic future. (The World in 2050 initiative, International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria, 2020).
8. Sachs, J. D. From Millennium Development Goals to Sustainable Development Goals. The Lancet 379, 2206-2211, doi:10.1016/S0140-6736(12)60685-0 (2012).
9. UNEP. Global Environment Outlook – GEO-6: Healthy Planet, Healthy People. (UN Environment Program, 2019).
10. IPBES. Global Assessment Report on Biodiversity and Ecosystem Services. (the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), Paris, France, 2019).
11. CBD. Global Biodiversity Outlook 5 (GBO-5). (The Convention on Biological Diversity (CBD), 2020).
12. OECD. The Post-2020 Biodiversity Framework: Targets, indicators and measurability implications at global and national level. (Organisation for Economic Co-operation and Development, 2019).
13. Roe, S. et al. Contribution of the land sector to a 1.5 °C world. Nat. Clim. Change. 9, 817-828, doi:10.1038/s41558-019-0591-9 (2019).
14. Mehrabi, Z., Gill, M., Wijk, M. v., Herrero, M. & Ramankutty, N. Livestock policy for sustainable development. Nat. Food. 1, 160-165, doi:10.1038/s43016-020-0042-9 (2020).
15. Eker, S., Reese, G. & Obersteiner, M. Modelling the drivers of a widespread shift to sustainable diets. Nat. Sustain., doi:10.1038/s41893-019-0331-1 (2019).
16. Rogelj, J. et al. Scenarios towards limiting global mean temperature increase below 1.5 C. Nat. Clim. Change. 8, 325-332 (2018).
17. Walsh, B. et al. Pathways for balancing CO2 emissions and sinks. Nat. Commun. 8, 14856, doi:10.1038/ncomms14856 (2017).
18. Mace, G. M. et al. Aiming higher to bend the curve of biodiversity loss. Nat. Sustain. 1, 448-451, doi:10.1038/s41893-018-0130-0 (2018).
19. Van Vuuren, D. P. et al. Integrated scenarios to support analysis of the food–energy–water nexus. Nat. Sustain. 2, 1132-1141, doi:10.1038/s41893-019-0418-8 (2019).
20. Obersteiner, M. et al. Assessing the land resource–food price nexus of the Sustainable Development Goals. Sci. Adv., e1501499, doi:10.1126/sciadv.1501499 (2016).
21. Leclère, D. et al. Bending the curve of terrestrial biodiversity needs an integrated strategy. *Nature*, doi:10.1038/s41586-020-2705-y (2020).

22. Randers, J. et al. Achieving the 17 Sustainable Development Goals within 9 planetary boundaries. *Global Sustainability* 2, e24, doi:10.1017/sus.2019.22 (2019).

23. van Vuuren, D. P. et al. Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm. *Global Environ. Change* 42, 237-250 (2017).

24. Sterman, J. D. *System Dynamics Modeling: Tools for Learning in a Complex World*. Calif. Manage. Rev. 43, 8-25, doi:10.2307/41166098 (2001).

25. O’Neill, B. C. et al. The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. *Global Environ. Change* 42, 169-180, doi:https://doi.org/10.1016/j.gloenvcha.2015.01.004 (2017).

26. Riahi, K. et al. The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environ. Change* 42, 153-168, doi:https://doi.org/10.1016/j.gloenvcha.2016.05.009 (2017).

27. Lamontagne, J. R. et al. Large Ensemble Analytic Framework for Consequence-Driven Discovery of Climate Change Scenarios. *Earth’s Future* 6, 488-504, doi:10.1002/2017EF000701 (2018).

28. Moallemi, E. A., Kwakkel, J., de Haan, F. & Bryan, B. A. Exploratory modeling for analyzing coupled human-natural systems under uncertainty. *Global Environ. Change* 102186, 102186, doi:https://doi.org/10.1016/j.gloenvcha.2020.102186 (2020).

29. UNFCCC. *The Paris Agreement*. (United Nations Framework Convention on Climate Change, 2015).

30. IPCC. *Global Warming of 1.5 °C: An IPCC special report on the impacts of global warming of 1.5 °C.*, (Intergovernmental Panel on Climate Change, 2018).

31. Tilman, D. et al. Future threats to biodiversity and pathways to their prevention. *Nature* 546, 73-81, doi:10.1038/nature22900 (2017).

32. Xu, Z. et al. Assessing progress towards sustainable development over space and time. *Nature* 577, 74-78, doi:10.1038/s41586-019-1846-3 (2020).

33. Gao, L. & Bryan, B. A. Finding pathways to national-scale land-sector sustainability. *Nature* 544, 217, doi:10.1038/nature21694 (2017).

34. Kroll, C., Warchold, A. & Pradhan, P. Sustainable Development Goals (SDGs): Are we successful in turning trade-offs into synergies? *Palgrave Commun.* 5, 140, doi:10.1057/s41599-019-0335-5 (2019).

35. Rogelj, J. et al. Mitigation pathways compatible with 1.5 C in the context of sustainable development., (Intergovernmental Panel on Climate Change (IPCC), 2019).

36. Pimm, S. L., Jenkins, C. N. & Li, B. V. How to protect half of Earth to ensure it protects sufficient biodiversity. *Sci. Adv.* 4, eaat2616, doi:10.1126/sciadv.aat2616 (2018).

37. Kebede, E., Goujon, A. & Lutz, W. Stalls in Africa’s fertility decline partly result from disruptions in female education. *PNAS* 116.8, 2891-2896 (2019).

38. Beckage, B. et al. Linking models of human behaviour and climate alters projected climate change. *Nat. Clim. Change.* 8, 79-84, doi:10.1038/s41558-017-0031-7 (2018).

39. O’Neill, B. C. et al. The effect of education on determinants of climate change risks. *Nat. Sustain.* 3, 520-528, doi:10.1038/s41893-020-0512-y (2020).

40. Rockström, J. et al. A roadmap for rapid decarbonization. *Science* 355, 1269, doi:10.1126/science.aah3443 (2017).
41. Friedman, J. et al. Measuring and forecasting progress towards the education-related SDG targets. *Nature* **580**, 636-639, doi:10.1038/s41586-020-2198-8 (2020).

42. IEA. Energy Efficiency 2019. (International Energy Agency, Paris, 2019).

43. Willett, W. et al. Food in the Anthropocene: the EAT-Lancet Commission on healthy diets from sustainable food systems. *The Lancet* **393**, 447-492, doi:10.1016/S0140-6736(18)31788-4 (2019).

44. Moallemi, E. A. et al. Achieving the Sustainable Development Goals requires transdisciplinary innovation at the local scale. *One Earth* **3**, 300-313, doi:10.1016/j.oneear.2020.08.006 (2020).
Methods

The FeliX model

FeliX is a system dynamics model that simulates complex interactions amongst ten sectors: population, education, economy, energy, water, land, food and diet change, carbon cycle, climate, and biodiversity. The model captures the underpinning feedback mechanisms of physical and anthropogenic change between these sectors as described in Supplementary Methods 1. FeliX has been used previously for exploring global energy and land-use emissions pathways\textsuperscript{17}, exploring the impacts of dietary changes on the food system\textsuperscript{15}, and evaluating socio-environmental impacts in the Earth observation systems\textsuperscript{45}. The model is calibrated with historical data\textsuperscript{46} from 1900 to 2015. The model projects the global average of future socioeconomic and environmental developments over the long-term to 2100.

We enhanced the latest version of FeliX\textsuperscript{15} by implementing global change pathways based on the Shared Socioeconomic Pathways (SSPs) scenarios\textsuperscript{25,26} and operationalising SDG indicators and targets in the model, closely related to the UN 2030 Agenda. A summary of the sectoral modules in FeliX is available in Extended Data Figure 1 and a detailed description is available in Supplementary Methods 1, in the original FeliX documentation\textsuperscript{46}, and in previous papers\textsuperscript{15,17}. The model and its supporting data are publicly available online (Data and Code Availability).

Pathway construction

We constructed five pathways consistent with the combinations of SSPs\textsuperscript{25,26} and the Representative Concentration Pathways (RCPs)\textsuperscript{47,48} scenarios. The SSPs and RCPs together represent the interactions of five socio-economic futures with different levels of global radiative forcing from 1.9 W m\textsuperscript{-2} to 8.5 W m\textsuperscript{-2}. Our constructed pathways represent plausible societal, technical, cultural, economic, and climatic developments playing out over the course of the 21\textsuperscript{st} century. Given the deep uncertainties inherent to the characterisation of these pathways, we simulated 10,000 realisations of each pathway (50,000 total), with each realisation representing how the pathway could unfold under one possible state of the world (Extended Data Figure 2). Pathway construction was performed in three steps:

1. **Construct pathway narratives:** We first elaborated a set of internally consistent and coherent narratives about the five pathways aligned with the assumptions under five SSP-RCP combinations from the Coupled Model Intercomparison Projects (CMIP6)\textsuperscript{49} to describe what the different futures could look like. This guided the selection of pathway drivers and their quantification (explained in the next two steps). We developed the pathway narrative for ‘Green Recovery’ consistent with SSP1-RCP2.6 — an indicative scenario for low-range greenhouse gas emissions — which had the highest potential for climate change mitigation facilitated by technology advances and strong measures for emissions reduction from the energy and land sectors. The narrative for ‘Business As Usual’ and ‘Inequality’ — two pathways with moderate mitigation challenges — was consistent with SSP2-RCP4.5 and SSP4-RCP6.0, respectively. We developed the narratives of ‘Fragmented World’ and ‘Fossil-Fuelled Development’ — indicative scenarios for high-
range emissions both with significant challenges to mitigation and weak measures for emissions reductions from energy and land sectors — consistent with SSP3-RCP7.0 and SSP5-RCP8.5, respectively.

Note that we aligned our pathways only with these five specific SSP-RCP combinations. We acknowledge that there were other potential combinations assessed in other studies that we did not investigate here. For example in Green Recovery, we aligned the pathway with SSP1-RCP2.6 as the most common level of radiative forcing for SSP1 across 715 SSP-related studies. However, Green Recovery could be also constructed inline with the pathways of more aggressive actions (e.g., EU, China, or the US pledges to comply with the Paris agreement) or more extreme mitigation (e.g., RCP1.9 or pathways proposed by the IPCC 1.5). This could make Green Recovery attain higher environmental achievements (e.g., faster reduction of fossil energy supply and emissions) compared to our study.

To construct the pathway narratives under the five SSP-RCP combinations, we elaborated on the qualitative assumptions of the original SSP storylines and their sectoral extensions. We also made assumptions describing the policy environment in both the near and long-term for climate mitigation to meet radiative forcing levels associated with each SSP. We made assumptions with respect to mitigating emissions from fossil fuels, bioenergy, and land via, for example, implementing carbon capture and storage for fossil fuels and bioenergy (BECCS) and imposing carbon price on fossil fuels. There was one set of policy assumptions associated with each pathway narrative, consistent with its inherent challenges for mitigation as outlined in Supplementary Table 1. Qualitative assumptions involved the descriptions of trends spanning socioeconomic (population, education, economy), energy and climate (demand, market share, technology advances, resources, production cost, and environmental concerns), land (land-use change, (land) productivity), food and diet (waste, consumption, and diet change), and climate mitigation policy dimensions. The details of all narratives (qualitative assumptions) are available in Supplementary Table 1.

2. Identify pathway drivers in FeliX: To quantify the socioeconomic and environmental trends of each pathway narrative, we needed to identify those model parameters (i.e., pathway drivers) that are key in the projection of these trends. To identify pathway drivers from an initial list of 114 model parameters (as potential drivers) (Supplementary Table 2), we performed a series of global sensitivity analyses to prioritise the model parameters based on their influence on key model outputs or control variables (Supplementary Table 3) whose trends were described qualitatively in the narratives (Supplementary Table 1). From several candidate global sensitivity analysis techniques, we adopted Morris elementary effects method and sensitivity index due to its ability to efficiently and effectively screen and identify benign parameters (i.e., factor fixing) from a large number of inputs in complex models. To compute , we used the SALib library implementation through the EMA workbench in the Python environment. We analysed the convergence of for each control variable across different experiment sizes over time (by 2030, 2050, and 2100) to ensure the reliability of the ranking results (Supplementary Figure 1). The sensitivity analysis
process resulted in the ranking of model parameters across control variables based on a total of 1,610,000 model evaluations (Supplementary Figure 2 and Supplementary Figure 3).

From the sensitivity ranking of 114 model parameters, we identified as pathway drivers those important parameters that captured most of the variance in SSP projections as reflected by the control variables. The Morris method however, does not provide a cut-off value on the sensitivity index to limit the ranking results to a subset of important parameters. Instead, we identified the number of influential parameters from the ranking by systematically evaluating the consequences of selecting various combinations of the top ranked parameters across the control variables. To ensure that no significant model interactions were lost by selecting a subset from the top ranked parameters, we ran two sets of Latin Hypercube Sampling experiments. In the first set of experiments, we ran FeliX many times varying only a subset of top ranked parameters, and in the second set of experiments varying all parameters, checking the degree of correlation across control variables produced by the two sets. This resulted in the identification of 60 influential parameters which we used as pathway drivers in FeliX (Extended Data Table 1 and Supplementary Table 4). The selected influential parameters were our pathway drivers which were annotated in Supplementary Figure 2. Details of the implementation are available in Supplementary Methods 2 and Supplementary Figure 4.

3. Calibrate FeliX under the pathway narratives: To define SSP-compliant pathways, we calibrated the identified drivers in FeliX under the assumptions of the SSPs and our pathways narratives (instead of using predetermined GDP and population projections as the model inputs) and also aligned with the projected radiative forcing levels with the respective RCPs. Fundamental socioeconomic drivers of pathways were calibrated based on quantitative projections of population, economic growth, and educational attainment using formal demographic and economic models (Supplementary Figure 5). We used the Powell algorithm with a payoff (i.e., objective) function in Vensim to optimise pathway drivers so as to match projections of population, economic growth, and educational attainment of the formal demographic and economic models under each SSP. The payoff was defined as the weighted difference between the model output variable ($v_M$) and the quantitative SSP estimate for the same output variable ($v_D$) at each time step $t$ ($\forall t \in T$) under each SSP ($\forall s \in S$). For each output variable $v$, a weighting factor $w$ ($\forall w \in W$) was used to normalise the influence of model parameters with different units. The payoff function $F$ was then computed following Equation 1.

$$\max F(p_i) = - \int_{t=2020}^{2100} \sum_{v \in V} (w_v(t) \times (v_M^s(t) - v_D^s(t))^2) dt$$

Equation 1

Subject to:

$$p_i \in \mathbb{U} (\forall p \in P, \forall i \in I)$$

Where $P$, $I$, and $\mathbb{U}$ denote socioeconomic drivers (related to population, economy, and education), the index of the driver, and the variation space of drivers for calibration, respectively. The calibration of FeliX’s socioeconomic drivers under each SSP involved 1000 iterations with 5 starts where the search is restarted.
from a different initialisation to avoid local minima, such that the maximum simulations per pathway calibration is 5000. To calibrate pathway drivers related to energy and climate, land-use, and food and diet, we varied the default (business-as-usual) values in line with the SSP narratives and the associated RCP radiative forcing levels. Supplementary Table 4 includes the detailed quantitative model parameter definitions, units, and assumptions and Supplementary Methods 2 has more details on the calibration process.

4. *Project pathways and validate with other IAM projections:* Using the calibrated pathway drivers, we projected future developments in population, education, economy, energy, land, food, and climate and checked these against projections of the same sectors by other research organisations and integrated assessment models as reported in the original SSP Database. Given the uncertainties inherent in the calibration of the pathway drivers, we considered parametric uncertainty in the calibrated value of the drivers and compared projected envelopes (rather than single indicative lines) with other IAMs. To create envelopes of plausible projections for each pathway, we used Latin Hypercube Sampling to randomly sample from the parameter uncertainty space of all drivers, creating 10,000 realisations (model projections) for each of five pathways. Extended Data Figure 4 and Supplementary Figure 6 characterise our modelled pathways and compare them against the projections of other IAMs.

**SDG implementation**

The SDG framework includes 17 goals and 231 unique indicators to measure progress towards 169 targets. Here we explain how we operationalised the SDGs in FeliX via selecting and modelling a subset of indicators, setting science-based targets on the selected indicators, and measuring progress towards targets at the indicator and goal level (Extended Data Figure 3).

1. *Model SDG indicators in FeliX:* We selected a list of 36 SDG indicators from the United Nations Statistical Commission (UNSC) and other sources (e.g., OECD, WHO, FAO, World Bank) based on three criteria. First, we looked at the global relevance of the potential output indicators generated by FeliX for measuring SDG progress (SDG applicability). Second, we assessed the ability of FeliX to quantify the SDG indicator (model fidelity). For those indicators that were not present in FeliX, we chose proxies. For example, we did not include an official indicator for biodiversity conservation such as the Red List Index as the required data is not produced in FeliX. Instead, we presented mean species abundance as a proxy indicator for biodiversity. Third, we ensured that the selected indicators are amenable to the specification of quantitative performance thresholds for measuring progress towards the SDGs (target relevancy). We did not include the indicators that FeliX could project such as ‘male or female population’ which could not be meaningfully interpreted in terms of progress towards the SDGs. All indicators from the global SDG indicator framework that passed these three criteria were implemented in the model (Extended Data Figure 3). Information on the methodology for computing indicator values in the model is available in Supplementary Equations 1 to 36.
2. *Set time-bound, science-driven targets for modelled indicators:* The successful evaluation of progress towards the SDGs required a science-driven characterisation of targets and a quantification of progress that can guide effective policy-making. We defined nine different targets for each indicator using a mixed method approach to acknowledge the uncertainty around each target and the high sensitivity of SDG assessment to target specification. First, we set three target levels across the selected indicators: weak, moderate, and ambitious. At each level, we also set three time-bound targets to measure the progress by 2030, 2050, and 2100. We defined the ambitious target level across these target years following a decision tree (Extended Data Figure 3).

First, we used available quantitative thresholds that were explicitly reflected in the official SDG framework (SDG absolute threshold) to set targets (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 ‘GDP per capita’ indicator.

Second, if an explicit target was not mentioned in the SDG framework, we used a technical optimum to set targets (27 indicators). We used targets, wherever relevant, that were identified in other scientific journal articles, global reports, and online databases. For example, we used the IPCC’s levels of radiative forcing for keeping the global temperature below 1.5 degree °C as target levels for the ‘radiative forcing’ indicator. The sources used for setting the technical optimum targets along with the justification for the value each target are available in Supplementary Table 5.

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 (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 agricultural arable land can have very low levels of fertilizer application. Therefore, the 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 larger contribution to global food production. Where performance data was not available at the country level, we used regional data (e.g., OECD, continents).

Fourth, in the absence of any relevant targets, we nominally set a proportional improvement target in the indicator value from the world average in a base year guided by historical data (global improvement) (1 indicator). For example, ‘total CO₂ 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. The base year for improvement can vary between indicators depending on the availability of data. The decision about the improvement rate from the base year value was made on a case-by-case basis for each indicator in a range between 5% improvement (e.g., in reducing CO₂ emissions from
land-use) to 50% improvement (e.g., reducing coal production) from the global average as the 2030 ambitious target. The reduction or increase percentage was also informed by other model-based projections of SSPs to set an improvement rate ambitious enough to surpass the current trends while still being achievable.

For the moderate and weak target levels (across all three target years), we assumed that the moderate and weak indicate 50% and 25% progress towards the ambitious target from the base year value in 2015 with the exception of indicators for which moderate and weak targets were already available in the literature (e.g., radiative forcing from CO₂ emissions). Extended Data Table 2 presents the target values at weak, moderate, and ambitious levels, in 2030, 2050, and 2100 for all modelled indicators, and Supplementary Table 5 explains the justifications of the set targets.

3. Measure progress towards targets: We normalised indicator with different scales and units of measurement to ensure comparability and consistent interpretation. For each target level (i.e., weak, moderate, ambitious) and at each target year (i.e., 2030, 2050, 2100), we normalised 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 normalised based on the rescaling formula in Equation 2.

\[
I_{ij} = \frac{x_i - w_i}{t_i - w_i} \times 100
\]

Equation 2

Where \(I_{ij}\) is the computed normalised 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 (see Data and Code Availability). We then aggregated the normalised indicator values into an index score to represent global progress towards each SDG (Equation 3).

\[
I'_j = \frac{\sum_{i=1}^{N_j} I_{ij}}{N_j}
\]

Equation 3

Where \(I'_j\) is the SDG \(j\) and \(N_j\) is the number of modelled indicators under goal \(j\). The index and its methodology were adopted from a similar index used in the global monitoring of the SDG progress\(^3\). 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\(^78\). Based on the normalised values at the indicator level and aggregated indices at the goal level, we measured world progress towards targets at four levels. **On track** indicates that progress highly likely to achieve (or exceed) global sustainability targets (i.e., indicator and goal level target achievement \(\geq 100\%\)). **Improving** indicates positive
trends towards 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%). Wrong direction indicates a deteriorating trend (i.e., target achievement between $\leq$0%).

Pathway-SDG evaluation

We evaluated the five pathways in terms of the modelled indicators and progress towards the SDG targets through exploratory ensemble modelling. In evaluating pathways across the SDGs, we simulated 50,000 world realisations (10,000 model evaluations per pathway) to capture plausible progress in response to the uncertainty in the characterisation of pathways and the sensitivity of progress to the number of indicators and target levels. We then interpreted each pathway’s performance under uncertainty in terms of percentage of simulated realisations.

Our evaluation had four steps. First, we initially looked at the performance of simulated pathways towards the targets at the indicator level over time (Extended Data Figure 5) to investigate the ambition and achievability of targets. Here, we analysed the projected value of modelled indicators, in their real units of measurement, under each simulated pathway (and its realisations) in relation to targets at three timesteps (i.e., 2030, 2050, 2100). Second, we analysed the normative value of the projected indicators (in 2030, 2050, and 2100) under each modelled pathway to measure and compare the progress across all targets consistently with a single unit (i.e., percentage of gap from target) (Figure 1). Third, we aggregated the indicators’ normalised values towards targets and measured the overall progress under each pathway at the goal level to account for possible synergies and trade-offs between the multiple modelled targets under each SDG (Figure 2). Fourth, from the comparison of pathway’s performance across goals and targets and over time, we identified the most promising pathway (i.e., Green Recovery) in the 21st century. We then characterised this identified pathway across multiple sectors (e.g., population, education, decarbonisation, food) and quantified the steps to be taken from the business-as-usual trajectories to realise the identified pathway (Figure 3).

Data and Code Availability

Results are available at https://github.com/enayatmoallemi/Moallemi_et_al_SDG_SSP_Assessment.

Data and Code Availability The full code and datasets generated are available at https://github.com/enayatmoallemi/Moallemi_et_al_SDG_SSP_Assessment.
Methods references

45. Rydzak, F., Obersteiner, M. & Kraxner, F. Impact of global Earth observation systemic view across GEOSS societal benefit area. *Int. J. Spat. Data Infrastruct. Res.*, 216–243 (2010).

46. Rydzak, F., Obersteiner, M., Kraxner, F., Fritz, S. & McCallum, I. FeliX3 – Impact Assessment Model Systemic view across Societal Benefit Areas beyond Global Earth Observation (Model Report and Technical Documentation). (International Institute for Applied Systems Analysis (IIASA), Laxenburg, 2013).

47. van Vuuren, D. P. et al. The representative concentration pathways: an overview. *Clim. Change* **109**, 5, doi:10.1007/s10584-011-0148-z (2011).

48. Meinshausen, M. et al. The shared socio-economic pathway (SSP) greenhouse gas concentrations and their extensions to 2500. *Geosci. Model Dev.* **13**, 3571-3605, doi:10.5194/gmd-13-3571-2020 (2020).

49. O'Neill, B. C. et al. The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6. *Geosci. Model Dev.* **9**, 3461-3482, doi:10.5194/gmd-9-3461-2016 (2016).

50. O'Neill, B. C. et al. Achievements and needs for the climate change scenario framework. *Nat. Clim. Change.* **10**, 1074-1084, doi:10.1038/s41558-020-00952-0 (2020).

51. Rogelj, J. et al. Mitigation pathways compatible with 1.5 C in the context of sustainable development. In: Global Warming of 1.5 °C an IPCC special report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change. (Intergovernmental Panel on Climate Change (IPCC), 2018).

52. Kriegler, E. et al. Fossil-fueled development (SSP5): An energy and resource intensive scenario for the 21st century. *Global Environ. Change* **42**, 297-315 (2017).

53. Calvin, K. et al. The SSP4: A world of deepening inequality. *Global Environ. Change* **42**, 284-296 (2017).

54. Bauer, N. et al. Shared Socio-Economic Pathways of the Energy Sector – Quantifying the Narratives. *Global Environ. Change* **42**, 316-330 (2017).

55. Popp, A. et al. Land-use futures in the shared socio-economic pathways. *Global Environ. Change* **42**, 331-345, doi:https://doi.org/10.1016/j.gloenvcha.2016.10.002 (2017).

56. Samir, K. C. & Lutz, W. The human core of the shared socioeconomic pathways: Population scenarios by age, sex and level of education for all countries to 2100. *Global Environ. Change* **42**, 181-192 (2017).

57. Dellink, R., Chateau, J., Lanzi, E. & Magné, B. Long-term economic growth projections in the Shared Socioeconomic Pathways. *Global Environ. Change* **42**, 200-214 (2017).

58. Cuaresma, J. C. Income projections for climate change research: A framework based on human capital dynamics. *Global Environ. Change* **42**, 226-236 (2017).

59. Jiang, L. & O'Neill, B. C. Global urbanization projections for the Shared Socioeconomic Pathways. *Global Environ. Change* **42**, 193-199 (2017).

60. Jaxa-Rozen, M. & Kwakkel, J. Tree-based ensemble methods for sensitivity analysis of environmental models: A performance comparison with Sobol and Morris techniques. *Environ. Model. Software* **107**, 245-266, doi:https://doi.org/10.1016/j.envsoft.2018.06.011 (2018).

61. Morris, M. D. Factorial Sampling Plans for Preliminary Computational Experiments. *Technometrics* **33**, 161-174, doi:10.2307/1269043 (1991).

62. Campolongo, F., Cariboni, J. & Saltelli, A. An effective screening design for sensitivity analysis of large models. *Environ. Model. Software* **22**, 1509-1518, doi:https://doi.org/10.1016/j.envsoft.2006.10.004 (2007).
63. Herman, J. D., Kollat, J. B., Reed, P. M. & Wagener, T. Technical Note: Method of Morris effectively reduces the computational demands of global sensitivity analysis for distributed watershed models. *Hydrol. Earth Syst. Sci.* 17, 2893-2903, doi:10.5194/hess-17-2893-2013 (2013).

64. Herman, J. & Usher, W. SALib: An open-source Python library for Sensitivity Analysis. *Journal of Open Source Software* 9, doi:10.21105/joss.00097 (2017).

65. Kwakkel, J. H. The Exploratory Modeling Workbench: An open source toolkit for exploratory modeling, scenario discovery, and (multi-objective) robust decision making. *Environ. Model. Software* 96, 239-250, doi:http://dx.doi.org/10.1016/j.envsoft.2017.06.054 (2017).

66. Hadjimichael, A. Factor prioritization and factor fixing: how to know what’s important. doi:10.5281/zenodo.4030955 (2020).

67. Powell, M. J. D. An efficient method for finding the minimum of a function of several variables without calculating derivatives. *The Computer Journal* 7, 155-162, doi:10.1093/comjnl/7.2.155 (1964).

68. Leimbach, M., Kriegler, E., Romaning, N. & Schwanitz, J. Future growth patterns of world regions – A GDP scenario approach. *Global Environ. Change* 42, 215-225 (2017).

69. Fricko, O. *et al.* The marker quantification of the Shared Socioeconomic Pathway 2: A middle-of-the-road scenario for the 21st century. *Global Environ. Change* 42, 251-267, doi:https://doi.org/10.1016/j.gloenvcha.2016.06.004 (2017).

70. Fujimori, S. *et al.* SSP3: AIM implementation of Shared Socioeconomic Pathways. *Global Environ. Change* 42, 268-283, doi:https://doi.org/10.1016/j.gloenvcha.2016.06.009 (2017).

71. IIASA. *SSP (Shared Socioeconomic Pathways) Database*, <https://tntcat.iiasa.ac.at/SspDb>. International Institute for Applied Systems Analysis (2018).

72. UNSC. *United Nations Global SDG Database*, <https://unstats.un.org/sdgs/indicators/database/>. United Nations Statistical Commission (2020).

73. OECD. *OECD.Stat*, <https://stats.oecd.org/>. Organisation for Economic Co-operation and Development (2020).

74. WHO. *WHO data collections*, <https://www.who.int/data/collections>. The World Health Organization (2020).

75. FAOSTAT. *Food and land-use data*, <http://www.fao.org/faostat/en/#home>. Food and Agriculture Organization of the United Nations (2020).

76. The World Bank. *World Bank Open Data*, <https://data.worldbank.org/>.

77. Maxwell, S. L. *et al.* Being smart about SMART environmental targets. *Science* 347, 1075, doi:10.1126/science.aaal451 (2015).

78. Lafortune, G., Fuller, G., Moreno, J., Schmidt-Traub, G. & Kroll, C. SDG Index and Dashboards: Detailed Methodological paper. (The Sustainable Development Solutions Network (SDSN), 2018).

79. van Zeist, W.-J. *et al.* Are scenario projections overly optimistic about future yield progress? *Global Environ. Change* 64, 102120, doi:https://doi.org/10.1016/j.gloenvcha.2020.102120 (2020).

80. Doelman, J. C. *et al.* Exploring SSP land-use dynamics using the IMAGE model: Regional and gridded scenarios of land-use change and land-based climate change mitigation. *Global Environ. Change* 48, 119-135, doi:https://doi.org/10.1016/j.gloenvcha.2017.11.014 (2018).

81. Springmann, M. *et al.* Options for keeping the food system within environmental limits. *Nature* 562, 519-525, doi:10.1038/s41586-018-0594-0 (2018).
82. Dinerstein, E. et al. A Global Deal For Nature: Guiding principles, milestones, and targets. *Sci. Adv.* 5, eaaw2869, doi:10.1126/sciadv.aaw2869 (2019).

83. IPCC. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. (IPCC, Geneva, Switzerland, 2014).

84. UNDP. *Human Development Report*, <http://hdr.undp.org/en/data>. United Nations Development Programme (2020).

85. UNESCO. *UIS.Stat*, <http://data.uis.unesco.org/>. The UNESCO Institute for Statistics (2020).

86. Lamontagne, J. R., Reed, P. M., Marangoni, G., Keller, K. & Garner, G. G. Robust abatement pathways to tolerable climate futures require immediate global action. *Nat. Clim. Change.* 9, 290–294, doi:10.1038/s41558-019-0426-8 (2019).

87. IFA. *IFASTAT: Fertilizer supply and consumption*, <https://www.ifastat.org/databases>. International Fertilizer Association (2020).

88. UNFCCC. *Greenhouse Gas Inventory Data*, <https://di.unfccc.int/detailed_data_by_party>. The United Nations Framework Convention on Climate Change (2020).

89. CBD. Cross-Roads of Life on Earth Exploring means to meet the 2010 Biodiversity Target: Solution-oriented scenarios for Global Biodiversity Outlook 2. (Secretariat of the Convention on Biological Diversity 2007).

90. Oita, A. et al. Substantial nitrogen pollution embedded in international trade. *Nat. Geosci.* 9, 111-115, doi:10.1038/ngeo2635 (2016).
Acknowledgements

This research was funded by The Ian Potter Foundation and Deakin University.

Author contributions

E.A.M. designed the study, enhanced the (original) model, and led the experiment runs, analysis, and writing of the article. S.K., L.G. contributed to the model development, design of the study, and analysis. M.H., J.K., and P.M.R. contributed equally to the analysis of the results. M.O. contributed to the (early version of) model development and analysis. B.A.B. contributed to the design of the study, analysis, and writing of the article. All authors contributed to the final editing.

Additional information

Supplementary Information is available for this paper.

Correspondence and requests for materials should be addressed to E.A.M. or B.A.B.

Peer review information Unspecified.

Reprints and permissions information is available at www.nature.com/reprints.
Extended data

Extended Data Figure 1. The overview of the FeliX model. The grey shaded boxes represent different sectoral modules in FeliX. The square and triangle markers show where in the model the SDG indicators and pathway drivers were implemented. The marker colours are consistent with their corresponding SDG colour. 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, vegetable, roots, and fruits. Fossil fuels include coal, gas, and oil. Energy includes fossil and renewable (solar, wind, biomass) energies. Diet categories include five diet compositions of high (low) to low (high) meat (vegetable) consumptions.
Extended Data Table 1. Descriptions of modelled pathway drivers in FeliX. In the first column, pathway drivers (e.g., population growth) are categorised into socioeconomic, energy and climate, land, and food and diet change in relation to their impacts on different SDGs. Each pathway driver is associated with a number of model parameters in FeliX. The fraction value in front each pathway driver in the first column shows the number of influential model parameters (that were identified through sensitivity analysis) to the total number of parameters modelled in FeliX. For example, we modelled ‘economic growth’ through five uncertain parameters two of which were identified as influential to be included in the quantification of pathways. From the second to the sixth column, the triangles qualitatively represent the direction and magnitude of change in the calibrated pathway drivers. The signs $\uparrow$ represents a strong increase, $\downarrow$ increase, $\Uparrow$ no change from business-as-usual, $\downarrow$ is decrease, and $\downarrow$ is strong decrease. The last column shows the effect of each driver on the related SDGs. ‘P’ and ‘D’ indicate that the increasing drive has pressurising (i.e., creating barriers) and depressurising (i.e., facilitating) effects on related SDGs respectively. See Supplementary Table 4 for the full list of parameters and their calibrated values in FeliX.

| Pathway drivers (modelled parameters: 114; selected parameters: 60) | Socioeconomic (SDGs 3, 4, 7, 8, 12, 13, 15) | Energy and climate (SDGs 7, 12, 13) | Land (SDGs 2, 13, 15) | Food and diet change (SDGs 2, 12, 15) |
|---|---|---|---|---|
| Population growth (3/3 parameters) | $\downarrow$ | $\Uparrow$ | $\Uparrow$ | $\downarrow$ | P |
| Higher Educational attainment (8/8 parameters) | $\downarrow$ | $\Uparrow$ | $\downarrow$ | $\downarrow$ | D |
| Economic growth (2/5 parameters) | $\downarrow$ | $\Uparrow$ | $\downarrow$ | $\downarrow$ | P, D |
| Energy demand (1/1 parameter) | $\downarrow$ | $\Uparrow$ | $\uparrow$ | $\downarrow$ | P |
| Market share of fossil energy consumption (9/9 parameters) | $\downarrow$ | $\Uparrow$ | $\Uparrow$ | $\downarrow$ | P |
| Fossil fuels recovery and exploration technology development (3/9 parameters) | $\downarrow$ | $\Uparrow$ | $\downarrow$ | $\downarrow$ | P |
| Investment in fossil fuels (8/8 parameters) | $\downarrow$ | $\Uparrow$ | $\downarrow$ | $\downarrow$ | P |
| Fossil fuel resource availability (3/3 parameters) | $\downarrow$ | $\Uparrow$ | $\downarrow$ | $\downarrow$ | P |
| Renewable energy technology investment and efficiency (3/10 parameters) | $\downarrow$ | $\Uparrow$ | $\downarrow$ | $\downarrow$ | D |
| Renewable energy production costs (2/7 parameters) | $\downarrow$ | $\Uparrow$ | $\downarrow$ | $\downarrow$ | D |
| Use of carbon capture and storage (1/2 parameters) | $\downarrow$ | $\Uparrow$ | $\downarrow$ | $\downarrow$ | D |
| Limit on emissions from fossil fuels (1/2 parameters) | $\downarrow$ | $\Uparrow$ | $\downarrow$ | $\downarrow$ | D |
| Deforestation (4/15 parameters) | $\downarrow$ | $\Uparrow$ | $\downarrow$ | $\downarrow$ | P |
| Land (crop, livestock, forest) productivity growth (2/9 parameters) | $\downarrow$ | $\Uparrow$ | $\downarrow$ | $\downarrow$ | D |
| Food waste (3/3 parameters) | $\downarrow$ | $\Uparrow$ | $\downarrow$ | $\downarrow$ | P |
| Food consumption (2/5 parameters) | $\downarrow$ | $\Uparrow$ | $\downarrow$ | $\downarrow$ | P |
| Sustainable diet change (5/15 parameters) | $\downarrow$ | $\Uparrow$ | $\downarrow$ | $\downarrow$ | D |
Extended Data Figure 2. Methodological steps in the model-based assessments of the SDGs under global pathways.

Pathway construction

**Construct pathway narratives**
- Develop 5 qualitative assumptions for socioeconomic and environmental drivers aligned with five SSP-RCP combinations.

**Identify pathway drivers**
- Identify 60 important model parameters (i.e., pathway drivers) in FeliX for the narratives through global sensitivity analysis.

**Calibrate pathway drivers**
- Calibrate FeliX’s socioeconomic, energy and climate, land-use, and food and diet scenario drivers under the assumptions of five pathway (SSP-RCP) narratives.

**Validate simulated pathways**
- Validate the simulated pathway projections with the SSP-RCP projections of other IAMs across 20 control variables.

SDG implementation

**Model SDG indicators**
- Model 36 SDG indicators across 8 SDGs in FeliX within the model scope.

**Set targets on indicators**
- Identify 9 target values (3 target levels x 3 target years) for each indicator based on original SDG framework, science-based metrics, the ‘leave no one behind’ principle.

**Measure progress (indicator level)**
- Normalise the indicators’ projections and targets between 0% and 100% and computing the distance taken from 2015 and the gap to achieve the targets.

**Measure progress (goal level)**
- Aggregate the normalised values of indicators into a SDG index and measuring the progress at the goal level between 0% and 100%.

Pathway-SDG evaluation

**Explore pathway x SDG interactions under uncertainty**
- Evaluate 50,000 realisations of pathways with respect to the targets for each indicator and aggregated in each SDG.
- Assessing comparative performance of pathways in meeting the targets under uncertainty.

**Elaborate the change need to achieve the post-2030 SDGs**
- Characterise the post-2030 transformative change based on the deviation of the best performing pathway from business-as-usual.
Extended Data Figure 3. Decision trees for selecting SDG indicators to model in FeliX and for setting targets on the modelled indicators. United Nations Statistical Commission (UNSC)\(^7\), The Food and Agriculture Organization of the United Nations (FAO)\(^7\), The Organisation for Economic Co-operation and Development (OECD)\(^3\), The International Fertilizer Association (IFA)\(^7\), The United Nations Educational, Scientific and Cultural Organisation (UNESCO)\(^8\), The World Health Organization (WHO)\(^7\), The United Nations Framework Convention on Climate Change (UNFCCC)\(^8\), The Intergovernmental Panel on Climate Change (IPCC)\(^8\), The Secretariat of the Convention on Biological Diversity (CBD)\(^9\), The Sustainable Development Solutions Network (SDSN)\(^1\), The World Bank\(^9\).

Extended Data Figure 3. Decision trees for selecting SDG indicators to model in FeliX and for setting targets on the modelled indicators.
Extended Data Figure 4. Characterisation of the modelled pathways and their comparison against the projections of major demographic and economic models\textsuperscript{56,57} and integrated assessment models\textsuperscript{23,26,52-55,70}. Felix projections cover the period 2020-2100 at an annual time step, calibrated based on assumptions described in Methods.
Extended Data Figure 5. Performance of global pathways towards SDG targets in 2100 under five SSP-compliant pathways.

Results for the performance of each pathway are represented by a specifically colour coded violin plot and boxplot. The violin shows the distribution of pathway’s performance across 10,000 simulated realisations of each pathway. The box shows the interquartile 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 coloured lines mark weak, moderate, and ambitious targets in 2100 (Extended Data Table 2). The red and blue (discrete) colour gradients 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.
Extended Data Figure 6. Performance of global pathways towards SDG targets in 2050 under five SSP-compliant pathways.
Extended Data Figure 7. Performance of global pathways towards SDG targets in 2030 under five SSP-compliant pathways.
### Extended Data Table 2. 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 Methods for the target setting process. Supplementary Table 5 for the justification of the method used for target setting in each indicator, and Supplementary Equations 1 to 36 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**<br>Target 2.4. By 2030, ensure sustainable food production systems and implement resilient agricultural practices |  |  |
| Improve the productivity of the croplands | *Cereal Yield (tons year\(^{-1}\) ha\(^{-1}\))* | SDSN, FAO<br>The annual production rate per hectare of harvested croplands dedicated to cereal (pulses and grains) production. | Technical optimum\(^7\)<br>2030 2050 2100<br>Ambitious 5.76 6.48 8.28<br>Moderate 4.90 5.26 6.16<br>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<br>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\(^8\)<br>2030 2050 2100<br>Ambitious 2484 2588 2809<br>Moderate 2404 2617 2727<br>Weak 2364 2631 2686 |  |
| | *Animal Food supply (kcal capita\(^{-1}\) day\(^{-1}\))* | FAO<br>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\(^8\)<br>2030 2050 2100<br>Ambitious 403 361 331<br>Moderate 419 398 383<br>Weak 427 417 409 |  |
| | *Total Food Supply (kcal capita\(^{-1}\) day\(^{-1}\))* | FAO<br>The total annual production of animal and vegetal foods per person per day. | Technical optimum\(^8\)<br>2030 2050 2100<br>Ambitious 2887 2949 3139<br>Moderate 2984 3015 3110<br>Weak 3032 3047 3095 |  |
| Reduce pressure on lands from food production and agricultural activities | *Ratio of Agricultural Lands to Total Lands (-)* | FAO<br>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\(^3\)<br>2030 2050 2100<br>Ambitious 0.5372 0.5135 0.4899<br>Moderate 0.5395 0.5276 0.5159<br>Weak 0.5406 0.5347 0.5288 |  |
| | *Pasture Land Indicator (million ha)* | IIASA<br>Total available permanent pasture and meadow lands. | Technical optimum\(^3\)<br>2030 2050 2100<br>Ambitious 3103 2787 2404<br>Moderate 3184 3026 2835<br>Weak 3225 3146 3050 |  |
| | *Total Croplands Indicator (million ha)* | IIASA<br>Total land allocated for energy and food (and feed) crops. | Technical optimum\(^3\)<br>2030 2050 2100<br>Ambitious 1482 1523 1765<br>Moderate 1540 1560 1849<br>Weak 1568 1579 1807 |  |
| **Goal 3. Ensure healthy lives and promote well-being for all at all ages**<br>Target 3.3. End the epidemics of communicable diseases<br>Target 3.4. Reduce one third premature mortality from non-communicable diseases |  |  |
| Increase life expectancy and advance human wellbeing and richness of life | *Life Expectancy (year)* | SDSN, WHO, World Bank<br>The average life expectancy of the population. | Leave no one behind\(^6\)<br>2030 2050 2100<br>Ambitious 75 84 92<br>Moderate 73 77 81<br>Weak 71 73 75 |  |
| | *Human Development Index (-)* | UNDP<br>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\(^4\)<br>2030 2050 2100<br>Ambitious 0.85 0.94 1.00<br>Moderate 0.78 0.82 0.85<br>Weak 0.74 0.76 0.78 |  |
Target 3.7. By 2030, ensure universal access to sexual and reproductive health-care services

| Indicator                                                                 | Leave no one behind | Ambitious | Moderate | Weak |
|--------------------------------------------------------------------------|---------------------|-----------|----------|------|
| Adolescent Fertility Rate (person year^{-1} 1000women^{15}) | 2030: 27.55 2050: 13.78 2100: 0.00 | 2030: 37.50 2050: 28.57 2100: 21.68 | 2030: 35.46 2050: 28.57 2100: 21.68 | 2030: 39.41 2050: 35.97 2100: 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

| Indicator                                                                 | Leave no one behind | Ambitious | Moderate | Weak |
|--------------------------------------------------------------------------|---------------------|-----------|----------|------|
| Mean Years of Schooling (number of years) | 2030: 10.56 2050: 10.90 2100: 11.23 | 2030: 13.44 2050: 14.78 2100: 16.13 | 2030: 11.52 2050: 12.19 2100: 12.86 | 2030: 10.56 2050: 10.90 2100: 11.23 |

4.3 By 2030, ensure equal access for all women and men to affordable and quality technical, vocational and tertiary education

| Indicator                                                                 | Leave no one behind^4 | Ambitious | Moderate | Weak |
|--------------------------------------------------------------------------|-----------------------|-----------|----------|------|
| Female to Male Enrolment in Tertiary Education (-) | 2030: 0.90 2050: 0.96 2100: 0.96 | 2030: 0.90 2050: 0.96 2100: 0.96 | 2030: 0.90 2050: 0.96 2100: 0.96 | 2030: 0.85 2050: 0.85 2100: 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

| Indicator                                                                 | Technical optimum^1 | Ambitious | Moderate | Weak |
|--------------------------------------------------------------------------|---------------------|-----------|----------|------|
| Share of Renewable Energy Supply (%) | 2030: 28.57 2050: 42.67 2100: 75.28 | 2030: 28.57 2050: 42.67 2100: 75.28 | 2030: 28.57 2050: 42.67 2100: 75.28 | 2030: 28.57 2050: 42.67 2100: 75.28 |

| Indicator                                                                 | Technical optimum^5 | Ambitious | Moderate | Weak |
|--------------------------------------------------------------------------|---------------------|-----------|----------|------|
| Solar Energy Production Indicator (EJ year^{-1}) | 2030: 5.70 2050: 22.60 2100: 70.50 | 2030: 5.70 2050: 22.60 2100: 70.50 | 2030: 5.70 2050: 22.60 2100: 70.50 | 2030: 5.70 2050: 22.60 2100: 70.50 |

| Indicator                                                                 | Technical optimum^1 | Ambitious | Moderate | Weak |
|--------------------------------------------------------------------------|---------------------|-----------|----------|------|
| Wind Energy Production Indicator (EJ year^{-1}) | 2030: 5.70 2050: 22.60 2100: 70.50 | 2030: 5.70 2050: 22.60 2100: 70.50 | 2030: 5.70 2050: 22.60 2100: 70.50 | 2030: 5.70 2050: 22.60 2100: 70.50 |

| Indicator                                                                 | Technical optimum^5 | Ambitious | Moderate | Weak |
|--------------------------------------------------------------------------|---------------------|-----------|----------|------|
| Biomass Energy Production Indicator (EJ year^{-1}) | 2030: 5.70 2050: 22.60 2100: 70.50 | 2030: 5.70 2050: 22.60 2100: 70.50 | 2030: 5.70 2050: 22.60 2100: 70.50 | 2030: 5.70 2050: 22.60 2100: 70.50 |

| Indicator                                                                 | Technical optimum^1 | Ambitious | Moderate | Weak |
|--------------------------------------------------------------------------|---------------------|-----------|----------|------|
| Oil Production Indicator (EJ year^{-1}) | 2030: 5.70 2050: 22.60 2100: 70.50 | 2030: 5.70 2050: 22.60 2100: 70.50 | 2030: 5.70 2050: 22.60 2100: 70.50 | 2030: 5.70 2050: 22.60 2100: 70.50 |

| Indicator                                                                 | Technical optimum^5 | Ambitious | Moderate | Weak |
|--------------------------------------------------------------------------|---------------------|-----------|----------|------|
| Decrease fossil energy share in the total final energy supply | 2030: 5.70 2050: 22.60 2100: 70.50 | 2030: 5.70 2050: 22.60 2100: 70.50 | 2030: 5.70 2050: 22.60 2100: 70.50 | 2030: 5.70 2050: 22.60 2100: 70.50 |
**Goal 12. Ensure sustainable consumption and production patterns**

| Indicator (unit) | Technical optimum | Goal achievement by 2030 | Goal achievement by 2050 | Goal achievement by 2100 |
|-----------------|-------------------|--------------------------|--------------------------|--------------------------|
| CO₂ Emissions per GWP (kg CO₂ $⁻¹$) | 2030 2050 2100 | 106.35 134.09 119.05 | 138.56 143.84 112.76 | 112.76 106.35 100.39 |
| Nitrogen Fertilizer Use in Agriculture (million tons N year⁻¹) | 2030 2050 2100 | 106.35 134.09 119.05 | 143.84 138.56 119.05 | 138.56 106.35 100.39 |
| Phosphorus Fertilizer Use in Agriculture (million tons P year⁻¹) | 2030 2050 2100 | 106.35 134.09 119.05 | 143.84 138.56 119.05 | 138.56 106.35 100.39 |
| Agro Food Nitrogen Production Footprint (kg year⁻¹ person⁻¹) | 2030 2050 2100 | 106.35 134.09 119.05 | 143.84 138.56 119.05 | 138.56 106.35 100.39 |

**Goal 13. Take urgent action to combat climate change and its impacts**

| Indicator (unit) | Technical optimum | Goal achievement by 2030 | Goal achievement by 2050 | Goal achievement by 2100 |
|-----------------|-------------------|--------------------------|--------------------------|--------------------------|
| Atmospheric Concentration CO₂ (ppm) | 2030 2050 2100 | 106.35 134.09 119.05 | 143.84 138.56 119.05 | 138.56 106.35 100.39 |
| 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 |
| **Stop biodiversity extinction from human activities and climate change** |
| **Mean Species Abundance (%)** | CBD |
| Mean abundance of measures the compositional integrity 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 |
Supplementary information

Access: Moallemi, Enayat A., Eker, Sibel, Gao, Lei, Hadjikakou, Michalis, Kwakkel, Jan, Reed, Patrick M., … Bryan, Brett A. (2020, December 8). Supplementary Information for the Manuscript "Global pathways to sustainable development to 2030 and beyond” (Version Submitted-v1). Zenodo. http://doi.org/10.5281/zenodo.4311139

Supplementary Methods

- Supplementary Methods 1. The FeliX model
- Supplementary Methods 2. Pathway construction
- Supplementary Methods 3. SDG implementation

Supplementary Tables

- Supplementary Table 1. The narratives of future pathways framed by the five SSPs-RCPs.
- Supplementary Table 2. The list of candidate uncertain model parameters identified in relation to pathway drivers.
- Supplementary Table 3. Control variables used in analysing the sensitivity of future projections to the candidate uncertain model parameters.
- Supplementary Table 4. The list of important uncertain model parameters and their quantification under future pathways.
- Supplementary Table 5. The description of indicators and the justification of the targets set on each indicator.

Supplementary Equations

- Supplementary Equations 1 to 36

Supplementary Figures

- Supplementary Figure 1. The convergence of parameter ranking and sensitivity index for the increasing number of experiments across 20 control variable.
- Supplementary Figure 2. The sensitivity of model parameters in FeliX across 20 control variables in year 2100.
- Supplementary Figure 3. The sensitivity of model uncertain parameters in FeliX across 20 control variables in 2030 and 2050.
- Supplementary Figure 4. The gradual increase in the correlation coefficient between Sets 1 and 2 and the gradual reduction in the correlation coefficient between Sets 1 and 3 in the top n important parameters.
- Supplementary Figure 5. Quantified projection of population, educational attainment, and GDP using demographic and economic models.
- Supplementary Figure 6. Characterisation of the modelled pathways and their comparison against the projections of other models.
- Supplementary Figure 7. Progress towards ambitious (a, b, c) and weak (d, e, f) targets on indicators by 2030 (a, d), 2050 (b, e), and 2100 (c, f) across 50,000 simulated world realisations.