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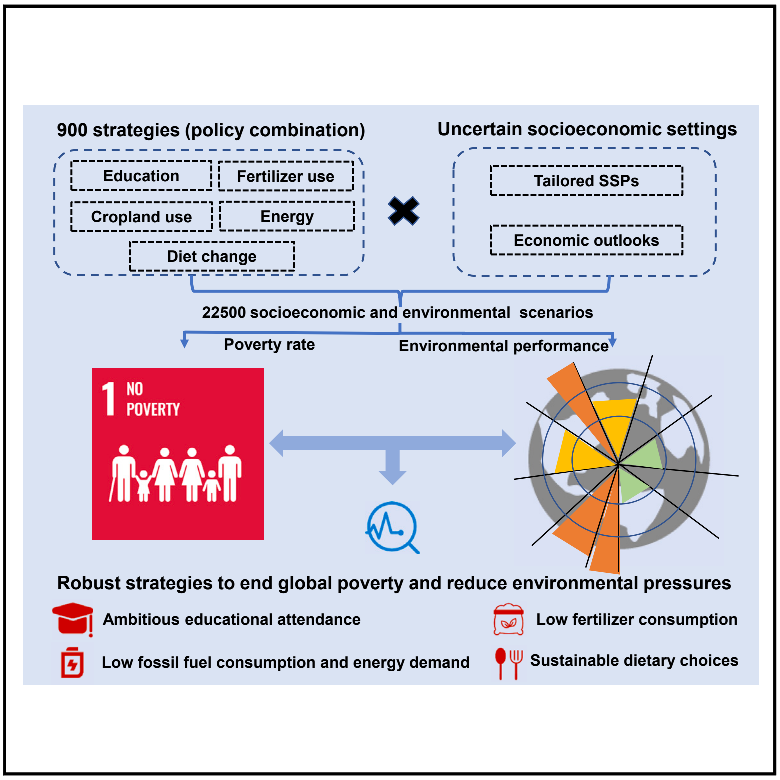
Robust strategies to end global poverty and reduce environmental pressures

Graphical abstract



Highlights

- We analyze global poverty and environmental pressures affected by 900 strategies
- A strategy is composed of policies from five poverty and sustainability dimensions
- Eradicating extreme poverty will require more than two decades
- Two robust strategies can end global poverty while reducing environmental risks

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In brief

Eradicating poverty remains a grand global challenge, and inappropriate poverty reduction policies can lead to environmental degradation. Our study shows that global extreme poverty would not be eradicated until 2049 under the current trend, lagging behind the target set by the United Nations by 19 years. Through taking concerted global actions of improving education, shifting to a plant-oriented diet, and reducing fossil-fuel consumption, energy demand, and fertilizer use, we can eradicate poverty sooner while reducing environmental pressures.

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Robust strategies to end global poverty and reduce environmental pressures

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SCIENCE FOR SOCIETY The UN Sustainable Development Goals aim to end poverty in all its forms by 2030, which seems to be unachievable given current trends. Various poverty reduction drivers have been suggested to accelerate progress; however, some might lead to environmental degradation and exceedance of the biophysical safe operating space for the Earth system. We find two effective global strategies that could offset humanity's negative impacts on the Earth system without compromising poverty eradication gains. To meet these dual objectives, the international community needs to move toward a future guided by integrated policy packages supporting strong economic development, ambitious educational attendance, sustainable dietary choices, low fossil fuel consumption and energy demand, and lower fertilizer consumption. Enhanced policy coordination by global and regional decision-makers appears to be paramount to avoid unforeseen environmental deterioration while implementing poverty eradication policies.

SUMMARY

Eradicating extreme poverty everywhere by 2030 has proved to be challenging. Uplifting millions out of poverty might lead to exceeding the Earth's environmental boundaries. Using a global integrated assessment model, we assess the effectiveness of 900 strategies under 25 socioeconomic settings in eliminating poverty and quantify their impacts on the Earth system by 2050. Our reference scenario, which follows a post-pandemic economic trend with an annual economic growth rate of 2.05%, projects an extreme poverty rate of 7.34% (uncertainty range 6.29%–8.73%) in 2030. Even under optimistic settings, it may take over two decades to eradicate extreme poverty. Focusing more on environmental drivers of poverty and following historical trends in fiscal policies and social safety nets, we identified two robust strategies characterized by ambitious educational attendance, sustainable dietary choices, low fossil fuel consumption and energy demand, and low fertilizer use, which offset negative environmental effects without compromising the poverty eradication gains.

INTRODUCTION

Ending poverty is the first of the 17 Sustainable Development Goals (SDGs) of the United Nations (UN). Following decades of effort to fight poverty, the global population living in extreme poverty (i.e., surviving on less than $1.90 per person per day at 2011 purchasing power parity) dropped from 44% in 1981 to just under 8% by 2019.[1] However, the pace of poverty reduction has slowed, and poverty eradication remains a grand challenge facing the world today.[2–6] SDG 1, i.e., eradicating extreme poverty for all people by 2030, is currently thought to be unachievable without significant intervention.[1,5,7] Moreover, the socioeconomic upheaval caused by the COVID-19 pandemic and the 2022 Russia-Ukraine war are expected to increase the number of people facing extreme poverty and risks wiping out the gains made toward eradicating worldwide poverty over recent decades.[8–11]

A variety of poverty reduction drivers (policies) have been identified in the literature, including economic growth[12–14]; better educational development[15]; sufficient energy use[16]; agricultural productivity growth[17]; adequate food consumption[18]; demographic changes toward increasing the working-age population[19]; redistribution of wealth (e.g., fiscal policies and social safety nets)[20,21]; structural change and industrialization for economic growth[22]; and climate mitigation.[23] However, poverty reduction drivers could have unintended consequences, particularly for the environment. For example, efforts boosting the global economy could lead to increasing greenhouse gas emissions,[24,25] land degradation,[26,27] and biodiversity loss.[28] Conversely, environmental sustainability-related policies (e.g., promoting renewable energies and shifting to plant-oriented diets) may alleviate poverty.[18,29]

It remains challenging to systematically assess the impacts of numerous policies concerning both poverty reduction and environmental sustainability on global poverty progress and the Earth system simultaneously. Previous studies mostly focused on the impacts of a single poverty reduction driver (e.g., economy,[30] education,[31] or energy[32]) or an environment-related issue (e.g., carbon emissions,[33] climatic risks,[34] or land degradation[26]) on poverty. Some studies assessed the impacts of only several policies on poverty reduction and/or environment sustainability by examining the relationships between poverty change and multiple influencing factors.[35,36] However, it is unclear which policies or combinations of policies would maximize reductions in poverty and environmental pressures simultaneously. Moreover, there is a lack of global models that can capture dynamic interactions between poverty and social, economic, and environmental sectors.[37] Previous studies used different types of models such as computable general equilibrium models,[38,39] econometric models,[30,40] and microsimulation models[41,42] to analyze poverty issues, most of which cannot effectively model and simulate dynamic interactive relationships of various sectors within a complex system.[37] Although system dynamics models are proficient in capturing dynamic causal loops, previous studies primarily aimed to develop regional models that failed to provide reliable analysis for global poverty eradication.[35,43]

Here, to address the research gap, our study aims to systematically assess the impacts of a wide range of policies on global poverty and the Earth system and find robust strategies that effectively eliminate extreme poverty as soon as possible while reducing environmental pressures under various socioeconomic settings. For this purpose, we developed a new poverty module that models the complex interactions between the global poverty rate and numerous influencing factors from economy, education, and population sectors. We then integrated this module into a global integrated assessment model—the functional enviro-economic linkages integrated nexus (FeliX) model[44] (experimental procedures). Our analysis revealed that even under optimistic settings, global extreme poverty eradication would take more than two decades. Moreover, the policy direction, characterized by ambitious educational attendance, sustainable dietary choices, low fossil fuel consumption and energy demand, and low fertilizer use, would be robust in eradicating poverty as soon as possible while reducing environmental pressures under 20 future socioeconomic settings. This policy direction can inform future actions to simultaneously reduce global extreme poverty and humanity's negative impact on the planet.

RESULTS

Methods summary

This research was conducted based on the FeliX model with our poverty module. The model encapsulates the complex connections and feedback mechanisms between 11 sectors of the human-Earth system. It was calibrated to accurately fit historical trends of global poverty rates and different socioeconomic and environmental indicators (experimental procedures), indicating that our calibrated model reflects the relationships between historical global policies and these indicators well.

We identified 900 strategies (i.e., one reference strategy, 15 individual strategies, and 884 compound strategies) to represent possible future policy directions of eradicating poverty and reducing environmental pressures (Figure 1). A strategy was defined as a combination of five policies, one from each of five policy clusters (i.e., education,[15] fertilizer use,[17] cropland use,[17] dietary change,[45] and energy use[16]) (experimental procedures; Table S1; Figure 1). An individual strategy contained only one active policy, and a compound strategy contained two or more active policies. By the calibrated FeliX model, we evaluated the performance of these strategies across 25 alternative socioeconomic settings (Table S1) defined as combinations of five economic outlooks and five tailored shared socioeconomic pathways (tSSPs) characterizing future developments in population, technology, climate, land use, and food consumption.[46,47]

The evaluation of 900 strategies across 25 socioeconomic settings using the FeliX model resulted in a total of 22,500 scenarios, with each scenario representing one way in which global poverty and environmental pressures could unfold. Among 22,500 scenarios, a total of 18,000 (900 strategies × 5 tSSPs × 4 future economic outlooks) scenarios were used to project plausible future trajectories of poverty rates and planetary boundary (PB) indicators, whereas the remaining 4,500 (900 strategies × 5 tSSPs × 1 economic outlook with pre-pandemic economic trend) scenarios were used to model plausible trajectories of poverty rates and PB indicators under the pre-pandemic trend. The 4,500 scenarios would be unlikely to happen in the future and were only used for comparison of poverty and environmental performances because the pandemic has already occurred.

The effectiveness of 15 individual strategies and 884 compound strategies in eradicating extreme poverty and their resultant environmental pressures were evaluated and compared with the outcomes under the reference scenario and the pre-pandemic-trend scenario. The reference scenario was formed by the reference strategy (i.e., no additional policy intervention from the five policy clusters) under the neutral economic outlook (*Econ_Neu*; which followed a 2.05% annual economic growth rate) and the reference tSSP (tSSP2; which followed historical and current social, economic, and technological trends). The pre-pandemic-trend scenario was formed by the reference

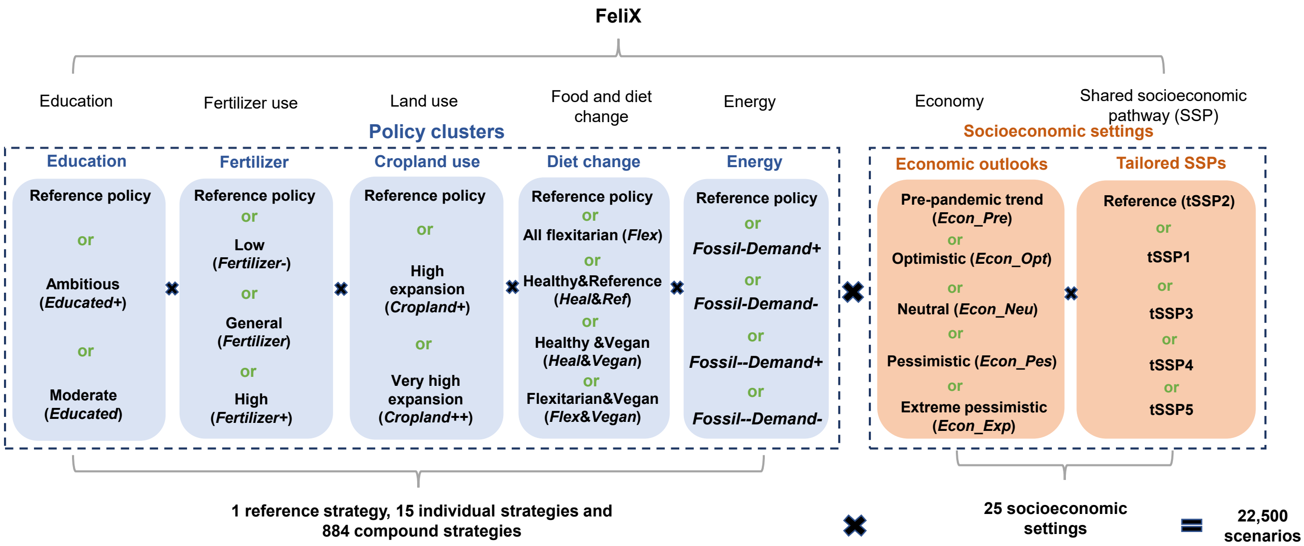

Figure 1. Schematic diagram of the construction of all 22,500 scenarios for extreme poverty eradication and environmental sustainability
Five policy clusters associated with educational enrollment, fertilizer consumption, cropland use, dietary changes, and energy consumption were identified, each consisting of one no policy (reference policy) and several active policies reflecting different ambition levels associated with poverty eradication and environmental sustainability. All strategies were formed by specifying exactly one policy in each policy cluster in which an individual strategy contained only one active policy and a compound strategy contained two or more active policies. The reference scenario was formed by combining the five reference policies from five policy clusters under the neutral economic outlook (*Econ_Neu*) and the reference tSSP (tSSP2). Similarly, the pre-pandemic-trend scenario was formed by combining the five reference policies from five policy clusters under tSSP2 and the economic outlook with pre-pandemic trend (*Econ_Pre*). The reference policy involved no additional policy being taken toward the specified goal. Each tSSP was constructed across the population, land use, food and diet change, energy, and economy modules (experimental procedures).

strategy under tSSP2 and the economic outlook with pre-pandemic economic trend (*Econ_Pre*).

Eradicating extreme poverty requires over two decades

Extreme poverty eradication (extreme poverty rate <3%[48]) could not be achieved by 2030 under any combination of policies and socioeconomic settings (Figure S1G), even following the pre-pandemic socioeconomic and environmental trend. The poverty rate under the reference scenario would be 7.34% (627 million people living in extreme poverty) in 2030, slightly higher than a recently reported projection (7%) by the UN[49] and lower than the value (8.1%) projected by the Bill & Melinda Gates Foundation[50] (Figure 2A). In the reference scenario, the eradication of extreme poverty would not be achieved until 2049.

Under the pre-pandemic-trend scenario, about 6.40% (546 million) of the global population would remain in extreme poverty in 2030, a figure higher than the pre-pandemic-trend estimation by the UN[2] in 2020 (6%) (Figure 2A) and lower than the corresponding estimation by Moyer et al. in 2030 (7.1%).[14] Among all scenarios under future economic outlooks, poverty rates would be 6.45%–8.24% in 2030, with poverty eradication achieved during 2042–2057. Compared with the poverty rate range of 6.15%–6.45% under the economic outlook with pre-pandemic trend, the occurrence of the pandemic increases the range to 6.55%–8.15% in 2030 under tSSP2 (Figure 2A).

Among the five tailored socioeconomic and environmental assumptions (tSSPs), the more inclusive and environmentally sustainable future (tSSP1) saw the greatest poverty reduction, while the high population, high consumption, and high environmental pressure future (tSSP3) saw the lowest reduction[51] (26.5 million more people in extreme poverty than in tSSP1 in 2030) (Figure 2C). Other individual policies (i.e., fertilizer consumption, cropland use, diet change, and energy) had negligible effects on poverty (Figure S2).

Trade-off between poverty reduction and the environment

Strong economic growth is one of main drivers for poverty reduction, which is consistent with general viewpoints from the literature.[52–54] Compared with the poverty rate of 7.34% (627 million) under the reference scenario in 2030, the poverty rates under tSSP2 decreased to 6.55%–6.86% (561–584 million people in extreme poverty) under the optimistic economic outlook (*Econ_Opt*) and increased to 7.83%–8.15% (670–693 million) under the extreme pessimistic economic outlook (*Econ_Exp*) (Figure 2D). Under the reference strategy and tSSP2, the poverty rate decreased to 6.82% under *Econ_Opt* and 8.12% under *Econ_Exp* in 2030 from the latest available poverty rate (8.60% in 2018) reported by the World Bank.[55] Under tSSP2 and the four future economic outlooks, the population facing extreme poverty was at 561–695 million in 2030, decreasing to 89–395 million in 2050 (Figure 2B). Under tSSP2, according to the pre-pandemic economic trend (*Econ_Pre*), the corresponding scenarios saw a fall in the number of people living in extreme poverty from approximately 525–549 million in 2030 to 89–180 million in 2050.

In addition to the economic outlooks, two educational strategies had identifiable effects on the poverty rate (Figures 2 and S3–S6). Compared with the reference scenario (with poverty rates of 7.34% in 2030 and 2.52% in 2050), the individual

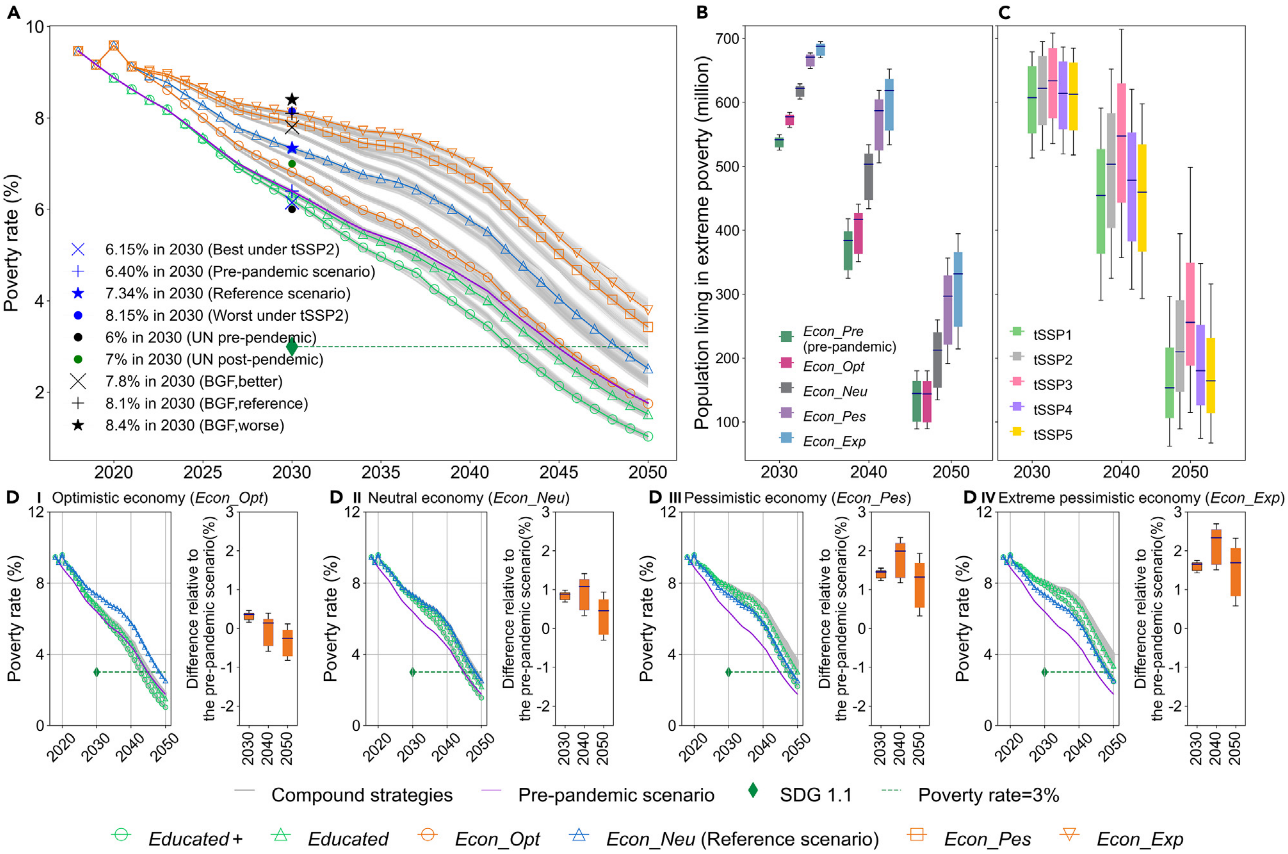

Figure 2. Trajectories of global extreme poverty from 2018 to 2050

The results presented in (A), (B), and (D) were generated under tSSP2.

(A) Poverty rate trajectories of all scenarios under tSSP2. BGF is short for Bill & Melinda Gates Foundation.[50]

(B) Population living in extreme poverty under all scenarios for one economic outlook with the pre-pandemic trend and four future economic outlooks.

(C) Population living in extreme poverty under all scenarios for the five tSSPs.

(D–D-IV). Poverty rate trajectories under all scenarios for each future economic outlook (*Econ_Opt*, *Econ_Neu*, *Econ_Pes*, or *Econ_Exp*) and their differences compared with the trajectory under the pre-pandemic-trend scenario. Following the World Bank[13,48] definition, extreme poverty is considered to be eliminated when the poverty rate falls below 3%.

In (A) and (D), two green lines with a specific symbol represent projections resulting from an education-only strategy under the neutral economic outlook (*Econ_Neu*) (in A) or a future economic outlook (in D), other lines with a specific symbol represent the reference strategy under a future economic outlook, and each gray line without a symbol represents a projection resulting from a compound strategy under either the *Econ_Pre* outlook or a future economic outlook. The trajectories of other individual strategies are not displayed here since they highly overlap with the trajectory of the reference strategy (Figure S2). Each subplot of D (D-I, D-II, D-III, and D-IV) shows the results generated by 900 strategies, including the reference strategy, 15 individual strategies, and 884 compound strategies, under the corresponding economic outlook. Some scenarios in D (D-I, D-II, D-III, and D-IV) led to lower poverty rates than the reference scenario and the pre-pandemic-trend scenario, which were caused by ambitious and moderate educational policies. In (B)–(D), each boxplot has three black lines from top to bottom, representing the maximum, median, and minimum values, respectively.

strategy of ambitious education (*Educated+*) under tSSP2 and the neutral economic outlook (*Econ_Neu*) reduced the poverty rate to 7.13% in 2030, with eradication achieved by 2046 (Figure 2D-II). Under the individual strategy of moderate education (*Educated*), the poverty rate decreased to 7.29% by 2030, with eradication by 2048.

Economic growth for poverty reduction could lead to environmental degradation (Figures 3, 4, 5, S3–S5, and S7). Although it is argued that economic growth could positively affect the environment after income per capita increases to a sufficiently high level,[56] it is still an open question of when this level can be reached and how economic development affects different Earth-system processes. Among the six PB indicators used, five indicators worsened under a stronger economy regardless of tSSP (Figures 3 and S4). The only exception is the forest land indicator. It has the opposite trend since the population under the scenario with a stronger economy is lower than that under the scenario with a weaker economy,[57] which lowers the conversion of forest land to agricultural, urban, and industrial land. The lower poverty rates always come with the higher carbon emissions under each tSSP (Figures 3 and S4), which is consistent with Soergel et al.'s findings[58] that climate mitigation has a substantial effect on poverty without progressive redistribution. Regardless of which individual strategy was taken, the indicators of biosphere integrity and ocean acidification (mean species abundance and

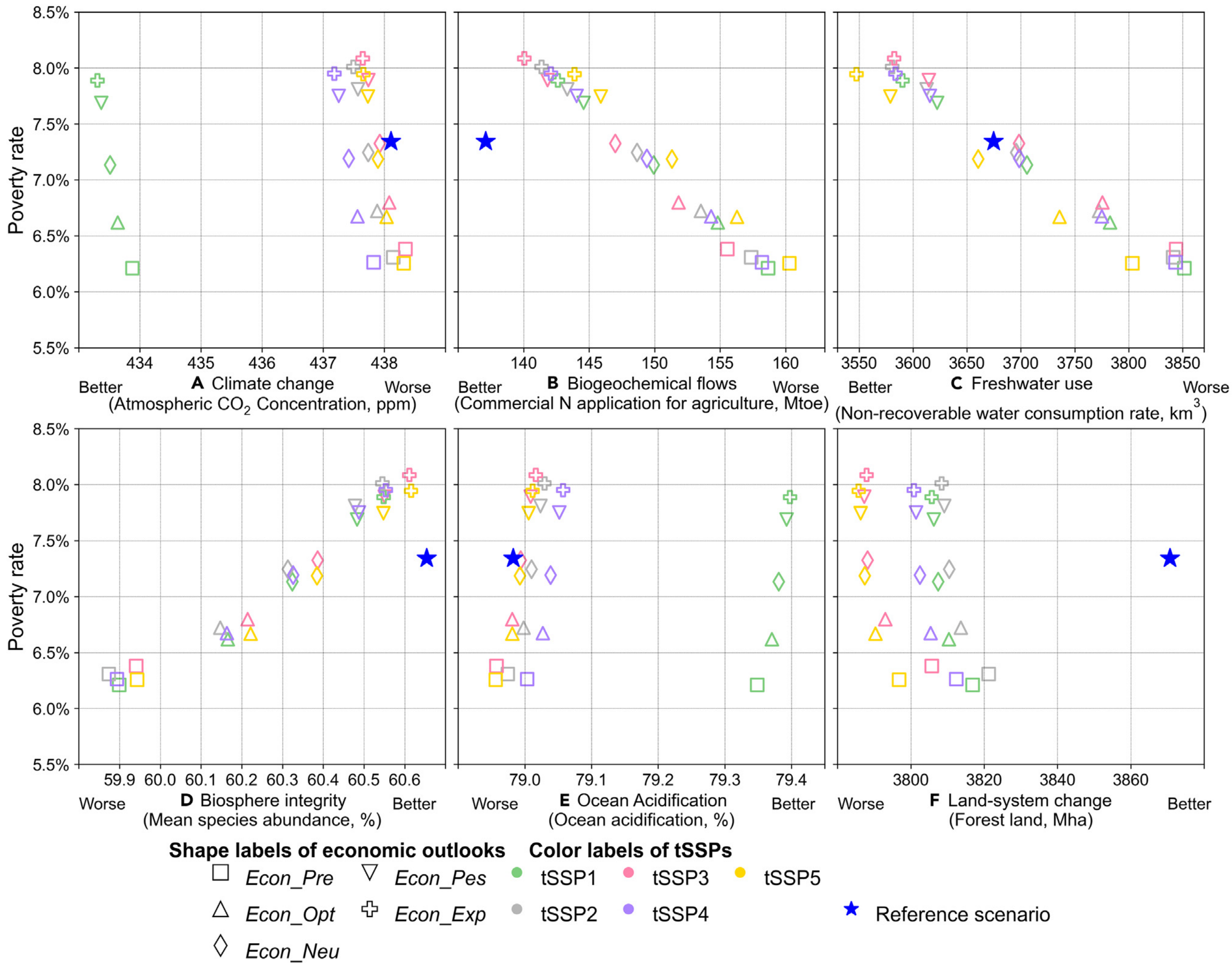

Figure 3. Average PB indicator values versus average poverty rates resulting from all scenario groups by economic outlook and tSSP in 2030
For (A)–(C), a lower PB value indicates better performance. For (D)–(F), a higher PB value indicates better performance.

ocean acidification) were always in the increasing-risk zones, while the indicator of climate change (atmospheric CO_2 concentration) was in the increasing-risk zone in 2030 and in the high-risk zone in 2040 and 2050 (Figures S1 and S8–S10). Under all 22,500 scenarios on the path to eradicating extreme poverty, only the PB indicator of freshwater use (non-recoverable water consumption) was in the safe region, while the remaining five PBs were projected to exceed their safe limits by 2030 (Figure S1). Some pathways would push the three PB indicators (i.e., atmospheric CO_2 concentration, commercial nitrogen (N) application for agriculture and forest land) beyond their high-risk boundaries. In 2050, only 47 scenarios achieved extreme poverty eradication while simultaneously keeping freshwater use and land-system change within safe environmental limits.

On the other hand, the global environment could benefit from the sustainable socioeconomic future (tSSP1) (Figures 3, 5, and S3–S5) and several individual strategies (e.g., *Fertilizer-*, *Flex*, and *Flex&Veg*) (Figures S6 and S8–S10), although they have negligible effects on poverty.

Two robust strategies

We identified two robust strategies that dominated (i.e., always performed better than) the reference strategy and other strategies in terms of poverty rate and environmental performance from 2022 to 2050 under all tSSPs and 4 future economic outlooks (experimental procedures; Figures 4 and S11–S14). Improvements in the poverty rate and PB indicators in 2050 resulting from different strategies under tSSP2 and other tSSPs, relative to the corresponding values under the reference strategy, are presented in Figures 4, S13, and S14, respectively. Both strategies contained policies of sustainable diet change (*Flex&Vegan*), ambitious education (*Educated+*), and lower fossil fuel consumption and energy demand (*Fossil–Demand-*), one of which also included low fertilizer use (*Fertilizer-*).

The two robust strategies fail to eradicate extreme poverty by 2050 under the combination of extreme pessimistic economic outlook and tSSP3 (Table S3). Compared with the reference strategy, the two robust strategies under the other 19 combinations of future economic outlooks and tSSPs took 2–5 fewer years to eradicate extreme poverty during 2042–2050 (Figure S1H).

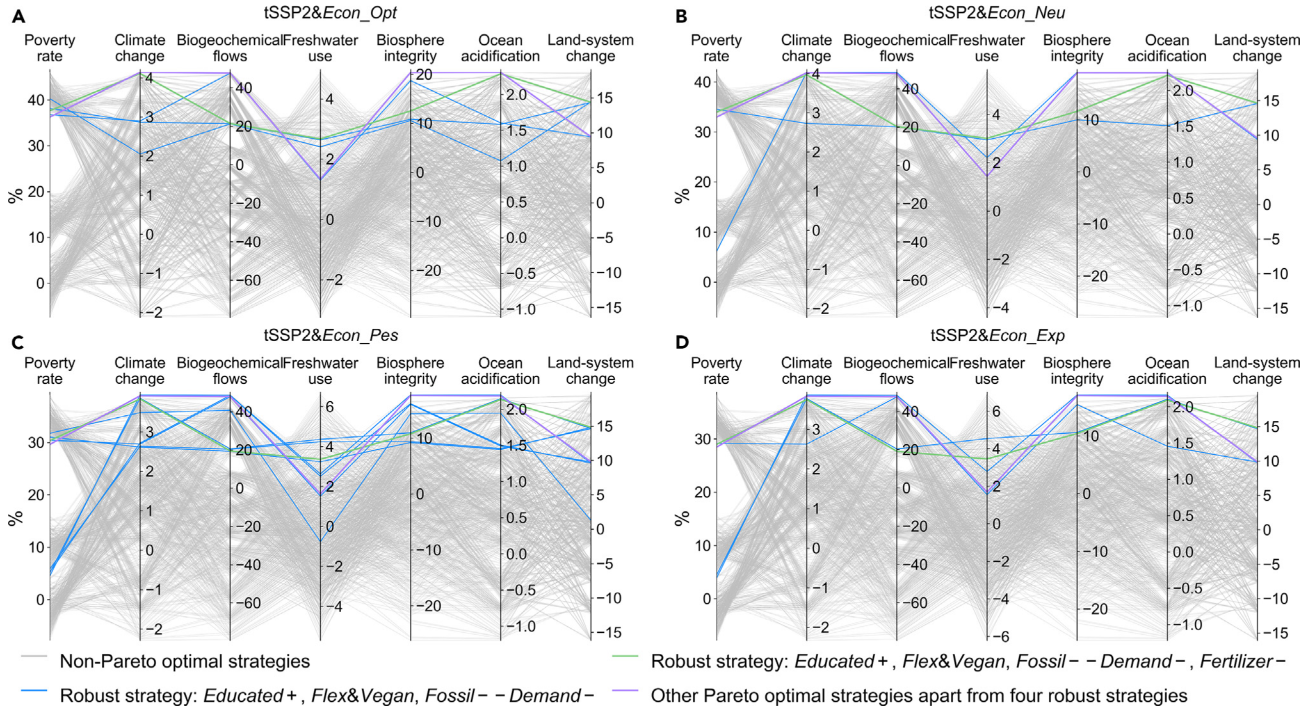

Figure 4. Percentage improvements in the poverty rate and PB indicators under different strategies relative to the corresponding values under the reference strategy in 2050 under tSSP2

(A)–(D) display the percentage of improvements under four post-pandemic economic outlooks (i.e., *Eco_Opt*, *Eco_Neu*, *Eco_Pes*, *Eco_Exp*) combined with tSSP2.

Robust strategies reduced the poverty rate by 2.3%–2.9% to 6.52%–8.01% in 2030 (Figure S11; Table S4) and by 28%–40% to 0.81%–3.29% in 2050 (Figure S12; Table S3). Simultaneously, they improved the performance against six PB indicators by up to 26% by 2030 and up to 49% by 2050 (Figures S11 and S12). In terms of PB indicators, the performance superiority of these robust strategies over the reference strategy was much greater in 2050 than in 2030. This is possibly because of (1) the delay in the effects of structural dietary change on land-use change[59] under dietary change policies and (2) the prominent reduction in fossil fuel consumption under energy policies. We define an overall environmental pressure (EP) as the average normalized score of the six PB indicator values (experimental procedures; supplemental experimental procedures). Compared with the reference strategy under 20 plausible socioeconomic futures in 2030 (EP scores ranging between 0.25 and 0.58), the robust strategy with three active policies would reduce EP scores by 15.85%–28.19% to 0.18–0.48 in 2030, and the robust strategy with four active policies would reduce EP scores by 31.52%–62.77% to 0.09–0.40 (Figures 5 and S7).

In summary, the two robust strategies contributed to eliminating extreme poverty while alleviating overall EP (Figures 5 and S7), balancing trade-offs between human development and the Earth system. For the robust strategies, under 20 plausible socioeconomic futures combined under the five tSSPs and the four future economic outlooks, the strategy with the active policies of *Educated+*, *Flex&Vegan*, and *Fossil–Demand-* was the best if reducing the poverty rate was prioritized over environmental considerations; otherwise, the strategy with four active policies of *Educated+*, *Flex&Vegan*, *Fossil–Demand-*, and *Fertilizer-* was superior since it had the lowest EP score (Figures 5 and S7) and outperformed the other one on most PB indicators (Tables S3 and S4).

Uncertainty analysis

To analyze the effects of parameter uncertainties in tSSPs and economic outlooks on poverty rates and EP, we took the reference strategy as an example and further generated a set of projections under this strategy with different parameter settings in each plausible socioeconomic future (experimental procedures). A wider range of poverty rates and PB indicators was observed (Figures 6 and S15). Under tSSP2, poverty rates ranged between 6.44% and 8.63% (550–751 million people living in extreme poverty) in 2030 and 1.63%–4.16% (155–498 million) in 2050 (Figure 6). tSSP1 and tSSP3 would see the poverty rate ranges of 6.29%–8.50% (533–720 million people living in extreme poverty) and 6.48%–8.73% (558–751 million) in 2030, respectively. Except for atmospheric CO_2 concentration and ocean acidification, the other four PB indicators had significantly larger variations under each plausible socioeconomic future (Figure S15). For example, under the reference strategy, the parameter uncertainties led to a change of -4% to 3.3% in commercial N application for agriculture (between 126 and 145 million tonnes) in 2030 under tSSP2 and the neutral economic outlook (*Econ_Neu*). Further considering the results generated by the two robust strategies under different parameter settings (experimental procedures; Figures S16 and S17), poverty rates would vary between 6.30% and 8.35% (520–732 million) in 2030 and 1.04% and 2.99% (74–371 million)

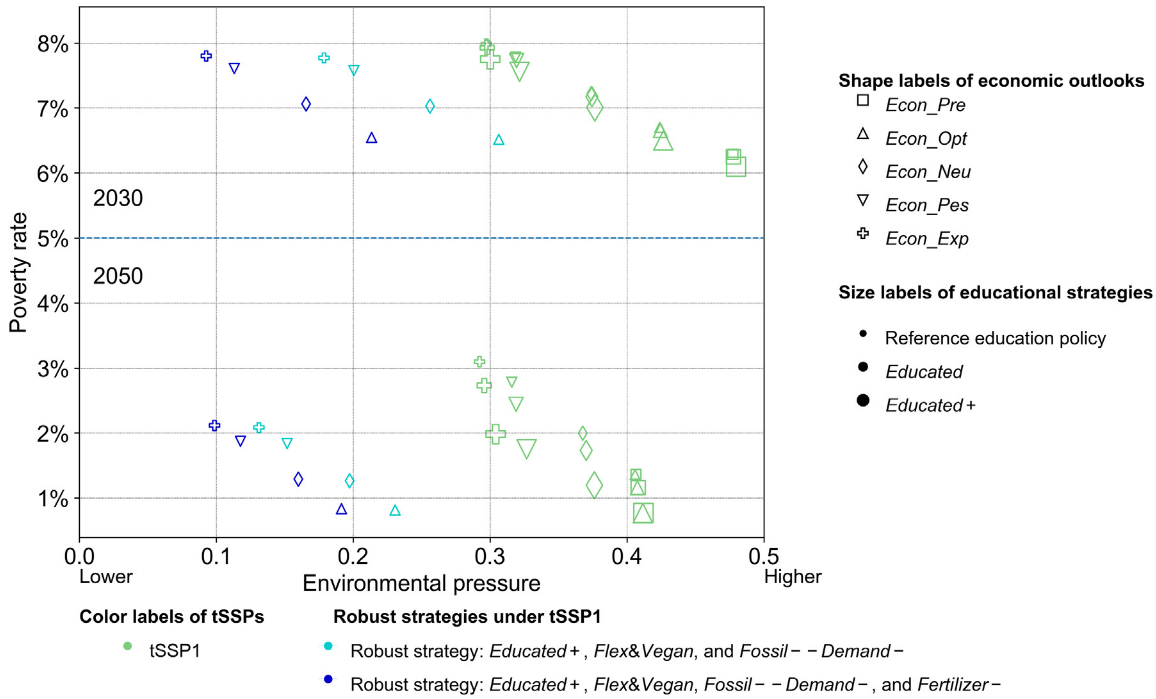

Figure 5. Average EP scores versus average poverty rates resulting from all scenarios grouped by education policy, economic outlook, and tSSP1 and from all scenarios of each robust strategy under tSSP1 with four future economic outlooks in 2030 and 2050

Each scenario has an EP score ranging between 0 and 1, and an average EP score is the average of all EP scores generated by a group of scenarios. The lower the EP score, the lower the corresponding environmental pressure. The range of EP scores generated by different economic outlooks in 2050 is smaller than that in 2030 because the impacts of economic decline caused by the COVID-19 pandemic lessened over time.

in 2050 under tSSP2 (caused by the robust strategy: *Educated*+, *Flex*&*Vegan*, and *Fossil–Demand*-) or between 6.26% and 8.42% (526–731 million) in 2030 and 1.04% and 3.01% (68–374 million) in 2050 (caused by the robust strategy: *Educated*+, *Flex*&*Vegan*, *Fossil–Demand*-, and *Fertilizer*-).

In some countries, there are no people living below the extreme poverty line but still people who live in relative poverty. We thus further explored the uncertainty of poverty line by considering two other common poverty lines (i.e., the upper-middle income class poverty line, $5.5 per capita per day in 2011 purchasing power parity, and $10 per capita per day, a common cut-off used to define the middle class) (Figure S18). For the $5.5 poverty line, the poverty rates of the reference scenario and the pre-pandemic-trend scenario in 2030 are 25.37% and 22.92%, respectively. The poverty rate range in 2030 under the 20 plausible socioeconomic futures would be 22.18%–27.61%. Similarly, for the $10 poverty line, the poverty rates would be 41.3% and 38.11% under the reference and pre-pandemic-trend scenarios in 2030, respectively, and would be 37.28%–44.14% under the 20 plausible socioeconomic futures. It is noteworthy that the two poverty lines lead to the same two robust strategies aforementioned. Compared with no policy intervention, robust strategies would take 5–14 years or 7–16 fewer years to eradicate the global poverty measured by the poverty line of $5.5 or $10 per capita per day under the 20 plausible socioeconomic futures.

The parameter uncertainty analysis, presented above, was conducted based on the reference strategy and two robust strategies. The average extreme poverty rate, resulting from the three strategies under tSSP2 and different parameter settings, is 7.51% in 2030, with the range between 6.26% and 8.73%, which is wider than the projection of 7.8%–8.4% projected by the Bill & Melinda Gates Foundation[50] and 7%–8% projected by Lakner et al.[21] These results present clearly possible future changes of poverty rates and EP with or without implementing our policy recommendations. A wider variation can be expected if the uncertainty analysis is conducted under all strategies given their feature differences compared with the reference strategy.

DISCUSSION

Implications and implementation of robust strategies

The analysis above indicates that the two robust strategies identified are the best policy choices for ending more broadly defined global poverty (not only extreme poverty) while alleviating EPs measured by six PB indicators. As suggested by the two strategies, it would be better for the international community to move toward a future characterized by a sustainable tSSP (tSSP1), strong economic development, and a much stronger policy underpinning higher attendance (*Educated*+) of education at all levels, more sustainable energy systems (*Fossil–Demand*-), widespread dietary change (*Flex&Vegan*), and less fertilizer consumption (*Fertilizer*-). This policy direction can inform future actions for decision-makers to simultaneously restore the pre-pandemic declining trajectory of extreme poverty and reduce humanity's negative impact on the planet.

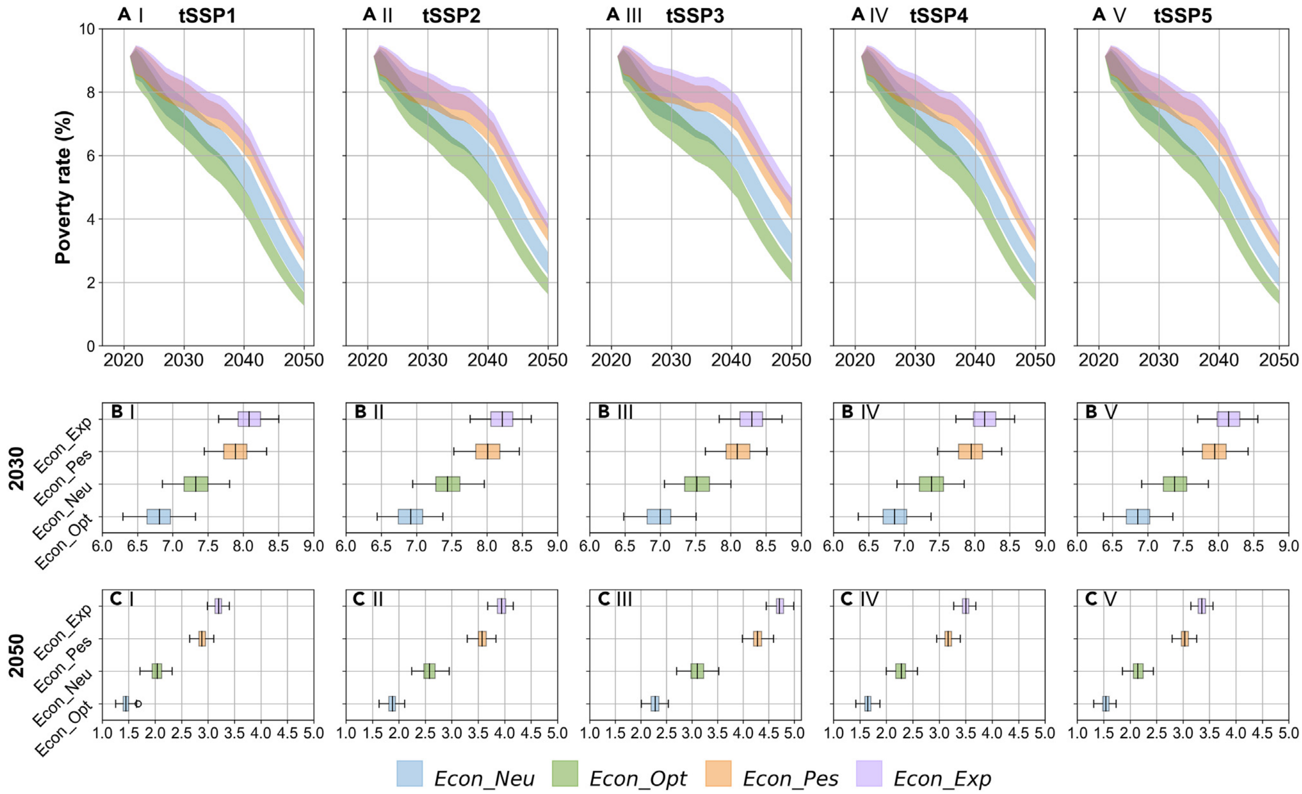

Figure 6. Uncertainty analysis for poverty rates under the reference strategy in 20 plausible socioeconomic futures based on the combinations of five tSSPs and four future economic outlooks

(A) Subplots (A-I) to (A-V) present trajectories of poverty rates during 2022–2050 under 5 tSSPs and 4 future economic outlooks.
(B) Boxplots (B-I) to (B-V) present distributions of poverty rates under 5 tSSPs and 4 future economic outlooks in 2030.
(C) Boxplots (C-I) to (C-V) present distributions of poverty rates under 5 tSSPs and 4 future economic outlooks in 2050.
In (B) and (C), each boxplot has three black lines from left to right, representing the minimum, median, and maximum values, respectively.

Achieving higher enrollment at all educational levels would reduce poverty by the improved labor force and economy,[60] which is needed to increase access to education and reduce educational inequality.[61] Measures to provide accessible and equal high-quality education include promoting online education, increasing local education investment, and strengthening international cooperation on education.[62] Access to quality education, especially for disadvantaged groups, can be facilitated through appropriate financing and aid mechanisms.[63] It is also critical to raise public awareness that better education can make individual lives better, which can be facilitated through national and worldwide publicity campaigns such as International Literacy Day.[64]

For the energy sector, many countries have established renewable energy development and energy-saving goals,[16] which is consistent with the direction of implementing the *Fossil–Demand-* policy in our robust strategy. This energy policy is not helpful for poverty reduction but is beneficial for environmental sustainability. This can be achieved by (1) developing and using renewable energies,[16] (2) raising public awareness of energy-saving behaviors, (3) developing energy-saving products and technologies (e.g., electric vehicle charging infrastructure and energy storage technologies in the transportation sector, heating technologies in the building sector),[65] and (4) promoting the use of energy-efficient products through legislation (e.g., improving energy specifications and standards for various types of equipment such as air conditioners, formulating minimum vehicle emission standards, and adjusting carbon prices to accelerate the decarbonization process).[16]

Our analysis shows that shifts to a plant-oriented diet (*Flex*&*Vegan*) contribute to reducing both the poverty rate and EPs, which can be implemented by taking measures on both the food supply and demand sides. Possible measures include strengthening the food production and processing capacity to provide affordable, popular, and environmentally responsible food,[66] imposing taxes on food-related greenhouse gas emissions and tax exemptions for some health-beneficial foods,[67] and making full use of education and publicity[66] to promote diet transformation.[44] Our analysis also suggests that reducing fertilizer use (*Fertilizer-*) can result in an increased poverty rate but decreased crop yields and EPs. This can be counteracted by developing and using high-efficiency and more environmentally benign fertilizer and advanced agricultural production techniques such as intensive food production, nutrient-use efficiency techniques, and mixed-crop cultivation.[66]

Model feasibility and scalability for regional analysis

Our findings are at the aggregated global level rather than being regionally disaggregated. Although the FeliX model is global scale and currently not applicable for regional poverty analysis, our poverty rate results provide a global baseline of poverty rates over time, based on which each nation can assess where it sits against the global average. To achieve the SDG 1.1 target, it is critical for the international community to provide assistance for eradicating extreme poverty at the local scale[68] and in poorer regions (e.g., Africa, East and South Asia, and Latin America and the Caribbean) by improving their economy and educational attainment levels. Wide implementation of our robust strategies would also require consideration of heterogeneity across nations or regions. The FeliX model can be extended by adding regional submodules of poverty and wealth redistributions for relevant analyses (e.g., poverty, environment) at the regional scale or with the consideration of each region's effects on the global performance. Each submodule, calibrated by historical data, can replicate our FeliX model structure for each region or model key interactions required for specific analyses. We can also integrate the FeliX model with other types of models (e.g., a national microsimulation model with household survey data) for national-scale analyses to capture household-level poverty. Given a consistent global context and nationally specific needs, through downscaled and tailored interventions, national-scale assessments can identify smart policies to address nation-specific challenges in poverty eradication and EP reductions. In spite of the heterogeneity across nations or regions, our robust strategies provide general policy directions for the international community to take concerted actions so that the global poverty reduction and environmental performance can be improved[69] and shared global aspirations can be achieved.

Insignificant impacts of agricultural yields on poverty

Policies related to improved agricultural yields (e.g., *Fertilizer+*, *Cropland++*) were not included in robust strategies because the impact of increased agricultural yields on the welfare of poor rural populations is not as great as we imagined due to rights and inequality issues in the food system (e.g., inequality in land use, water use, technology, and agricultural products sales).[70,71] As modeled in the FeliX model, increasing fertilizer consumption and cropland use would lead to an increase in agricultural yields, which further reduces poverty. However, the effects of improved agricultural yields on poverty reduction were not substantial. This phenomenon can be explained in terms of both observed real-world data and the model structure.

In terms of real-world data, around 80% of the world's food is produced by smallholder farmers, who are often food insecure (80% of the world's hungry) and poor (70% of the world's extreme poor).[70] Agricultural production is a major factor in poverty reduction strategies. However, considering access to natural resources and agricultural technologies (e.g., rights to land use, water use, technology, seeds, and agricultural products sales), poor rural populations are disadvantaged, and their access is not guaranteed. Hence, the impact of increased agricultural production on their welfare is not strong.[70,71] In addition, studies have found that higher crop yields can reduce rural poverty, but these effects are strong only if some certain conditions are met, such as strong support for agricultural research to provide effective improvements for smallholder activities and the poor being directly involved in the design and implementation of programs to ensure efficient use of resources and equitable distribution of benefits.[72]

In terms of model structure, the FeliX model divides the population into two categories, skilled labor force and unskilled labor force, as per many other models including the International Futures (IFs) model[3,73]—a global integrated assessment model utilized in several international organization reports (e.g., the National Intelligence Council's Global Trends 2020, Global Trends 2030 report). The poverty rate was directly calculated through the economic outputs produced by two types of labor force and their distribution (Equations S9–S16 in the supplemental experimental procedures). It means that the welfare (living conditions) of all people (including those people living in subsistence conditions) are, on the whole, related positively to the economy as represented by gross world product (GWP). The effects of agricultural yields on the poverty rate are achieved through the indirect linkages between agricultural yield (related positively to GWP) and the poverty rate, which can be found in the supplemental experimental procedures. The FeliX model captures these weak impacts of agricultural yield on poverty reduction as observed in the reality.

Rationality of the lognormal distribution assumption

In poverty rate calculation, the log-normal distribution assumption of income is adopted. The log-normal assumption fits well for the vast majority of the population but is much less suitable for extreme tails.[74,75] However, it is reasonable to use the log-normal distribution in this research. The reasons are 2-fold.

First, this assumption has been verified by statistical analyses based on various empirical data[76–78] and has been widely used to assess global and regional inequality and poverty in international organization reports[21,79–81] and research papers.[1,58,82]

Second, using other distribution functions of income would lead to similar results because the poverty rate calculation is actually independent of the functional form of the distribution in our research. Theoretically, the poverty rate was defined and calculated based on the mean value μ and the standard deviation σ of the natural logarithm of income (Equation S9 in the supplemental experimental procedures), with the assumption that income followed a log-normal distribution. However, in the FeliX model, μ and σ were obtained approximately based on their relationships with the Gini coefficient (Equations S12 and S13 in the supplemental experimental procedures), which is consistent with the method in the IF model.[73,83] Once the Gini coefficient was obtained, the poverty rate could be calculated. The Gini coefficient was calculated by the sizes of skilled and unskilled labor forces and their corresponding reference economic outputs (Figure S19; supplemental experimental procedures), which are independent of the distribution form of income.

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

Further information and requests for resources should be directed to and will be fulfilled by Zhaoxia Guo (zx.guo@alumni.polyu.edu.hk).

Materials availability

This study did not generate new unique materials.

Data and code availability

The FeliX model and computer codes used to generate the results reported in this study are available at Github via the website https://github.com/iiasa/Felix-Model/tree/master/FeliX-Poverty.

The FeliX model was developed by the Vensim software (https://vensim.com/).

Model selection

We investigate the change of global poverty rates and environmental performances under different policies and scenarios based on their historical global change trends. Common types of models that can be used to simulate poverty changes and analyze the impacts of policy include computable general equilibrium models,[84] system dynamics models, microsimulation models,[23] and hybrid models.[58] Instead of using a regional model, which is typically used for analyzing local poverty issues,[85,86] a global integrated model is adopted. The reasons for this include that (1) this research not only assesses global poverty (SDG 1) but also quantifies global EPs through six PB indicators, which can only be quantified on a global scale; (2) SDG 1 is a global goal proposed by the UN, and assessing poverty rates from a global perspective can better show the achievement of SDG 1; (3) the global economy and environment are inextricably intertwined, and the changes of poverty rates and PB indicators in a specific region (e.g., Africa, India) are fundamentally affected by what is happening in the rest of the world; and (4) a global model considers various global changes, which avoids the limitations of regional models that cannot consider the dynamic effects of relevant regions effectively.

Via an extensive review of existing regional and global integrated models that can be used for poverty scenario analysis,[37] we identified FeliX[87] as a preferred model for our research purposes, although there exist different models for projecting poverty regionally and globally.[23,58,84] First, as a global system dynamics model, FeliX can explore the causal mechanisms and the dynamic and complex feedback interactions among multiple sectors/factors, a capability that is limited in other models. This feature facilitates policy assessment for poverty eradication, which is inextricably linked with the entire human-Earth system and impacts the achievement of other SDGs. Second, the FeliX model is a system dynamics-based integrated assessment model that consists of 12 modules with thousands of variables, namely poverty, population, education, economy, energy, land use, biogeochemical cycling, carbon cycling, climate, water, biodiversity, and food and diet change modules. The model captures the core physical and anthropogenic mechanisms of global environmental and economic change within and between these 12 modules. It is one of very few models that boasts such a broad span of feedback interactions between multiple social, economic, and environmental sectors, although there exist others that model interactions among different sectors.[58,88]

The FeliX model is capable of effectively modeling the non-linear interactions and synergistic effects of various variables from social, economic, and environmental sectors within an integrated framework. Moreover, this model follows a relatively easy-to-understand modeling logic, by which the model can track the relationships between the model structure and its resultant behaviors (e.g., values of poverty rates and PB indicators of extensive scenarios). This ability is lacking in other models.

FeliX modeling

Overview of the FeliX model

FeliX is a system dynamics model that quantifies the complex connections and feedback mechanisms associated with 11 modules, including population, education, economy, energy, land use, biogeochemical cycling, carbon cycling, climate, water, biodiversity, and food and diet change. In FeliX, economic-related mechanisms mainly exist in the economy, energy, and food and diet change modules. In the economy module, GWP is formulated based on a neoclassical growth model referring to the Cobb-Douglas production function.[89] In the energy module, an economic mechanism of price-based competition among different energies (i.e., oil, gas, coal, solar, wind, and biomass) determines their market shares. In the food and diet change module, an economics mechanism that incorporates food supply-demand relationships and average food prices influences the agricultural capital and, finally, the economy.

FeliX works based on differential equations[90] that capture the relationships between natural resources and human development within and across these 11 modules.[44,87] The model is calibrated against available global historical data from 1950 to 2021 sourced from published articles and reports, mainly from international organizations.[87] After calibration, the model projects global-scale changes over time resulting from different policy and technological interventions. FeliX has been fully described, calibrated, and validated[87] and has been applied in a broad range of contexts including the exploration of the global socioeconomic and environmental dynamics of the human-Earth system,[87] the quantification of emissions pathways using microalgae as a raw material in livestock production,[91] the exploration of emissions mitigation pathways for global energy and land use to limit global warming,[91,92] the analysis of the causes of global dietary changes and their impacts on food systems,[44] and the analysis of future uncertainty and complexity of alternative socioeconomic and climate scenarios.[93]

To investigate the impacts of various policies on extreme poverty eradication and environmental sustainability, we further advanced FeliX by developing a poverty module and extending three existing modules (i.e., population, education, and economy) based on the interlinkages among the poverty, population, education, and economy modules in the global socioeconomic system. We present these modules in detail in the following subsections, while the details of the other modules can be found in the original FeliX documentation.[87] The linkages among and within the modules of the enhanced FeliX model are illustrated in Figure S20.

Population and education modules

In addition to the calculation of the female and male population sizes, our extension of the population and education modules[44] calculates the sizes of the skilled labor force, the unskilled labor force, and the population not in the labor force, which together form the whole population. The size of the labor force is equal to the size of the population aged between 15 and 64 multiplied by a labor force participation fraction. The skilled labor force is composed of the labor force population with a tertiary degree and a portion of the labor force population with secondary education.[73] The remaining labor force is defined as the unskilled labor force. The size of the population not in the labor force is the difference between the total population size and the labor force size.

The education module considers four education levels: uneducated and primary, secondary, and tertiary educated. This module computes the male and female population sizes at the four education levels based on the population size of each 5-year age group and the enrollment and graduation rates of each education level.

Economy module

In the economy module, its foundation is a neoclassical growth model. GWP was modeled as the product of the total reference economic output (denoted by *REO*) of the population, the impact factor of climate change on the economy (IF_{cli}), and the impact factor of biodiversity on the economy (IF_{bio}):

$$\mathrm{GWP} = REO \times IF_{cli} \times IF_{bio}. \quad \text{(Equation 1)}$$

The two impact factors are contained in the climate module and the biodiversity module. IF_{cli} and IF_{bio} are functions of temperature change (from the climate module) and mean species abundance (from the biodiversity module), respectively. Both have positive effects on the global economy, i.e., better climate and richer biodiversity lead to a better economy. The total reference economic output is equal to the sum of the reference economic outputs generated by the skilled and unskilled labor forces referring to the Cobb-Douglas production function.[89] Growth in GWP is driven by increases in the labor force, which is modeled explicitly in the population module, along with capital accumulation and technological change (see supplemental experimental procedures for details).

Poverty module

This module captures the dynamic relationships between the poverty rate of the global population and relevant influencing variables from the economy, population, education, energy, and land-use modules (Figure 7).

The global poverty rate (*PR*) is defined as the portion of the population living below a specified poverty level (*PL*)[73,94] (Figure S21), which is formulated as

$$PR(x \le PL) = \varphi\left(\frac{\ln(PL) - \mu}{\sigma}\right), \quad \text{(Equation 2)}$$

where x is the average daily income per capita; μ and σ are the mean and the standard deviation of the normal distribution function of $ln(x)$, respectively; $\varphi(\cdot)$ is the standard normal cumulative distribution function; and *PL* is set to the international extreme poverty line ($1.9 per capita per day in 2011 purchasing power parity). σ can be expressed as a function of the Gini coefficient, whereas μ is a function of σ and the average income of the population (represented by the GWP per capita)[95] (supplemental experimental procedures).

The poverty rate is thus determined by the poverty line, GWP per capita, and Gini coefficient. The Gini coefficient is determined by the sizes and reference economic outputs of the skilled and unskilled labor forces based on the Lorenz

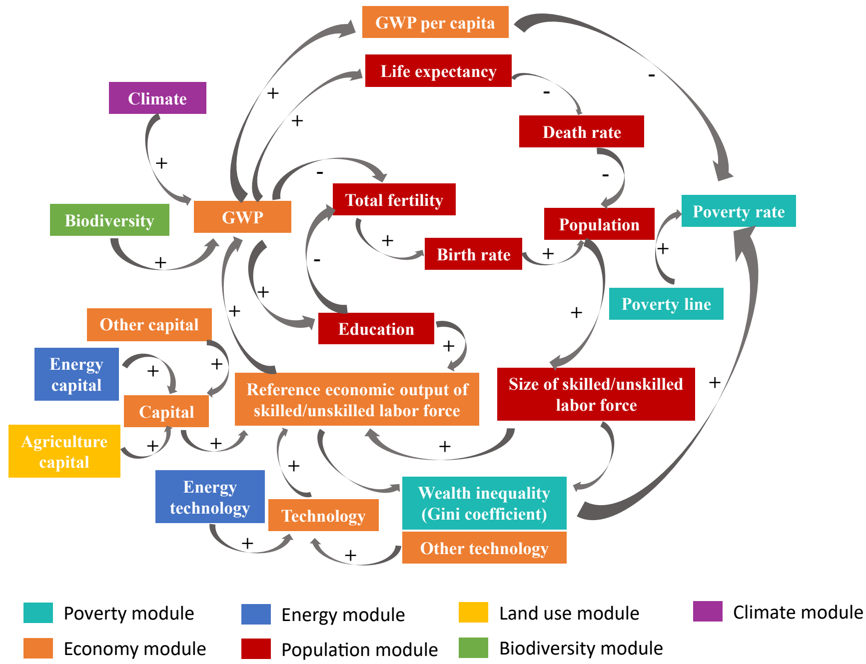

Figure 7. Conceptual relationships between the poverty module and other modules
Each text box indicates a variable, and the background color of the text box indicates the module from which the variable proceeds. Each arrow represents a causal relationship between two variables. The +/− sign on an arrow indicates a positive/negative relationship. The poverty rate is determined by the poverty line, GWP per capita, and Gini coefficient. GWP is related to the reference economic output (REO) of skilled and unskilled labor forces, climate change, and biodiversity. The REO of the labor force is positively related to the size of the labor force, technology, and capital. The Gini coefficient is related to the sizes and REOs of skilled and unskilled labor forces.

curve.[73] The calculation of the global poverty rate is detailed in supplemental experimental procedures.

Model validation

We calibrated the FeliX model using two commonly used validation methods for system dynamics models: common structure validation and historical behavior validation.[96,97] First, common structure validation was performed by informal and qualitative methods. We mainly used expert reviews, a model equation logic test, and a dimensional consistency test to ensure the reliability of the model structure. The expert reviews and the model equation logic test were used to compare the model structure and the form of the model equations with their general knowledge in the literature or in real systems.[96] The dimensional consistency test checked whether the units on the right and left sides of each equation were consistent.[98] Next, a historical behavior test (i.e., fit to historical data) (supplemental experimental procedures) was used as the behavior validation method to examine how well the model-generated behavior matched observed historical behavior.[98] For historical behavior validation, we adjusted 41 selected parameters (influencing factors) (Table S5) to obtain the best fit with global historical data for 12 control variables (Table S6) from 1950 to 2020. The historical data were collected mainly from international organizations such as the UN Food and Agriculture Organization (FAO), the International Energy Agency, the International Renewable Energy Agency, the Wittgenstein Center for Demography and Human Capital, and the Intergovernmental Panel on Climate Change. The comparison of model outputs and historical data can be found in Figures S1 and S22, which show the model outputs match the real historical observations well. The model's performance was also verified by using out-of-sample validation (supplemental experimental procedures), with the same results shown in Figures S1 and S22.

The FeliX model captures key system elements and their feedbacks necessary to assess the major dynamics in poverty and its interactions with environment rather than attempting to capture all factors and complexities in the real system. We acknowledge that our model does not capture the processes of global- and country-level wealth redistribution via policies such as social protection, global social security and safety nets, and wealth transfers and tax policies. Although these are important processes that influence poverty, they have been omitted from the model due to the following four reasons. First, it was difficult to find a unified standard for the setting of redistribution policies. Second, actual real-world global wealth redistribution and redistribution policies were difficult to capture within the FeliX model for several reasons (e.g., regional conflicts and competitions).[99,100] Third, it was challenging to model the many different social protection systems and analyze relevant fiscal policies (e.g., transfers, tax policies) operating within individual countries. Finally, it was hard to link redistribution mechanisms within different countries to the global redistribution system. Despite this limitation, the FeliX model effectively serves our research purpose well by implicitly capturing the higher-level effects of redistribution policies on global poverty rates and different socioeconomic and environmental indicators. Specifically, we use the Gini coefficient and GWP per capita in the model to reflect the impact of redistributions. Our model accurately fits historical trends of global poverty rates and different socioeconomic and environmental indicators (Figure S22), indicating that the model reflects implicitly the relationships between historical global redistribution policies and these indicators well.

Scenario construction

We constructed scenarios (Figure 1) to investigate the changes in poverty rates and EP under different policies as well as socioeconomic settings up to 2050. As mentioned in introduction, various poverty reduction-related drivers have been proposed, which can be divided into industry-specific drivers (e.g., industrial and urban development, services and industry productivity growth) and non-industry-specific drivers (e.g., economic growth, demographic change). Due to the diversity of drivers and the complexity of their interactions, we targeted the selection of poverty-related policy clusters on the basis of (1) wide acceptability of poverty reduction drivers by society, (2) simplicity and integrity of policies, and (3) the feasibility of policy implementation in the FeliX model.

Four rules were used to select policy clusters for scenario construction. First, policy clusters are recognized to be associated with global poverty reduction. Second, policy clusters are diverse enough to cover most of the key dimensions of poverty reduction. Third, policy settings in each cluster at the global scale are supported by scientific literature or international organization reports. Last, industry-specific policy clusters are excluded if the effects of an industry-specific policy cluster (e.g., transport) on poverty and environmental performances is covered by other policy clusters.

On the basis of the selection rules mentioned above, we selected fertilizer use,[17] cropland use,[17] education levels,[15] dietary change,[18] and energy use[16] as policy clusters. In addition, plausible socioeconomic futures were also considered in scenario construction. Economic growth and demographic and climate changes[58,84] were taken as uncertainty dimensions in the settings of socioeconomic futures. A total of 25 socioeconomic settings were created by combining five economic outlooks with five tSSPs.

Each policy cluster involved a reference policy and several active policies that could influence poverty rates and EP (e.g., active policies in the education policy cluster included a moderate [*Educated*] and an ambitious [*Educated+*] policy). The reference policy assumed no additional action toward specified goals for a given policy cluster. A strategy was composed of five policies (one from each of the five policy clusters). We specified a reference strategy (composed of five reference policies), 15 individual strategies (composed of a single active policy from one policy cluster and four reference policies in the remaining four clusters), and 884 compound strategies (composed of at least two active policies). Finally, a strategy combined with an economic outlook and a tSSP was regarded as a scenario. Since we considered five economic outlooks (an outlook with the pre-pandemic trend and four future economic outlooks) and five tSSPs, a total of 22,500 ((1 + 15 + 884) × 5 × 5) scenarios were constructed. The reference scenario was formed by the reference strategy combined with the neutral economic outlook (*Econ_Neu*) and the reference tSSP (tSSP2). The pre-pandemic-trend scenario was formed by the reference strategy combined with the pre-pandemic-trend economic outlook (*Econ_Pre*) and tSSP2.

The policies in each policy cluster, along with the economic outlooks and tSSPs, are described in detail in the following subsections and are summarized in Table S1. Tables S7 and S8 present the variables and parameters used in FeliX for setting various policies, economic outlooks, and tSSPs.

Education cluster

Education has been regarded as the key to improving the quality of labor resources and thereby contributing to the eradication of poverty. In FeliX, educational attainment is reflected by enrollment rates of primary, secondary, and tertiary education. Different enrollment rates are used to indicate different intensities of education policies. The education policy cluster consisted of a reference policy, a moderate policy (*Educated*), and an ambitious policy (*Educated+*).

We used net enrollment rates from the UN International Children's Fund (UNICEF)[101] as the enrollment rates for primary and secondary education. Due to the unavailability of net enrollment rates for tertiary education, we used gross enrollment rates from the World Bank.[102] Trends in enrollment rates in primary and secondary education were relatively stable over the past decade, and the continuation of these trends defined the reference policy in education. According to this trend, the enrollment rates of men and women are 95% and 94% by 2050 for primary education and 86% and 90% by 2050 for secondary education.

We used SDG 4 as a reference to formulate the two active policies in education. We assumed that the ambitious policy (*Educated+*) is consistent with SDG 4 targets for primary, secondary, and tertiary education, while the moderate policy (*Educated*) takes longer to achieve the same targets. Specifically, we set the enrollment rates of boys and girls for primary and secondary education to 100% by 2030 (2050) under the ambitious (moderate) policy. For tertiary education, we assumed that the popularization stage (enrollment rate >50%) under the ambitious policy would arrive 10 years earlier than under the moderate policy based on predictions of previous research.[103,104] The enrollment rate for girls reached 45% (equal to the rate for boys) in 2030, and both genders would reach 50% by 2050 under the moderate education policy. For the ambitious policy, enrollment rates of both genders would reach 50% by 2040 and 56% by 2050.

Fertilizer cluster

Land fertility for agriculture is influenced mainly by fertilizer application.[29] Fertilizer policies aim to reduce poverty by improving agricultural productivity and food production. We used different growth rates in the use of N fertilizer to differentiate policies in fertilizer use. According to the trend projection up to 2050 by the FAO,[29] fertilizer use will increase continuously, but the growth rate is expected to gradually ease after 2030, which aligns with our pre-pandemic-trend scenario. Consistent with this trend, policies in this cluster involve two periods, including 2005–2030 and 2030–2050.

Dividing the world into seven regions, the FAO[29] projected each region's average growth in fertilizer use from 2005 to 2030 and from 2030 to 2050. We took the growth rates in fertilizer use from developed countries, developing countries (excluding China and India), and Latin America as low (*Fertilizer-*), general (*Fertilizer*), and high (*Fertilizer+*) policies in fertilizer consumption, respectively.

Cropland use cluster

Agricultural land can be classified into three types: arable land, land under permanent crops, and pasture land, of which the first two can be considered cropland.[105] Cropland policies alleviate poverty by promoting agricultural productivity and food security.[26,106] According to the FAO projections,[29,107] agricultural land peaks around 2040 at 4.80 billion hectares and reaches approximately 4.76 billion hectares in 2050, and the three types of lands occupy 28.7%, 2.4%, and 68.9% of total agricultural land, respectively. To be consistent with these projections, the reference policy is set as an 11% expansion in global cropland area from 2010 to 2050.

Various cropland use scenarios have been reported.[105] Previous studies have estimated different rates at which cropland would grow in the future. We used the projections by Odegard and Van der Voet[108] to populate our high (*Cropland+*) and very high (*Cropland++*) cropland expansion policies. Under these two policies, cropland area expands by 100% and 180%, respectively, from 2005 to 2050.

Diet change cluster

Undernutrition and low-quality diets lead to poor health and an inability to work, which further exacerbate poverty (SDG 1).[18] Dietary change policies reduce EPs and poverty by shifting to plant-oriented diets to improve food security and sustainable agriculture.[18] With a projected increase in the population[29] and the trend in diets moving toward greater satiety and overnutrition,[29] satisfying increasing food demand presents a significant challenge. Sustainable dietary changes (e.g., reducing meat intake) have been adopted as a promising direction to alleviate pressures on the global food and environment system.[18]

Eker et al.[44] divided the world's population into meat eaters and vegetarians and proposed three meat eater diet compositions (i.e., a reference meat-based diet [17.2% animal products], a healthy diet [14% animal products], and a flexitarian diet [11.7% animal products]) and two vegetarian diet compositions (i.e., a reference vegetarian diet consisting of 9% animal products and a vegan diet consisting of 0% animal products) in FeliX. Based on these diet compositions, we formed one reference diet policy and four dietary change policies (i.e., all flexitarian, healthy and reference, healthy and vegan, and flexitarian and vegan). The reference diet policy is defined as meat eaters and vegetarians following the reference meat-based diet and the reference vegetarian diet, respectively. Under the flexitarian (*Flex*) policy, the entire population shifts to a flexitarian diet by 2050 from 2022. The healthy and reference (*Heal*&*Ref*) policy specifies that meat eaters shift to a healthy diet by 2050 from 2022 and that vegetarians follow the reference vegetarian diet. Under the healthy and vegan (*Heal*&*Veg*) policy, meat eaters shift to a healthy diet and vegetarians shift to a vegan diet by 2050 from 2022. The flexitarian and vegan (*Flex*&*Veg*) policy shifts meat eater and vegetarian diets to flexitarian and vegan diets by 2050 from 2022.

Energy cluster

Energy access and sustainable energy use are crucial to securing livelihoods and protecting the ecosystem. Global energy demand is increasing rapidly due to population growth and economic growth,[16] and approximately 13% of the global population still has no electricity at home.[16] Satisfying energy demand and promoting a shift to renewable energies is helpful to reduce poverty and achieve environmental sustainability.[16]

Based on different trends in the energy market, Walsh et al.[92] presented scenarios of energy use that projected fossil fuels and renewables production and per capita energy demand up to 2100. Under our reference policy, production of fossil fuels would be 13,700 Mtoe in 2050, close to Walsh et al.'s reference projection (approximately 13,800 Mtoe in 2050).[92] Based on Walsh et al.'s projections of fossil fuel production and per-capita energy demand[92] and the opinion that fossil fuels are likely to continue to dominate the global energy market for decades to come,[65,109] we considered two possibilities for production and per-capita energy demand. Specifically, based on the average change rates in Walsh et al.'s research,[92] we set the production of fossil fuels to reach 12,500 or 11,200 Mtoe in 2050 and per-capita energy demand to change to 2.12e−06 or 1.64e−06 Mtoe per capita per year in 2050. The combinations of these possibilities formed the four active energy policies.

Economic outlooks

Poverty rates are highly related to the development and overall health of the economy.[52–54] To examine the effects of various economic settings on poverty and EP, we considered five economic outlooks by setting different projections of GWP growth rates, including one with the pre-pandemic trend and four future economic outlooks (neutral, optimistic, pessimistic, and extreme pessimistic). Under the pre-pandemic-trend economic outlook (*Econ_Pre*) with the assumption following the pre-pandemic economic trend, GWP increases with the pre-pandemic economic trend, GWP increases at an average annual rate of 2.79% during 2019–2050, and the growth rates of GWP would slow down over the decades ahead. This outlook is consistent with the projections by other integrated assessment models (e.g., IMAGE, MESSAGE-GLOBIOM).[110] A recent report by the UK Department for International Trade[111] projected that, influenced by the COVID-19 pandemic, the growth rates of GWP would slow down over the decades ahead, and the average annual growth rate is 2.3% during 2019–2050. To compare with the prediction value (i.e., 2.3%) in the UK report,[111] we predicted the annual growth rates during 2019–2050 by fitting 31-year moving averages of the historical annual GWP values from 1961 to 2020 presented by the World Bank.[55] The resulting forecasts of annual growth rates are 1.99% and 1.80% by using linear and exponential fitting, respectively (Figure S23). Based on these projections, we set the average annual growth rate to 2.05% during 2019–2050 in the neutral economic outlook (*Econ_Neu*).

The neutral outlook is subject to wide uncertainty due to downside risks (e.g., further economic shocks) and upside surprises (e.g., technological progress acceleration). Therefore, compared with the average annual growth rate in the neutral economic outlook, the average annual growth rates of GWP increase by 0.75% in the optimistic outlook and decrease by 0.75% in the pessimistic outlook according to the uncertainty band (± 0.75%) proposed by the UK Department for International Trade.[111] Under the optimistic economic outlook, the growth rate of GWP in 2050 reaches the corresponding value under the prepandemic-trend outlook. We also considered an extreme pessimistic economic outlook (*Econ_Exp*) because some unpredictable global disasters and conflicts (e.g., wars, extreme climate events) could lead to far-reaching global economic downturn (e.g., the Great Depression). The average annual growth rate is assumed to decrease to 1.05% from the rate (2.05%) in the neutral economic outlook. For each economic outlook setting, the values of GWP for 2021 and earlier use historical data published by the World Bank,[55] and the values of GWP for 2022 and beyond are predicted using annual growth rates.

tSSPs

Each original SSP has a narrative storyline that depicts various socioeconomic and environmental aspects.[112–114] Based on the original SSP storylines with broad socioeconomic and environmental assumptions, we formed 5 tailored global SSPs (i.e., tSSP1–tSSP5) to represent five plausible trends for global social development up to 2050.[46] We first described the five tSSPs by providing a set of internally consistent narratives based on the original widely used SSP storylines for capturing a range of long-term future uncertainties (Table S9). Then, a set of qualitative assumptions applicable to FeliX were made based on these narratives (Table S8), including population, fossil fuel technology improvement, renewable energy technology improvement, production costs and market share, greenhouse gas emissions, deforestation, and the expansion of agricultural land, crops, and livestock yield, as well as food waste and diet prevalence. Some parameters were then specified to quantity these qualitative narratives. Other aspects (i.e., economic development, educational attainment, energy demand and production, cropland change, land fertility influenced by fertilizer, and dietary change) were excluded since they were incorporated into the economic outlooks and policy clusters. On the basis of the Morris elementary effects screening method,[115] we adjusted the population-, energy- and technology-, climate-, land use-, and food-related parameters in FeliX (Table S8) to formulate the tSSPs.

Following the global SSPs,[47] the five tSSPs can be described as follows: sustainability (tSSP1), a green trajectory under which the world turns to a more sustainable path; middle of the road (tSSP2), a reference pathway capturing the current global trajectories; regional rivalry (tSSP3), a rocky road characterized by regional rivalry rather than global cooperation; inequality (tSSP4), a road with high inequality both across and within countries; and fossil fuel-driven development (tSSP5), a pathway with a prosperous socioeconomic but unsustainable environmental path.

We assumed that the values of the model parameters under each tSSP gradually changed toward their quantified values (Table S8) within 20 years starting from 2022. The population projections under our tSSPs are consistent with those of the International Institute for Applied Systems Analysis (IIASA).[110] As SSPs vary in terms of inequality assumptions, we considered inequalities implicitly in constructing our tSSPs by various policies included in the scenario construction. First, income inequality was reflected by the Gini coefficient, which was directly affected by the economy and education and indirectly affected by other sectors (e.g., agriculture, energy). Thus, the changes in income inequality were realized via different policies and economic outlooks. Second, gender inequality was reflected in education policies as educational attendance of different education levels took gender differences into account.

Scenario evaluation and robust strategies

Evaluation measures

We used the poverty rate and six PB indicators (Table S2; supplemental experimental procedures**)** to measure the performance of each scenario. We further defined a new indicator, the EP index, to synthesize the EP in each scenario by normalizing six PB indicator values and taking their average. Three PB indicators (i.e., mean species abundance, ocean acidification, and forest land) corresponded to better performance and lower EPs at larger values, and vice versa for the other three PB indicators. To make them consistent, we normalized the values of the first three indicators to the range [−1, 0] and the other indicator values to [0, 1]. For a specific scenario, the average of the normalized PB indicators was taken to obtain the corresponding EP score. The resulting EP scores ranged from −0.5 to 0.5. For simplicity, we transformed the EP score range to [0, 1] by adding 0.5 to each original EP score. The lower the EP score, the lower the corresponding EP. That is, the lowest and the highest EPs are achieved when the EP scores are 0 and 1, respectively.

Identification of robust strategies

Robust strategies were those strategies adopted in Pareto-optimal scenarios under 20 plausible socioeconomic futures (5 tSSPs × 4 future economic outlooks) and were effective in each future. Identifying Pareto-optimal scenarios to eradicate extreme poverty as early as possible at a lower EP is equivalent to a multi-objective sorting and ranking in terms of the poverty rate and the six PB indicators (i.e., 7 performance criteria) simultaneously. Pareto-optimal scenarios were required because there exists no single best scenario that maximizes achievements on all conflicting performance criteria simultaneously. To find the Pareto-optimal scenarios, first, we selected out scenarios that outperformed the scenario with the reference strategy across all performance criteria under each plausible socioeconomic future from 2022 to 2050. Second, Pareto-optimal scenarios were selected from these scenarios by multi-objective sorting and ranking. A scenario is considered Pareto optimal if there is no way of improving its performance on any performance criterion without degrading at least one other criterion. Finally, the same strategies adopted in Pareto-optimal scenarios under each of the 20 plausible socioeconomic futures were taken as robust strategies to eradicate extreme poverty while reducing EPs. That is, a strategy is identified as robust if it was adopted in 20 different Pareto-optimal scenarios. In comparing performance against the reference strategy, we considered two indicator values equivalent if their percentage change was within ±1%.

Uncertainty analysis

Given the deep uncertainty associated with the plausible socioeconomic futures defined by tSSP and economic outlook combinations, we considered their parameter uncertainties and calculated the resulting uncertainty across model outputs. We assumed that the values of uncertain parameters characterizing the tSSPs and economic outlooks varied by 15% and 5%, respectively,[116] reflecting the potentially greater variability in economic outlook parameters.

To create envelopes of plausible projections for each socioeconomic future (i.e., combinations of 5 tSSPs and 4 future economic outlooks), we used Latin hypercube sampling to randomly sample from the parameter uncertainty space of all drivers to simulate 1,000 realizations (model projections) of the reference strategy and two robust strategies under each plausible socioeconomic future, with each realization representing how the future could unfold under one possible state of the world. For each strategy, a total of 20,000 model evaluations were performed.

The setting of different poverty lines was achieved by directly changing the parameter consumption standard per capita per day. The parameter consumption standard per capita per day was set as 1.9, 5.5, and 10, respectively, to represent different levels of poverty. The setting of 1.9 represents the international extreme poverty standard (i.e., $1.9 per capita per day in 2011 purchasing power parity). The setting of 5.5 represents the upper-middle income class poverty standard, and the setting of 10 is a common cut-off used to define the middle-class.[117]

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.oneear.2023.03.007.

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AUTHOR CONTRIBUTIONS

L.G. and Z.G. conceived and designed the study. Q.L. developed the new version of the model and performed the experiments. Q.L., Z.G., and L.G. conducted the results analysis, and Q.L., Z.G., L.G., and Y.D. prepared the manuscript. Z.G. and Y.D. supervised the work. All authors participated in revising the manuscript. Q.L. and L.G. contributed equally to the work.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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