The Earth4All scenarios: Human wellbeing on a finite planet towards 2100

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Abstract
How can wellbeing for all be reached while reducing risks of destabilizing the planet? This ambition underlies the 2030 Agenda but analyzing whether it is possible requires linking global socioeconomic developments with life-supporting Earth systems, incorporating feedback between them. The Earth4All initiative explores integrated developments of human wellbeing and environmental pressures up to 2100 based on expert elicitation and a computational model. The relatively simple model focuses on quantifying and capturing some high-level feedback between socioeconomic and environmental domains. It analyzes economic transformations towards increased wellbeing with reduced pressures on planetary boundaries. The model includes two key novelties: a social tension index and a wellbeing index, to track societal progress this century. The scenarios suggest that decision-making as usual likely leads to rising social tensions, worsening environmental pressures and declining wellbeing. We propose five turnarounds that in the model can shift the human world off the current trajectory, improve global wellbeing and ease environmental pressures. The model, its two scenarios and the five turnarounds can be used as boundary objects in discussions on future trajectories.

Supplementary info:
https://docs.google.com/document/d/1ZEcQ08bfYSWutGhNRWVxzNbtwBauVhHaARrSLsS92wo/edit#heading=h.es2208kok9ij

The decades since the mid-20th century have been marked by unprecedented expansion of economic activity, biophysical resource consumption, environmental pressures, industrialization, urbanization, and population growth(Head et al., 2022; Jouffray et al., 2020; Steffen, Broadgate, et al., 2015). Global warming is one symptom of this 'Great Acceleration', with over half of all anthropogenic carbon emissions ever released being emitted since 1990(IEEP, 2022). Current projections estimate global warming well in excess of the 'safe' 1.5 °C target with policies currently in place pointing to a 2.8ºC temperature rise(UNEP, 2022), risking multiple and cascading climate-related tipping points with devastating consequences for human wellbeing(McKay et al., 2022; Rocha et al., 2018). Multiple planetary boundaries have been pushed into high-risk zones(Persson et al., 2022; Steffen, Richardson, et al., 2015). According to the IPCC, there is now 'a brief and rapidly closing window of opportunity to secure a liveable and sustainable future for all'(IPCC, 2022).

Moreover, many countries tend to overstep biophysical thresholds faster than they satisfy human wellbeing, with no country yet succeeding in meeting the basic needs of its residents while respecting planetary boundaries(Fanning et al., 2021; Vogel et al., 2021). Even with large increases in mean incomes, half of the world's population still lives below the 6.85 $/day poverty line, with over 600 million people living in extreme poverty(Schoch et al., 2022). Contributions to environmental pressures are extremely unequally distributed(Bruckner et al., 2022; Oswald et al., 2020), with a billionaire responsible for a million times the carbon emissions of the average person(Maitland et al., 2022). Yet despite evidence that reducing inequality and improving public services are key to sustainably securing wellbeing(Millward-Hopkins & Oswald, 2023; Vogel et al., 2021), within-country inequalities are rising and the public share of wealth is declining(Chancel et al., 2022).

The Earth4All initiative (https://earth4all.life) is a response to the systemic crises the world is facing, investigating how environmental risks could be minimized while maximizing human wellbeing for the global majority throughout the 21st century. Its book, *Earth for All: A Survival Guide for Humanity,*(Dixson-Declève et al., 2022) was published in connection with the 50th anniversary of *The Limits to Growth*,(D. H. Meadows et al., 1972) which used system modeling to spur international debate on the problems of overshoot in human pressures on the environment.

The Earth4All model: Causal determinants of human wellbeing

To investigate potential big-picture long-term futures, we chose to develop a new highly aggregated quantitative simulation model. Earth4All, a model built in system dynamics software, represents an alternative approach to conventional equilibrium-based integrated assessment models and allows for the transparent exploration of pathways of future human wellbeing. The Earth4All model builds on insights gained from earlier integrated system dynamics world modeling endeavors (Forrester, 1961; Hughes, 2019; D. L. Meadows et al., 1974; Pedercini et al., 2020; Randers, 2013; Randers et al., 2016, 2019; Saeed, 2016). The overall research question the model and expert elicitation has aimed to answer is: *How can human wellbeing be improved within Earth's biophysical limits in the 21st century?* The model is built to simulate linked socio-economic and environmental developments over time towards 2100, incorporating measures from national accounting, population, inequality, and environmental degradation.

To begin with, one might ask if it is at all sensible to build a new model: do we have enough understanding of human, societal and biogeophysical processes to construct such a model, and can a relatively simple model still capture main drivers explaining long-term future developments? Our answer is "yes", with important caveats. General trends can be depicted. Over the last 50–100 years, human and Earth system dynamics at the macro level have developed along pathways broadly consistent with our past scenarios. An indication of this is the well-documented correspondence between some of the scenarios published in the 1972 *Limits to Growth* book and the observed development until 2022 (Herrington, 2021; Turner, 2008, 2014).

With that said, it remains impossible to make point predictions of future developments. Some macro-trends are triggered by unpredictable events with global consequences. Some would argue that the Anthropocene represents a departure from the predictability of the Holocene into a realm of systemic risk and uncertainty (Steffen et al., 2018). We agree with this judgment to some extent: in the last 50 years, the climate has changed substantially, changes in Earth system processes are accelerating and becoming more visible, and there are growing concerns that profound tipping points are likely to be crossed in the coming decades(McKay et al., 2022). The zone of habitability in the tropics is likely to shrink considerably this century, putting potentially billions of people within climate conditions that today are considered on the edge of habitability(Xu et al., 2020).

Climate-related events that cannot be predicted by projecting historical trends have been called 'Green Swans' and described as 'alternative epistemologies of risk'(Bolton et al., 2020). A different group of risks are the systemic risks emerging from global intertwined social-ecological systems interacting across a range of spatial and temporal scales(Keys et al., 2019). Despite the profound forecasting difficulties posed by emergent behavior in the Anthropocene(Steffen et al., 2018), we argue that this uncertain landscape calls for increased modeling efforts with new modeling approaches. Employing multiple approaches can seize the strengths of different paradigms and methods when exploring potential future scenarios on different levels, their underlying dynamics and consequences for humanity.

To answer the overall research question, the Earth4All model's causal structure is a first attempt built to account for selected main determinants of human wellbeing. In our original overarching conceptualization of what human wellbeing entails, we mainly drew on the capabilities approach(Nussbaum & Sen, 1993; Sen, 2001) and the human needs approach(Doyal & Gough, 1991; Max-Neef et al., 1991). The capabilities approach emphasizes freedom for people "to achieve outcomes that they value and have reason to value"(Sen, 2001). The human needs approach understands that a set of universal, non-substitutable, satiable, and cross-generational needs must be met as an essential precondition for human flourishing(Gough, 2017). The *wellbeing economy alliance* has developed a closely related set of qualitative definitions of wellbeing components(Wellbeing Economy Alliance, n.d.). While many important aspects of wellbeing have qualitative characteristics (including, for example, quality of governments, subjective wellbeing, and legal frameworks allowing for democratic and inclusive decision-making), the development of the model structure requires a conceptualization of wellbeing that can be meaningfully assessed quantitatively and integrated with the other model components, including Earth-system related ones. In the model, we rely on quantitative proxies whose development patterns can be tracked in a simulation model over a time horizon of 30-100 years.

Earth4All's wellbeing index, further described below, incorporates the following five components along five dimensions:

1. Dignity: Workers' disposable income (measured in PPP-adjusted 2017$)
2. Nature: Global warming (global surface average temperature, in degrees Celsius)
3. Institutions: Government services (spending per person indicating government institutions related to infrastructure, health and education etc., in PPP-adjusted 2017$)
4. Fairness and inequality: the ratio of owners' income share to workers' income share.
5. Participation as citizens: People's perceived rate of progress in wellbeing improvement relative to earlier levels of wellbeing.

The model is a disequilibrium simulation(Barlas, 1996) model built in system dynamics software, and not an optimization model. It aims to capture some of the global systems' causal structure with important feedback loops, its cross-sectoral dynamics, and with (degrees of) stock-flow consistency. It can generate internally consistent scenarios to assess potential future long-term developments for the selected human wellbeing variables during the rest of this century.

The model was constructed to track the determinants and dynamics of the selected indicators over the time period chosen, i.e. 1980 to 2100. The model starts runs in 1980 and replicates the behaviors of societal decision-making and world dynamics for the past time period, 1980-2022. While the replication of past behaviors on its own by no means represents a thorough validation test of the model, together with sound causal hypotheses based on scientific literature and expert knowledge it supports the argument that the model could approximate global trends in future decades. In the supplemental material we present stylised relationships between industrial-capitalist developments (approximated by per-capita GDP) and key socioeconomic variables, showing that the model broadly follows these trends (see also(Randers & Collste, 2023)). No structural changes and only a few limited parameter changes were added to the model from 2020. This was done in order to align better with the 'standard' middle-of-the-road scenario (SSP2) from the Shared Socioeconomic Pathway scenarios(O'Neill et al., 2017), so that the Earth4All model standard run results can be more easily compared with other integrated system modeling work.

To capture the selected wellbeing indicators, the Earth4All model includes key wellbeing determinants from both the human world and the natural world, as well as the interactions between the two. The model can be described as a highly aggregated global integrated assessment model (Fig. 1).

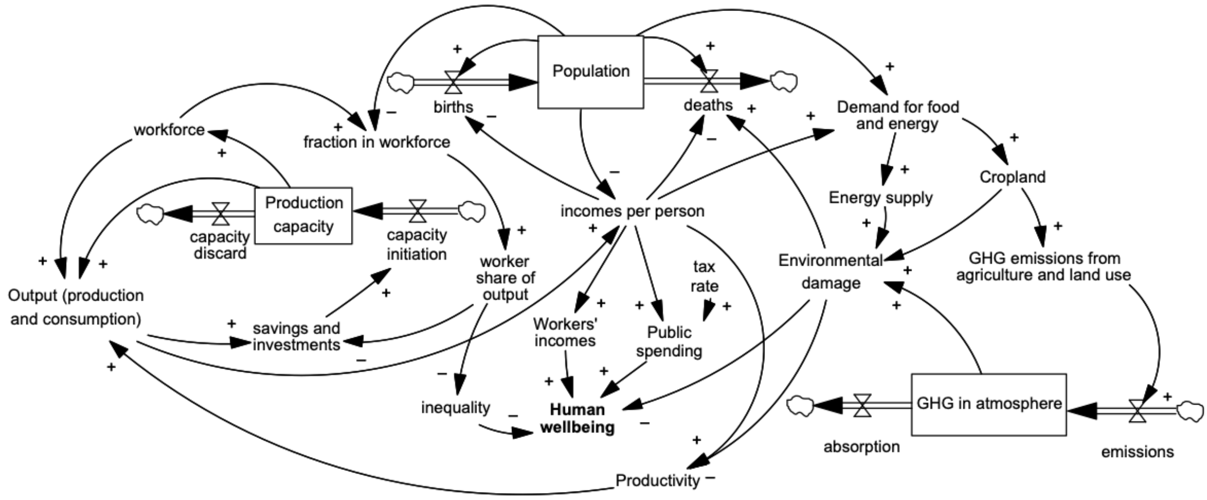

Fig. 1: As simple as possible representation of the Earth4All model showing key links. Each arrow represents a causal relationship. The '+' signs at the arrowhead indicate that the effect is positively related to the cause (e.g. an increase in population causes deaths to rise above what it otherwise would have been). The '–' signs at the arrowhead indicate that the effect is negatively related to the cause (e.g. an increase in environmental damage causes productivity to fall below what it otherwise would have been).

Key model modules and cross-sectoral dynamics[1]

In order to understand long-term determinants of human wellbeing over the century one needs to capture how the global population could develop. In the Earth4All model system, the ***population module*** generates the total population and population in different age cohorts. The population age structure provides the numbers of children, pensioners and people in the potential workforce and child-bearing ages – central in determining the long-term population and macroeconomic developments. The population development depends on the modelled fertility and mortality rates which are endogenously derived from the causal structure of the model.

The ***labor market module*** generates workforce, workforce participation rate, and the workers' share of output. The model distinguishes between workers, whose primary source of income is paid labor, and owners who receive capital incomes. The labor market module produces a cyclical behavior in the economy, representing the Juglar cycle, reflecting the undulating co-development of workers', and owners' income shares, and related unemployment dynamics. This can be most easily observed in the long-term time series of employment and investments(A'Hearn & Woitek, 2001; Ayres, 2020; Korotayev & Tsirel, 2010).

The labor market module feeds into the ***output module*** that tracks how investment leads to the formation, accumulation and consequent depreciation of capital. Combined with the

[1] Here, only a few of the model assumptions are presented. A more thorough presentation can be found in the Methods section below as well as in the supplementary materials and in (Randers & Collste, 2023).

total amount of employed labor and the total factor productivity component, it generates the Gross Domestic Product, from which incomes are paid.

The ***public module*** calculates public spending based on tax revenues (from workers and owners) and the creation of additional public debt, allocating the budget on governmental goods and services, including welfare transfers. Tax rates also affect owners' saving rates, and consequently investment rates.

The population and production developments give rise to food and energy demands. The ***food module*** tracks the expansion of agricultural and urban lands and the cutting of forests. Agricultural yields depend on productivity determined by fertilizer use and type of agriculture, and are also affected by emissions and global warming. If there is not enough land to satisfy the food demand, then agricultural land use will be expanded. The production of fertilizers causes N_2O emissions that are tracked by the climate module. The model's ***energy module*** generates fossil-fuel based and renewable energy production. The consequent greenhouse gas emissions are also tracked by the climate module.

The ***climate module*** tracks how greenhouse gas emissions from energy, industry and land use are accumulated in the atmosphere (and eventually absorbed by land and oceans), and how increased radiative forcing gives rise to global warming. Global warming, in turn, serves as a proxy for many environmental problems that negatively affect the economy by causing destruction of capital, increasing the cost of capital and harming productivity. Global warming also, in the long run, increases human mortality rates.

The ***wellbeing module*** gives the average wellbeing index from the components mentioned above: incomes per person, public spending per person, inequality, global warming and progress. Fig. 2 portrays causal links between these main determinants of human wellbeing. We have chosen to focus on the concept of progress in society, which is novel to this type of world modeling. We introduce a 'Progress reinforcing loop': if human wellbeing increases, this gives a sense of social progress being made which, in turn, further increases wellbeing. Fig. 2 also portrays the concepts of 'social tension' and 'social trust'. In the model, if 'rate of progress' stagnates or decreases, 'social tension' builds up, which restricts 'government capacity to act'. Our hypothesis is that if citizens experience increasing inequality and limited public investments, then this causes decreasing trust in governmental institutions and 'social trust' deteriorates(Blind, 2006; Keele, 2007; Reiersen, 2019). This, furthermore, negatively affects 'government capacities to act' which slows down policymaking, in the model world referred to as 'reform delay'(Blind, 2006; Klijn et al., 2010; Wallis & Dollery, 2002).

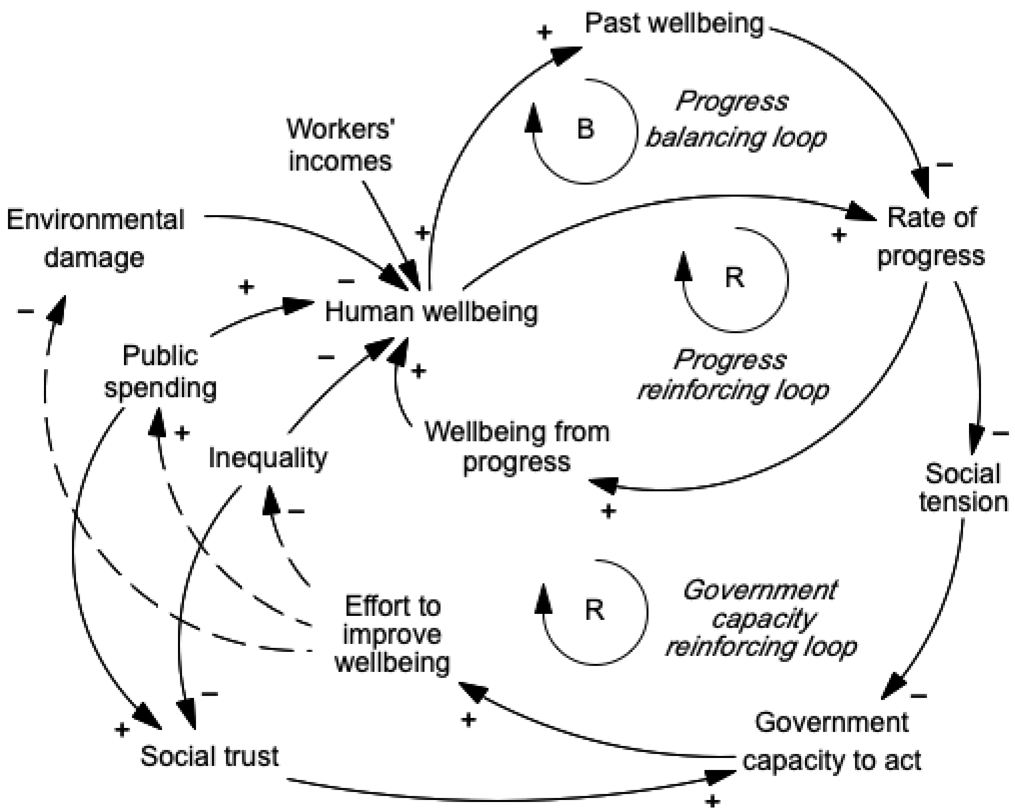

Fig. 2: Main determinants and components of wellbeing in the Earth4All model. See the description of the use of links and polarities ('+' and '-') in the caption to Fig. 1. 'R' signifies a reinforcing loop and 'B' a balancing loop.

Two scenarios: Too Little, Too Late (TLTL) and Giant Leap (GL)

We have designed two scenarios to study wellbeing in the model. The first scenario, *Too Little, Too Late* (TLTL), reflects decision-making continuing in the same vein as in 1980-2020. The TLTL scenario could be referred to as 'decision-making as usual'. That is, it does not presume the continuation of current trends but assumes that causal decision-making structures remain the same. Only the same type and scale of responses are being made to tackle rising inequalities and growing environmental concerns as in the previous 40 years.

The second scenario is titled *Giant Leap* (GL). The GL scenario reflects a situation in which governments and investors around the world take extraordinary and transformative actions to 'change the system' by implementing five major policy turnarounds(Dixson-Declève et al., 2022)'(Randers et al., 2019). The turnarounds are briefly presented below, with details including parameter values given in the supplementary materials.

1. The *Poverty* Turnaround: Rapid poverty reduction in all low- and middle-income countries by massive investments in private and public sector capacity, debt cancellation, and increased productivity growth rates.
2. The *Inequality* Turnaround: Increased government capacity through higher taxes, especially on owners. This generates more transfers to workers. This also incorporates a universal basic dividend, in which extraction from commons is taxed.
3. The *Empowerment* Turnaround: Reflecting more opportunities for women and girls, including major improvements in women's health and education. This is

operationalized in the model environment through decreased fertility rates and raised taxes.

4. The *Food* Turnaround: improved food sector productivity through sustainable intensification incorporating more efficient use of fertilizers, eliminating food loss and waste, and change in diets including less consumption of red meats. These changes are operationalized in the model environment through increased crop productivity rates, more regenerative agriculture and less red meat consumption.
5. The *Energy* Turnaround: Investments in energy efficiency, increasing the fraction of renewables through electrification and investments in renewable electricity capacity. This turnaround also includes direct air capture through carbon capture and storage technologies.

Megatrends over the next 80 years

The model was applied to world development between 1980 and 2100, with the resulting behavior of the main model variables presented in Fig. 3a and 3b.

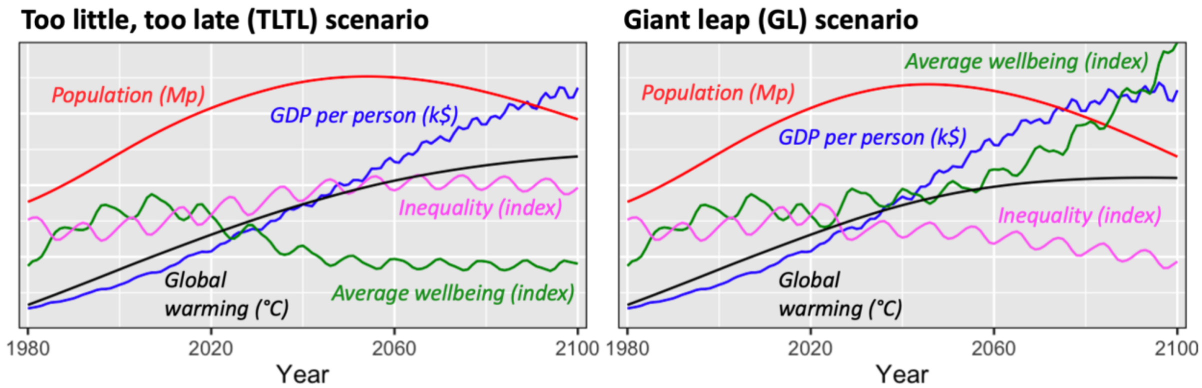

Fig. 3: Scenario results of (a - on the left) Too Little, Too Late and (b - on the right) Giant Leap for: Population (red), GDP per person (blue), global warming (black), average wellbeing (green), and inequality (pink)

The TLTL scenario (Fig. 3a) shows a rapidly increasing world population up to mid-century after which population peaks and starts to decline. The slowing population growth rate is well documented in the literature and reflects how increased access to health and education services enabled through increased incomes causes fertility rates to decline (see (Callegari & Stoknes, 2023)). However, the world population in the TLTL scenario still increases by 10–20 percent which, together with the increases in incomes, implies significant increases in material consumption and environmental pressures up to mid-century. As a consequence, we see global average temperatures increasing to well above 2.0 ^{o}C above pre-industrial levels. In the real world this would imply (unacceptably) high risks of triggering several Earth system tipping points(McKay et al., 2022). Inequality continues to rise due to limited taxation as well as a limited public service provision.

In the GL scenario, the population growth is curbed and the world population peaks and begins to decline already before 2050. The slower population growth compared with the TLTL scenario is interpreted in the model as a consequence of decreased fertility rates due to substantial investments in poverty reduction, health, education and women's empowerment. Also the worsening within-country inequality since 1980 is in the simulation curbed through progressive taxation and strengthening worker rights and trade unions as well as transfers including Universal Basic Dividend. Inequality begins to decline already in the 2020s. Although the income per person continues to increase throughout the century, economic development in the GL scenario causes significantly less environmental damage. This is achieved through both relative and absolute decoupling of GDP from pollution including through electrification, reforestation, regenerative agricultural practices and a smaller global population in the second half of the century. In this scenario, global warming is kept below 2 °C before the end of the century, with a declining trend toward 2100.

Results and discussion: Determinants of human wellbeing over the next 80 years

The model's main megatrends lead to the wellbeing determinants outcomes as shown in Fig. 4.

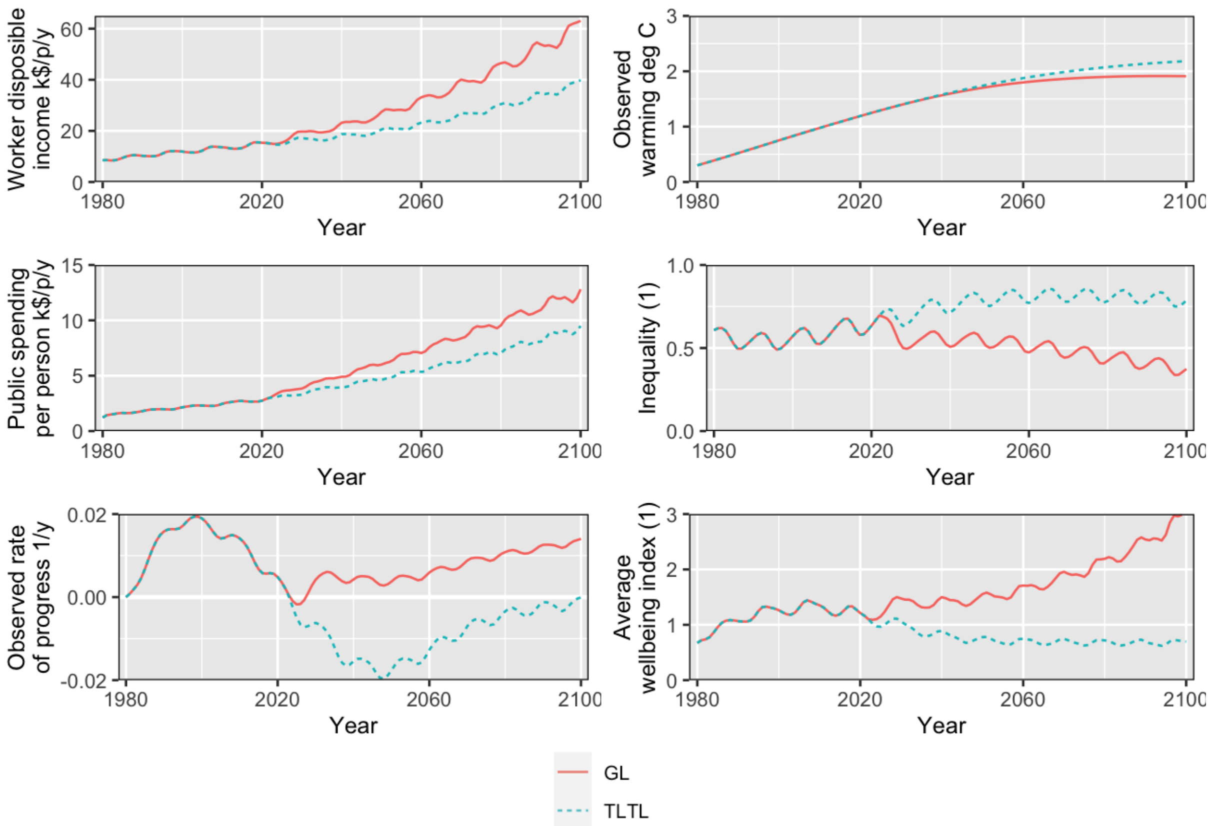

Fig. 4: Scenario results for the five determinants (components) of global average wellbeing: disposable income, global warming, public spending per person, inequality, and observed rate of progress in wellbeing. The last graph shows the resulting average wellbeing index. GL - red solid line, and TLTL - turquoise dotted line.

In the TLTL scenario, the graphs show a declining wellbeing index from the 2020s onwards. Despite increases in GDP, private incomes and public spending per person, rising inequality and escalating global warming causes limited progress, which further pulls the average wellbeing downwards from 2020 all the way to 2100 and also causes rising social tensions.

In the GL scenario, on the other hand, the decline in the wellbeing index since around 2010, is turned around during the 2020s and wellbeing starts to rise throughout the century. This is because, in the modeling world, inequality and environmental degradation are curbed by the turnarounds. The investments in rapid greening of food and energy systems also contribute to societal progress and a reduction in social tensions, feeding back and improving governments' capacity for further action.

The megatrends and the resulting wellbeing in the model invite two important insights. Firstly, given the model'srather straight-forward hypothesis, it is very difficult to change the course of the world juggernaut. In the GL scenario, despite radical changes in the proposed turnarounds, the world only slowly shifts towards a more sustainable trajectory. However, secondly, despite similarities with the TLTL trajectories, GL has more space for action - and such actions may be enough to considerably change the global course of the main constituents of human wellbeing, especially in the longer run. Although the bifurcation where future development of human wellbeing shifts from a negative to a positive trajectory may be difficult to judge and estimate, the behaviors resulting from the assumptions ingrained in our model suggest that the proposed policies may contain what is needed for a more desirable development.

Furthermore, the modeled wellbeing index illustrates that it is possible to gain an understanding of wellbeing that is compatible with dynamics taking place in an integrated systems model. The exercise also highlights the need to endogenize relationships between the human world and biophysical Earth in order to design policies for societal transformations. Our modeling can provide cues for the designing of integrated policies to advance on the 2030 Agenda and what comes beyond(Dixson-Declève et al., 2022), and support more transparent science-policy-society dialogues.

The current model version, as all models, comes with many limitations; its greatest value is probably in illuminating our questions by giving better general systems understanding rather than providing precise answers(Saltelli et al., 2020). The model findings (as presented in the Earth4All book(Dixson-Declève et al., 2022)) have therefore been accompanied with scrutiny by Club of Rome's Transformational Economics Commission(Earth4All, 2023). It is crucial to mention that although the future always is terra incognita, the further that critical planetary boundaries are transgressed, the less predictable the world is becoming.

Concluding remarks
We asked: How can wellbeing for all be reached while reducing risks of destabilizing the planet? We have shown, in a new simplified model at least, that this sustainability aim can be achieved. The model results of the Giant Leap display eliminated poverty, healthier diets and clean energy, as well as reduced inequality. Similar to other modeling efforts, the simulation displays a stabilized climate at below 2°C – with colossal efforts. Even this level of warming would bring severe hardship and risks shocks at unprecedented scales, for example potentially simultaneous breadbasket failures. We also address the '*how*'. The GL scenario's five extraordinary yet plausible and quantified turnarounds that break with 'decision-making as usual' seen since 1980 have the potential to deliver increasing human wellbeing on a relatively stable planet by mid-century.

While the GL scenario is far from a utopia, the TLTL scenario is a gradual slide into what could plausibly become a series of catastrophes for humanity. The global average temperature rises of hte TLTL scenario would in the real world imply profound implications for the long-term viability of societies in vulnerable coastal areas and in large parts of the tropics. Climatic and ecological instabilities bring more frequent and costly extremes relative to the pre-2020 world, claiming much higher shares of public spending just to maintain and repair after each worsening event.

The Earth4All model can also be used to illustrate other transformation pathways, both ‘better’ and ‘worse’ than GL or TLTL. Among the novelties of our work is the inclusion of two indices that act as proxies for wellbeing and social tension. In the model we link social tension to perceived social progress. If people feel their standard of living is improving then social tension will fall. If people feel they are falling further behind the ‘elites’ then social tensions could rise. The assumption is that strong societal cohesion is unlikely if tensions within societies are high, making it challenging to govern effectively for long-term outcomes. The GL scenario thereby requires strong societal cohesion and governments with a strong mandate to act decisively to transform economies.

We can draw three insights from this. First, if the world behaves as in our model, current increases in inequality risk driving deep divisions in society as elites move further away from the vast majority of society - contributing to rising social tensions, a pullback from democracy, and slow progress on existential challenges like climate change. Second, this trend seems set to continue unless there is a major turnaround. Economic policies in many places are deepening inequalities within countries. Social progress is stagnating. This could make it increasingly difficult to effectively address existential challenges. Third, action to reduce social tensions and promote social progress will be key to building the necessary political support for the Giant Leap transformations to secure, as the IPCC Chair Hoesung Lee puts it, ‘a liveable and sustainable future for all’(IPCC, 2023).

Methods

Theoretical background. The Earth4All model is an integrated systems model(Pedercini et al., 2020, p. 20) with global scope that gives quantitative illustrations for the Earth for All book(Dixson-Declève et al., 2022). The model links aspects of the natural Earth and the human world, and interactions between the two. Here, we provide a more detailed note on the model than in the main text but refer to the fuller documentation that can be accessed in ref(Randers & Collste, 2023). The model is built in system dynamics software and the initiative is inspired by the system dynamics methodology and philosophy(Sterman, 2000). The (Sterman, 2000)model generates scenarios for the rest of the century for the variables in the focus of the Earth for All study.

As the model has been structured to reflect the past behavior 1980-2020, it is typically more likely that it more reliably captures megatrends in the period for 2020-2060 than for 2060-2100. The focus of the model is however to provide an overarching image of the hypothesized dynamics of the world-Earth system, to provide further questions for analyzes by more detailed and calibrated models, and not to provide precise point predictions. In line with this purpose, the model has not been calibrated to exactly match past behaviors. Furthermore, as we warn in the paper, social-ecological scenario development past 1.5°C and 2°C is profoundly difficult as our species and planet enter *terra incognita* (see (McKay et al., 2022)). If anything, the assumptions that the model illustrate are underestimating the potential effects of crossing Earth system tipping points(Dixson-Declève et al., 2022).

The perspective of the model is similar to the World3 model(D. L. Meadows et al., 1974) of the *Limits to Growth* book(D. H. Meadows et al., 1972), but with significant modifications in economic modules to more clearly distinguish between growth in footprint (including land use and energy) and economic growth (GDP). Planetary boundaries (global warming, land use and fertilizer uses) are modeled in the form of rising costs for obtaining the same physical flow in resources or pollution absorption. The harder the pressures against boundaries, the more physical labor and physical capacity (capital) must be used to maintain flows without degrading the environment. This means shifting labor and capital from conventional activity into more sustainable activity. Such a shift does not reduce the number of jobs, but shifts jobs from providing conventional goods and services to providing a better environment. By shifting labor and capital in the model, humanity gets slightly fewer goods and services (measured in physical units per year) in exchange for a more sustainable world. The Earth4All model hence explores growth in the human footprint on a finite planet where it is possible to reduce the negative effect of boundaries' transgression on production through the use of more labor and capital. In other words, the possibility exists to achieve a more sustainable world in exchange for a reduction in the physical output of goods and services.

In conventional macroeconomic language, "running into limits" in the model leads to (slightly) lower rates of growth in real GDP matching the (slightly) lower growth in output of goods and services (measured in physical units) compared to a situation without limits. Running into limits leads to a (slight) reduction in real labor productivity because labor and capital is shifted into sectors with (slightly) higher costs. In the E4A model this slowing is represented as a (slight) slowing of the rate of growth in total factor productivity (TFP).

Below follows a summary of the model's modules. Note, however, that the modules have all been constructed given the overarching aim of representing the most important determinants of human well-being. Therefore, much module detail has been sacrificed for giving an overall image of the structure and behaviour of the world the model represents.

Population module. The population module considers four age cohorts (0-19, 20-39, 40-59 and 60+) with fertility and mortality endogenously calculated based on a lagged function of GDP per person (based on the assumption that fertility rates depend on access to healthcare and education which are strongly correlated with GDP per person). The prevalence of global warming causes increased mortality. In order for the model to reproduce SSP2 scenarios, a life expectancy multiplier and fertility multiplier have been introduced in 2022. The population module generates the working-age population. As an example of the crude level of the model calculations, the model is not using age-specific death rates but instead every person in the model is reaching the average life expectancy and then dies. Our hypothesis is that this does not change the overarching image that we provide, but we invite other modeling teams to investigate this further.

Output module. The output module generates real GDP from (1) real capital formation and discard, (2) jobs from the capital labor ratio, and total factor productivity using a Cobb-Douglas function. The output module depicts economies as the sum of a private sector and a public sector, with their separate capitals.

Labor market module. The model separates workers, whose primary source of income is paid labor, from owners, whose primary source of income stems from ownership of the means of production. The module calculates the worker share of output, which increases when labor is in short supply and owners can reduce wages. The long-term dynamics is reflected in the capital-labor ratio – defined as the amount of capital supporting each worker. The capital-labor ratio grows as society gets richer reducing the number of jobs per unit of output.

Public sector and demand modules. The public sector and demand modules calculate total factor productivity which is mainly set exogenously but affected by inequality (negative effect), state capacity (positive effect), and investments in unproductive activities (negative effect. The sectors also generate public spending from tax revenues, the net effect of debt transactions (public and private), and the distribution of the budget on governmental goods and services (including on technological advance and the five turnarounds).

Finance and inventory modules. The finance and inventory modules generate inventories and interest rates. The modules generate short-term (around 4 years) fluctuations in inventory, inflation, interest rates and asset values.

Food and land-use module. The food and land-use module tracks forest areas, croplands, grazing lands, and urban areas. It tracks overall soil quality as a function of fertilizer use and regenerative agricultural practices. Cropland expansion is a function of the size of the population and people's preference for red meats depending on income levels. The sector also calculates yields that are negatively affected by warming but positively affected by increased carbon in the atmosphere.

Energy module. The energy demand is calculated based on the size of the population as well as its overall wealth, accounting for the increasing energy demands of wealthier societies. Energy demand from industries and households is distributed among fossil (for electricity and non-electricity), nuclear and renewable sources. The module calculates the cost of energy and share of renewables with an exogenously defined goal for the fraction of renewable electricity (50%).

Climate module. *Observed warming* is simply calculated as a consequence of the *Extra heat on surface level* resulting from the albedo effect, water vapour, and anthropogenic forcing from greenhouse gases. These include CO_2 from energy and industry (*Energy module*), as well as from LULUC (Land use, and land-use change, from *Food and land-use module*); CH_4 from agriculture and land-use (from *Food and land-use* module); and N_2O from fertilizer use (*Food and land use module*).

Wellbeing, trust and tension module. The wellbeing, trust and tension modules are where the average wellbeing index and social tension index are calculated, using the factors presented earlier in this paper, see above.

Author contribution statement

PES and DC wrote the initial draft of the paper, and contributed to model building, testing and analysis, including providing country, regional and global time series data. PES initiated the project and contributed to the building of the Earth4All model with inputs from the rest of the team. FB made regressions, wrote the paper and documented analysis in the global guides. BC, SEC, and NS wrote the paper, with OW providing editing.

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Limitations

Fertility and mortality rates have been slightly modified in order for the model to be closer to the Shared Socioeconomic Pathways from 2022.

Assumption of no structural change (except for when it comes to the TAs being implemented) – particularly when it comes to implications of falling GDP under capitalism.

Use of global averages – e.g. lack of international inequalities assume all benefit equally from global public spending

Use of targets in the turnarounds

Weighting of variables in the wellbeing index

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Boundary object

The transparency of the model construction furthermore accommodates the nature of the model as a 'boundary object' that can be used for cooperation between researchers and other stakeholders in the knowledge-action interface

The research explores the intersection between the knowledge-producing processes of global sustainability research, and the actions necessary to achieve global sustainability goals, e.g., in the form of policy implementation. This form of knowledge-action interface can, according to Cash et al. (2003), be explored with different types of 'boundary objects', including models and scenarios. Exploring the knowledge-action interface can allow research to more effectively contribute to translating knowledge to action (Cornell et al. 2013).

The importance of boundary objects in tackling the polycrisis.