Ecological Modelling 475 (2023) 110164

Contents lists available at ScienceDirect

Ecological Modelling

journal homepage: www.elsevier.com/locate/ecolmodel

A model of Sustainable Development Goals: Challenges and opportunities in promoting human well-being and environmental sustainability

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ARTICLE INFO

Keywords:
UN Sustainable Development Goals
Well-being
Sustainability
Environmental sustainability
Human–nature modeling

ABSTRACT

The United Nations is dedicated to bringing countries together to solve international problems and to shape a better future. One of the greatest challenges facing society today is meeting the population's basic needs, while protecting the environment, hence the UN Sustainable Development Goals — 17 goals to overcome current and future sustainability challenges. We incorporate the 17 goals into a simplified global socio-ecological model to analyze what actions are necessary to promote a desirable future. We find that the current population size and resource use are not sustainable with any one goal or combination of goals. In the sustainable scenarios described here the global population decreases, while maintaining higher consumption levels. We estimate that sustainability hinges on maintaining an equivalence between natural and agricultural land areas and the human population — approximately 1ha of land per person is necessary to promote human well-being and environmental sustainability. Furthermore, we find that long-term sustainability hinges on changes within the next 50 years and goals that solely target environmental degradation or consumption are too slow to drive sustainability. Social progress is occurring much faster than environmental progress, therefore actions that target shifts in power dynamics, inequality, development and education in lower income countries should be prioritized to maintain ecosystem services and promote well-being. The goals that incorporate a combination of socio-ecological policies (SDGs 3,6,8,9,10,11) promote well-being and sustainability.

1. Introduction

Sustainability is a convoluted word, one that invokes images of humans living harmoniously with nature; or a system that benefits people, planet and profit. The most comprehensive definition of sustainability refers to practices that allow the current population to meet their basic needs, without jeopardizing the needs of future generations. The topic of sustainable development has become ubiquitous in the last 30 years (Salvia et al., 2019), yet how to achieve such a goal, or whether it is even possible, remains a major unknown.

Currently, there is no country that meets the basic needs of its population, while also using sustainable levels of resources (O'Neill et al., 2018). Therefore, the business as usual practices will not provide a sustainable socio-ecological system and alternative strategies are needed to promote a balance between societal needs and the environment. Yet sustainable development is far from straightforward and management practices, even though well-intentioned, such as restoration and conservation initiatives can hinder recovery of natural systems and even lead to declines in human population size and well-being (Henderson and Loreau, 2018; Kaplan-Hallam and Bennett, 2018). Nonetheless, the United Nations (UN) makes continuous and considerate efforts to overcome current and future sustainability challenges. The 17 UN Sustainable Development Goals (SDGs) and 169 targets represent a major achievement in the development of sustainable practices on a global scale. However, there is no quantifiable strategy to achieve sustainability nor the goals; although interconnected, the goals provide no details on their synergies and trade-offs when it comes to overall human and ecosystem well-being (Costanza et al., 2016). Two recurrent themes in the literature on SDGs relate to uncertainties surrounding interactions and indicators (Kubiszewski et al., 2022; MacFeely, 2019; Bennich et al., 2020; Horvath et al., 2022; van Noordwijk et al., 2018).

Reducing poverty and feeding the population are major challenges facing many African nations, but it has been argued that first other issues need to be addressed, such as access to clean water and improved sanitation (Mugagga and Nabaasa, 2016). The goals outlined by the UN are intricately linked with synergies between energy access, food production, medical facilities and water treatment (Nerini et al., 2018); climate change policies and renewable energy (Beg et al., 2002); urban ecosystems, sustainable consumption and infrastructure development (Maes et al., 2019). Trade-offs often relate to socio-economic and environmental sustainability, as raising environmental standards

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https://doi.org/10.1016/j.ecolmodel.2022.110164
Received 28 April 2022; Received in revised form 6 September 2022; Accepted 3 October 2022

can prove costly and beyond the capacity of smallholders (Brandi, 2017). These trade-offs between socio-economic sustainability and environmental sustainability can have detrimental effects on the desired outcome, by either hampering the well-being of the human population (Cazalis et al., 2018) or forcing individuals to relocate (Brockington and Igoe, 2006), and by causing environmental degradation to spillover into other regions, ultimately undermining the environmental policy (Milner-Gulland, 2012).

In the 1970s the Limits to Growth predicted that continuous growth would reach its limit in the 21st century resulting in a collapse of non-renewable resources, agricultural land and the capacity to absorb pollutants (Meadows et al., 1972). The model investigated feedbacks between population, industrial production, food supply, pollution and non-renewable resources, concluding that the pursuit of growth at the expense of the environment would lead to an uncontrollable decline in population and industrial capacity. However, the authors suggested that economic and ecological stability could be attained by reducing consumption and redistributing wealth. More than a decade later, the concept of sustainability as we know it today appeared in the Brundtland (1987) report, highlighting the need to maintain both present and future generations ability to access resources. The debate continues over 'sustainable growth' and the role of technology and population planning, with more coupled human–environment models using socio-ecological indicators — such as inequality (Motesharrei et al., 2016; Henderson and Loreau, 2021), well-being (Dietz et al., 2009; Cazalis et al., 2018), social learning (Barfuss et al., 2017), food trade (Tu et al., 2019), rebound effects (Freeman, 2018) and investment in sustainable development (Ursino, 2019) – to warn against unsustainable practices (Azar et al., 1996; Le Kama, 2001; Wang and Grant, 2021). Following the introduction of the UN SDGs there have been numerous models analyzing the synergies and trade-offs between goals and measuring indicators or quantifying achievement of goals (Costanza et al., 2016; Spaiser et al., 2017; Collste et al., 2017; Schulze et al., 2017; De la Poza et al., 2021). Of the models mentioned, only a handful explicitly model human population as a function of well-being and the feedbacks with resource use. A recent article by Crist et al. (2022) warns that population size must be reduced through improved human rights to ensure long-term well-being for all life on Earth, suggesting that population size and social infrastructure are critical in modeling sustainability.

To better understand the challenges of sustainable development in our global socio-ecological system, we analyze the 17 UN SDGs using a simplified model with two regions – a lower income region and a higher income region, resource inequality, and potential human biases. Our model cannot mimic the exact targets of the UN SDGs, but it is able to provide key components of change that contribute to sustainable development and gives insight into why some well-intentioned policies and solutions have undesirable consequences.

2. Methods

2.1. Base model

An existing model of global two-region system with inequality (Henderson and Loreau, 2021) – a lower income region with higher and lower income subpopulations and a higher income region with lower and higher income subpopulations — provides the framework for this work (Fig. 1). In addition to four population variables ($P_{i,j}$, i = income status of people, j = income status of region), the model consists of natural land in lower and higher income regions (N_j), agricultural land in L and H regions (A_j), conserved natural land in each region (C_j), and technology/development in lower and higher income regions (T_j). In the Henderson and Loreau (2021) model resource accessibility drives societal feedbacks within the system, but resource accessibility is also determined by numerous variables, making it the nucleus of the model. Resource accessibility per individual is dependent on the power wielded by their region (a combination of technological development and population size), the availability of agricultural and natural resources, the ability to acquire such resources, and the potential to enhance production yield with technology. The population growth curve follows an inverted u-shape with respect to resource accessibility, where the growth rate increases as resource accessibility increases, reaching a peak when resource accessibility is below a moderate level, after which it decreases with greater resource accessibility and well-being.

The change in population size in each region ($P_{i,j}$) includes social aspects such as migration (emigrating, $\delta_{i,j}(P,N,A,C,T)$ and immigrating, $\delta_{i,\bar{j}}(P,N,A,C,T)$), change in income status ($s_{i,j}(P,N,A,C,T)$, $s_{i,\bar{j}}(P,N,A,C,T)$), while other social norms are intrinsic within the resource accessibility/well-being function that determines the growth rate ($g_{i,j}(P,N,A,C,T)$) (Henderson and Loreau, 2019). The change in population size within each subgroup is given by

$$\begin{aligned}\frac{dP_{i,j}}{dt} =& \Big(g_{i,j}(P,N,A,C,T) - s_{i,j}(P,N,A,C,T) \\ &- \delta_{i,j}(P,N,A,C,T) \Big) \cdot P_{i,j} + \\ & s_{\bar{i},j}(P,N,A,C,T) \cdot P_{\bar{i},j} + \delta_{i,\bar{j}}(P,N,A,C,T) \cdot P_{i,\bar{j}},\end{aligned} \tag{1}$$

The model uses resource accessibility and power dynamics to determine social changes and consumption patterns. Resource accessibility is determined by technology and development, which facilitates access to resources: natural land — the availability of resources and ecosystem services; and agricultural land — the availability of resources and provisioning services. The change in natural land is given by

$$\begin{aligned}\frac{dN_j}{dt} =& \big(-dN_j(P,T) - xdN_j(P,T) - cv_j(P,T)\big) \cdot N_j \\ &+ a_d A_j + rt_j(P,N,A,C) - cs_j(N,C) \cdot N_j.\end{aligned} \tag{2}$$

Natural land declines with consumption — both domestic ($dN_j(P,T)$) and foreign ($xdN_j(P,T)$) and conversion to agriculture ($cv_j(P,T)$). N can also be set aside as conserved natural land ($cs_j(N,C)$), which provides supporting and regulating services, but not provisioning services. Natural land restoration in the model either occurs naturally through abandonment of agricultural land (a_d) or through active restoration ($rt_j(P,N,A,C)$). Agricultural land conversion is the primary driver of natural land degradation, but it is also highly dependent on the ecosystem services natural land provide. Therefore, agricultural land will continuously degrade without sufficient natural land. The change in agricultural land is given by

$$\frac{dA_j}{dt} = (-dA_j(P,N,C,T) - xdA_j(P,N,C,T) - a_d) \cdot A_j + cv_j(P,T) \cdot N_j, \tag{3}$$

Population size has both a positive and negative impact on agricultural land, by increasing degradation (domestic, $dA_j(P,N,C,T)$ and foreign, $xdA_j(P,N,C,T)$) and increasing conversion from natural to agricultural land ($cv_j(P,T)$). In the model, technology decreases the need to convert land by increasing efficiency. The benefits of technology have been debated based on the rebound effect (Freeman, 2018), this is taken into account by different rates for higher and lower income consumers. For example, a larger higher income subpopulation results in greater conversion.

Some SDGs aim to limit degradation of natural land and maintain ecosystem services, therefore we have included conserved natural land in the model. The equation for changes in conserved natural land is given by

$$\frac{dC_j}{dt} = cs_j(N,C) \cdot N_j. \tag{4}$$

There is a negative feedback that slows the rate of conversion to conserved natural land when the total area of natural and conserved natural land increases.

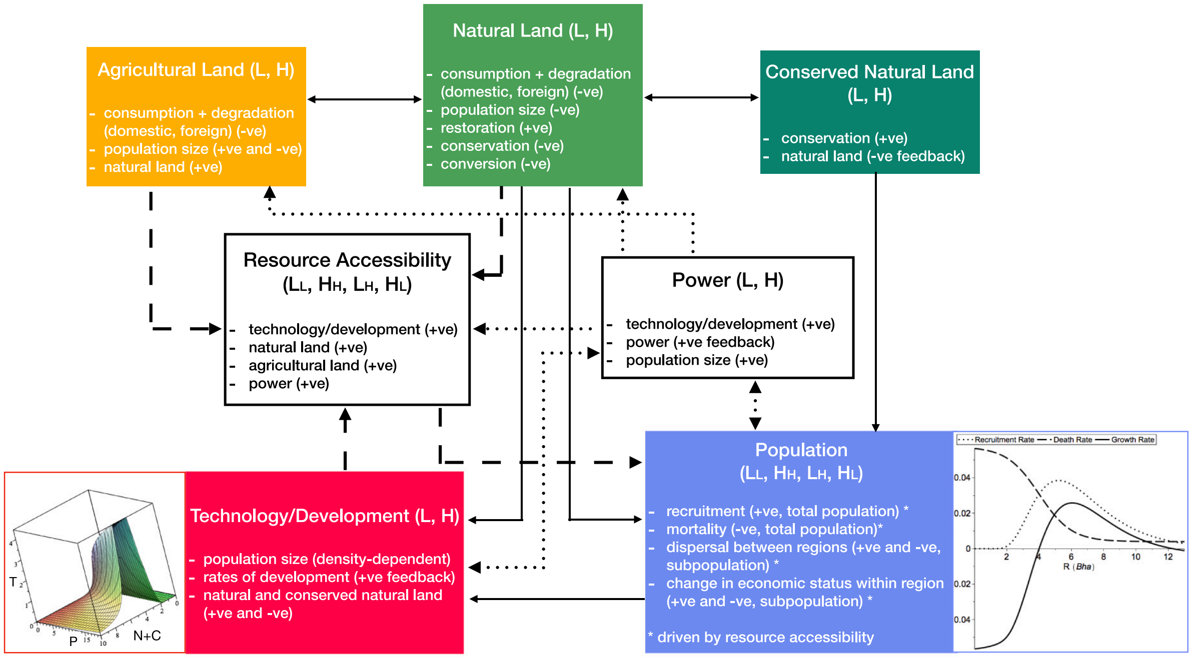

Fig. 1. Model framework from Henderson and Loreau (2021) used to analyze the impact of the UN Sustainable Development Goals. There are two main functions in the model that drive changes in the variables (Agricultural Land, Natural Land, Technology/Development and Population): Resource Accessibility and Power. The model is separated into lower income (L) and higher income (H) regions and the parameters reflect differences between the regions. The Population variable (P) and resource accessibility are separated into four subpopulations: higher income individuals in the H region (H_H) and the L region (H_L); and lower income individuals (L_L, L_H) in lower and higher income regions, respectively. In the brackets next to each factor is its impact on each variable, either positive, negative or a feedback. The technology and population curves are included, given their more complex non-monotonic relationships.

Finally, the model uses technology as a proxy for economic development, infrastructure, innovation, education and processing efficiency. The change in technology is given by

$$\frac{dT_j}{dt} = min(1,T_j)\cdot t_j \cdot \left(\frac{P_j^{0.5}}{max(1,(P_j^{0.5}-(N_j+e_sC_j))^2)}\right) \cdot min(1,(max(-0.001,(N_j+e_sC_j)-N_{th}))). \qquad (5)$$

Technology is represented by a non-monotonic curve that is density-dependent (P/N) and is dependent on the area of natural and conservation land, which provides essential ecosystem services. Furthermore, technology builds upon itself ($min(1,T_j)$), therefore the region with greater advances in technology has the potential to develop new technologies more quickly, akin to the power cycle described by Scheffer et al. (2017).

The initial conditions are set to reflect current population figures in lower and higher income regions using data from The World Bank (2019), land variables according to Food and Agriculture Organization of the United Nations (2019) and the technology/development variables are set to reflect current Human Development Indices (United Nations Development Programme, 2019). Resource accessibility is calculated from land and technology/development variables and translated into well-being status (poor (0.5–1 ha/pers.), moderate (1.1–3 ha/pers.), good (3.1–5.9 ha/pers.), excess (>5.9 ha/pers.)). Well-being ranges were calibrated using data from Global Footprint Network (2019) and The World Bank (2019), these results are available in Henderson and Loreau (2021). Further details regarding the model equations and functions are provided in the supplementary information.

2.2. Parameterization

There are no clear mechanisms indicated in the UN Sustainable Development Goals (SGDs) nor outlines as to how the goals are interconnected; therefore we used the targets to modify our model parameters in an effort to best represent each goal and specific targets within the goal (details in the supplementary information). The model is constrained and modified to meet the targets of each goal (details in Table 1). The base model is parameterized to conceptually reflect differences in lower and higher income regions using data from The World Bank (2019) and Global Footprint Network (2019), while the SDG parameterization is based on the desired outcome of each goal (i.e., reduction targets, increases in development, decreases in inequality). The modifications made to the model, in the majority of scenarios, are represented by changes in rates or bounds placed on functions. The mechanisms that drive actions (i.e. resource accessibility dynamics, technology curve, population dynamics) and model functions are not modified. Even without changing these mechanisms, the many feedbacks within the model (Fig. 1), and the socio-ecological system it represents, provide avenues for the SDGs to make changes.

Nearly all goals modify the rate of change of technology/innovation and the generation of new technology (t_L, t_H, technology & innovation coefficients in each region). Many of the SDGs specifically target lower income regions, which is reflected in the parameter changes, as well as an emphasis placed on technological and innovative improvements (i.e., large increases in technology & innovation coefficient) in the L region. The precise increase in the t_L and t_H coefficients is based on the percent change in development required to achieve the goal. Changing the technology & innovation coefficient in the model leads to long-term changes in power dynamics, social development, infrastructure development, and the ability to access resources. The modifications to the model in Table 1 are based on ideal outcomes.

2.3. Implementing UN SDGs in model

A more detailed explanation of the parameter changes and bounds for each of the UN Sustainable Development Goals is given in the supplementary information (table S1 a) 'ideal' values and b) 'realistic' values). We run an 'ideal' scenario (table S1.a), where each goal is executed efficiently and effectively, and a 'realistic' scenario (table S1.b), based on the degree of importance assigned to each goal per region and

Table 1

Constraints, parameter changes and model modifications for specific targets detailed in each of the 17 Sustainable Development Goals (SDGs).

SDG	Model modifications & parameterization
1 No Poverty	Minimum resource accessibility for all (moderate, $R = 1.7$ha/pers.); Redistribution of wealth through power dynamics (min 80% domestic power); ⇑ technology/innovation ($1.5 \cdot t_L$)
2 Zero Hunger	⇑ agricultural yield and technological efficiency in conversion rate to agriculture (2X in H, 5X in L); Redistribution of food supply through power dynamics (min 70% domestic power)
3 Good Health & Well-being	⇓ mortality rates ($0.83 \cdot m_{max}$); ⇑ technology/innovation ($2 \cdot t_L$, $1.04 \cdot t_H$)
4 Quality Education	⇑ technology/innovation ($2.4 \cdot t_L, 1.07 \cdot t_H$)
5 Gender Equality	⇑ technology/innovation ($1.5 \cdot t_L, 1.25 \cdot t_H$)
6 Clean Water & Sanitation	⇓ degradation rate of natural land (20% ⇓ in H,40% ⇓ in L); Include conservation of natural land ($max 10\% \cdot N$); ⇑ technology/innovation ($2 \cdot t_L$)
7 Affordable & Clean Energy	⇓ degradation rate of natural land (20% ⇓ in H, 40% ⇓ in L); ⇑ technology/innovation ($1.66 \cdot t_L, 1.1 \cdot t_H$ %)
8 Decent Work & Economic Growth	⇓ in natural and agricultural land degradation (10% ⇓ dN, dA, xdN, xdA); ⇑ technology/innovation ($1.66 \cdot t_L$); Redistribution of wealth through power dynamics (min 70% domestic power); ⇑ efficiency of resource use ($1.1 \cdot R$).
9 Industry, Innovation & Infrastructure	⇓ resource accessibility gap between H and L regions; ⇑ technology/innovation ($2.2 \cdot t_L$, $1.04 \cdot t_H$)
10 Reduced Inequalities	Redistribution of land management through power dynamics (min 70% domestic power); ⇑ technology/innovation ($2.2 \cdot t_L, 1.04 \cdot t_H$); Redistribution of resources through resource accessibility ($R_H = 1.1 \cdot R_L$)
11 Sustainable Cities & Communities	⇓ natural land and agricultural land degradation (20% ⇓ dN, dA, xdN, xdA); ⇑ technology/innovation ($2.2 \cdot t_L, 1.04 \cdot t_H$)
12 Responsible Consumption & Production	⇓ environmental degradation (20% ⇓ dN, dA, xdN, xdA); ⇑ resource efficiency ($1.2 \cdot R$); ⇑ technology/innovation ($1.1 \cdot t_L$)
13 Climate Action	Include conservation of natural land ($max 20\% \cdot N$); Restore natural land (5X); ⇑ technology/innovation ($1.66 \cdot t_L, 1.1 \cdot t_H$)
14 Life Below Water	⇓ natural land and agricultural land degradation (10% ⇓ dN, dA, xdN, xdA); Include natural land conservation ($max 2\% \cdot N$); ⇑ technology/innovation ($1.1 \cdot t_L$).
15 Life on Land	Include conservation of natural land ($max 30\% \cdot N$); Restore natural land (25X); ⇓ natural land degradation (20% ⇓ in dN, dA, xdN, xdA)
16 Peace, Justice & Strong Institutions	Redistribution of land management through power dynamics (min 80% domestic power); ⇑ technology/innovation ($1.1 \cdot t_L$)
17 Partnerships for the Goals	Redistribution of resources through power dynamics (min 80% domestic power); ⇑ resource efficiency ($1.1 \cdot R$); ⇑ foreign consumption of L resources (10% ⇑ xdN_{HL}, xdA_{HL}); ⇑ technology/innovation ($1.7 \cdot t_L$)

the ease of implementing the targets (Salvia et al., 2019). For example, climate change is deemed critical by all, however the likelihood of individuals implementing the necessary changes to mitigate climate change remains a challenge (Gifford, 2011). Furthermore, the damage to the coral reefs, rising sea levels and ocean acidification cannot be undone (Frölicher and Joos, 2010), which makes climate change a difficult goal to achieve.

2.4. Time scale

Sustainability in the human context is discussed over relatively short time scales. Discussions of human development beyond the beginning of the 22nd century are often seen as irrelevant given how rapidly society progresses. Therefore, the model simulations are run for 70 years. We also include long-term simulations to analyze the sustainability of the system for each scenario under current conditions. After 700 years the results reach a sustained value. Given that the model contains 12 variables we are unable to calculate an analytic equilibrium, hence we run the model over an extended period to give an idea of possible trends. These long-term results are unlikely to be quantitatively realistic nor do they infer an equilibrium, but they can give an idea of which practices are sustainable under current conditions.

3. Results & Discussion

The model shows the potential for positive change along the environmental, social and economic axes, all of which are pillars of sustainability. Here, socio-economic sustainability is quantified by population size and well-being. Well-being is measured quantitatively by access to resources, which is calculated as a function of resource availability and technology/development. Qualitatively this resource accessibility measure is a proxy for education, wealth, health and environmental quality (Henderson and Loreau, 2019; OCDE, 2020). Environmental sustainability is determined by the extent of land cover change.

Under the 'ideal' scenario (i.e., goals implemented efficiently and in accordance with targets), the majority of SDGs promote higher well-being and more sustainable land use (Fig. 2). However, there is a discrepancy between the stated goals and what individuals in each region are willing to change or what they believe needs to change (Salvia et al., 2019). Therefore, we also included a more realistic scenario where we skew the goals based on the regional interest in pursuing each goal and the ease of implementing the goals. In the 'realistic' scenario (Fig. 3), the number of goals providing positive change compared to the business as usual (BAU) scenario decreases from 15 out of 17 in the 'ideal' scenario, to 10 out of 17. In the 'ideal' scenario, nearly all goals slow the degradation of natural land, reduce population size and improve well-being (Fig. 2). In contrast, the 'realistic' scenario decreases the rate of land degradation in the lower income region only, improves well-being in 8 scenarios and reduces population growth in 9 out of 17 scenarios (Fig. 3), which suggests if the goals are only partially implemented the outcome is unlikely to improve and in some scenarios may result in faster land degradation and a larger global population (e.g., SDGs 2, 12 in Fig. 3). In the following paragraphs we give possible reasons for the unintended consequences and potential drivers of increased population size and land degradation.

3.1. Well-being

Improving well-being in the next 70 years is shown here to be critical in achieving long-term sustainability (Fig. 4), as sustainability requires that the needs of the current population are met, while also ensuring that the needs of the future population can be met. If within the next 70 years well-being improves in the P_L, such that well-being is 'good' (3.1 ha–5.9 ha/pers.) then the long-term outcome is a sustainable population with 'excess' well-being (>5.9 ha/pers.). Otherwise, regardless of the goal or target, the population well-being in both regions declines to 'poor' or worse overtime, with the degradation of land (Figs. 2&4, 3&5). The exception being no poverty (SDG 1), which maintains a moderate well-being for long enough to allow the population and land cover to balance out.

Additionally, the life on land goal (SDG 15) is highly susceptible to changes in income status and dispersal, which are dependent on the access to resources. In the 'ideal' scenario, the recovery of the natural land prevents the collapse of resources long-term and allows the population well-being to improve overtime from moderate to excess

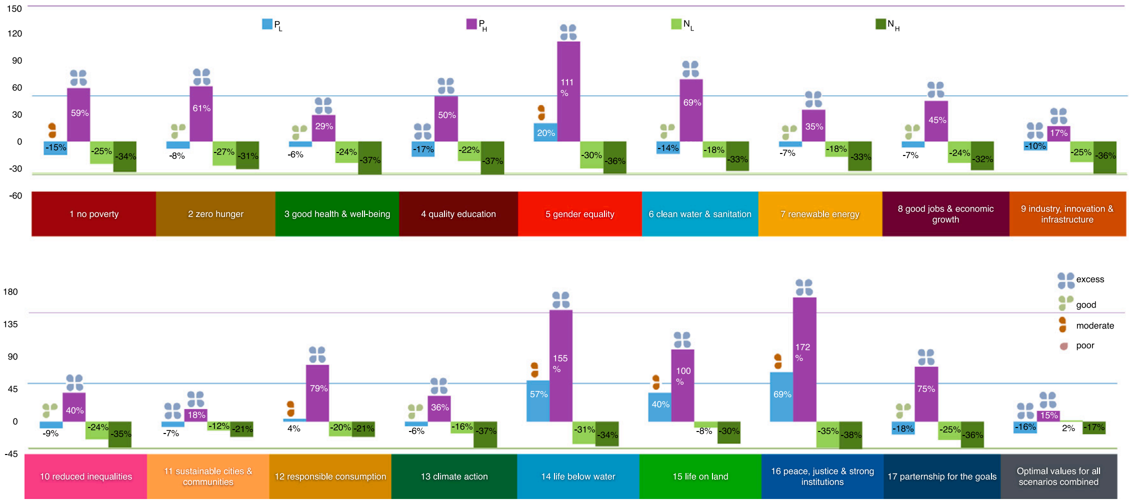

Fig. 2. Ideal goals scenario. The above chart shows the population (P) change in each region, lower income (L) and higher income (H) over the next 70 years for each goal under 'ideal' implementation of the UN SDGs ('ideal'= goals implemented to achieve targets in the absence of bias and without considering difficulty of implementation). The natural land cover (N) diminishes over the next 70 years in each region (light green bar, N_L; green bar, N_H). Natural land cover contributes to resource accessibility, which determines well-being. Well-being is shown by the number of petals: 1 – poor (0.5–1 ha/pers.), 2 – moderate (1.1–3 ha/pers.), 3 – good (3.1–5.9 ha/pers.), 4 – excess (>5.9 ha/pers.). The business as usual well-being over the next 70 years in the absence of the SDGs is excess in the higher income (H) region and moderate in the lower income (L) region. The lines represent the business as usual (BAU) values for positive population change and natural land degradation. Blue = P_L; purple = P_H; light green = N_L, green = N_H.

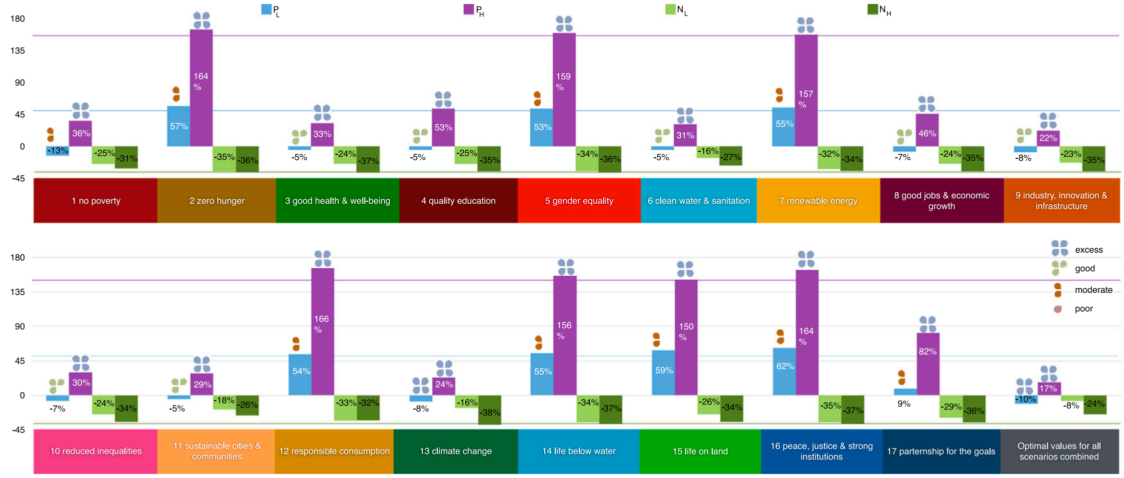

Fig. 3. Realistic goals scenario. The above chart shows the population (P) change in each region, lower income (L) and higher income (H) over the next 70 years for each goal under 'realistic' implementation ('realistic' = bias and difficulty of implementation included using Salvia et al., 2019) of the UN SDGs. The natural land cover (N) diminishes over the next 70 years in the L region (light green bar, N_L). Well-being is shown by the number of petals: 1 – poor (0.5–1 ha/pers.), 2 – moderate (1.1–3 ha/pers.), 3 – good (3.1–5.9 ha/pers.), 4 – excess (>5.9 ha/pers.). The business as usual (BAU) well-being over the next 70 years in the absence of the SDGs is excess in the H region and moderate in the L region. The lines represent the BAU values for positive population change and natural land degradation. Blue = P_L; purple = P_H; light green = N_L, green = N_H.

resource access. However, in the 'realistic' scenario the recovery of natural land is not fast enough to prevent population displacement due to insufficient resources, pushing the system away from sustainability. Natural land recovery efforts, in the absence of social consideration, need to be sufficient and well-received, otherwise the outcome is less desirable than the business as usual scenario. However, if combined with social development the risk of counteractive feedbacks are reduced and sustainability is achievable.

3.2. Land cover & consumption

Surprisingly, the effort to decrease land degradation and promote natural land recovery – as seen in SDGs 14 and 15 – further increases population growth. If changes to the environment are prescribed, without considering inequality and other social issues, the outcome of decreasing degradation, restoration and conservation is undermined by insufficient development in lower income regions and the unequal distribution of goods. This occurs as feedbacks within the system move people and goods between regions causing an improved sense of access to resources and increased consumption. These feedbacks lead to time lags between actual change and perceived change (Henderson and Loreau, 2021), and as a result there is no change in well-being (i.e., resource accessibility per capita). However, if social issues and infrastructure development in the lower income region are included with environmental management the overall well-being improves, the environment degrades more slowly and the population becomes wealthier and grows more slowly over the next 70 years, as is the case with sustainable cities and communities (SDG 11), climate change (SDG 13), clean water & sanitation (SDG 6) development goals, and all the goals combined. The feedbacks described above are suspended by more equal distribution of goods and resources.

The impact of reduced consumption (SDG 12) is similar to the environmental goals (SDGs 14, 15). Conceivable decreases in consumption (10%–30% reduction) are too slow to promote sustainable land use

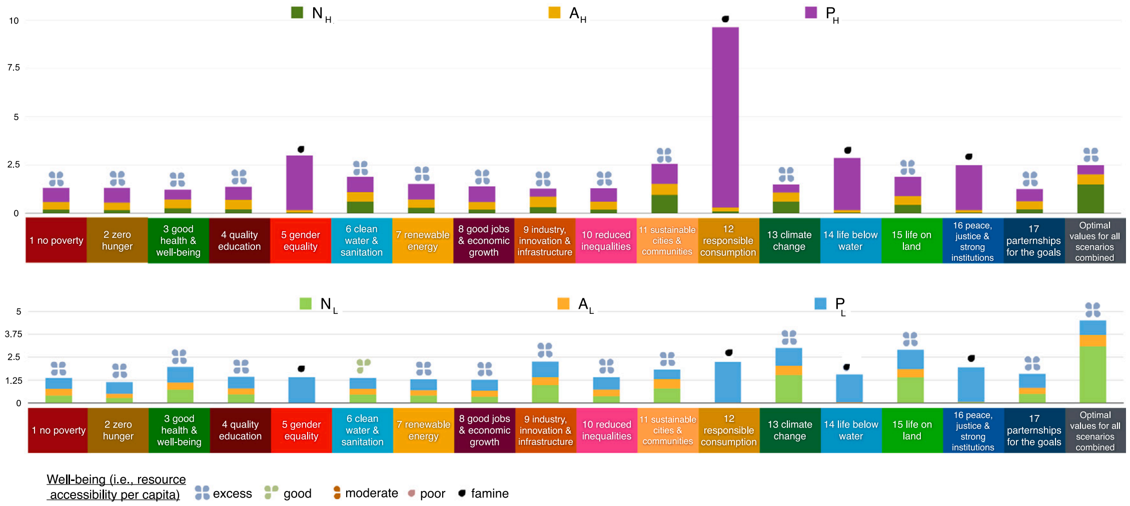

Fig. 4. 'Ideal' scenario long-term. Long-term proportion of land (natural (N_L, N_H) and agricultural (A_L, A_H)) and individuals (population (P_L, P_H)) in the higher income (H) and lower income (L) regions for the 'ideal' scenario. The population described here includes both higher income and lower income individuals within each region. The stacked bars show that well-being after 700 years, once the variables settle, is 'poor' or worse when there are more people than available land in the region. In contrast, when there is a balance between land area and population size, the well-being is 'excess'. The combination of all goals results in the greatest natural land area and highest population with 'excess' well-being. The technology curve in the L region continues to grow, which maintains large areas of natural land and the greatest population size with a desirable well-being, compared to the other scenarios.

over the next 70 years. We tested various rates of land degradation to determine if reduced consumption and degradation alone could increase well-being, while reducing the degradation rate of natural land, and we found that the decline in consumption and degradation of land needed to be 10 times the current rate to avoid feedbacks in the system that counteracted land use changes.

The climate change goal (SDG 13) has garnered the most attention and is a priority for both higher income and lower income regions, which is why the implementation of climate change action has such a positive impact on the modeled system: the population only increases by 0.16B globally over the next 70 years, compared to 5B in the business as usual (BAU) scenario over the same period, and well-being in the L region doubles (Figs. 2, 3). The decrease in the H population results in less consumption and slower land degradation in the L region (≈ 20% more natural land). That being said, this goal is also difficult to achieve. The description of the climate change goal provides very few targets compared to the other goals, but in our model we give optimistic values for parameter changes based on the bias towards promoting SDG 13 (Salvia et al., 2019). The challenges related to the climate change goal arise from the ambiguity in how to implement actions and the resistance to perceived paradigm shifts in daily habits in order to meet climate change targets. Nonetheless, the climate change goal combines many other SDGs that are more manageable at the regional scale, such as education (SDG 4), reduced consumption (SDG 12), development of green technologies (SDG 9). Therefore, if individuals gave the attention they do to climate change to these synergistic goals, the outcome could be favorable for the human population, the environment and the economy, without being overwhelming or politically/economically polarizing.

3.3. Population

The lower income and higher income regions have drastically different lifestyles and habits (Henderson and Loreau, 2021; Cumming and von Cramon-Taubadel, 2018), which is why implementing the same goal in two distinct regions may not be effective and can even have negative consequences, due to differing feedbacks and behaviors within each system. Our model shows that the lower income region needs to develop in order to have any chance at sustainability, but that will also increase the need to consume responsibly, to avoid the same errors made by higher income countries. This work, along with others (Salvia et al., 2019; United Nations, 2019), emphasizes the need for higher income countries to focus on SDGs 12, 13 and 15, while promoting equality (SDG 10), both locally and abroad. The model suggests that the current development and technology in the H region is sufficient to promote sustainability, but the resource use needs to be reduced and more evenly distributed among society for long-term maintenance of resources.

Given the differences between the two regions, the future population dynamics (how many, where and in what income bracket) will play a critical role in sustainability. The higher income region experiences the greatest population increases (Figs. 2,3), either from migration ($\delta_L(P,N,A,C,T) > g_H(P,N,A,C,T)$) or populations shifting income groups ($s_{L,H}(P,N,A,C,T) > s_{H,L}(P,N,A,C,T)$). Recently, migration rates have outpaced the population growth rate (United Nations Population Division, 2019), as individuals seek better opportunities (United Nations Global perspective Human stories, 2019). The move from the L region to the H region in SDGs 2, 5, 12, 14, 15, 16 can be explained by the described recent migration trends. Furthermore, as the flow from the L region into the H region increases so does the inequality gap between the two regions, which tends to increase the volume of individuals migrating (Lee, 1966), and explains the massive population increase in the H region seen in the simulations. The 'realistic' scenario increases the number of people searching for better opportunities, as inequality is greater in the 'realistic' scenario ($avg(R_L)$ = moderate, $avg(R_H)$ = excess, 'realistic' scenario; $avg(R_L)$ = good, $avg(R_H)$ = excess, 'ideal' scenario). Only in the combined goals scenario, where the largest parameter change for all the SDGs is selected, do both regions become equal with only higher income subpopulations and no migration ($\frac{avg(R_j)}{R_{i,j}} \leq 1 \Rightarrow \delta_{i,j}(P,N,A,C,T) \Downarrow$).

Additionally, simulations show a major increase in development in the L region and therefore, in many cases, growth of the higher income population results from whole countries becoming wealthier. In scenarios for SDGs 1, 3, 4, 6, 7, 8, 9, 10, 11, 13, 17, a portion of the L region becomes wealthier and therefore the total higher income population increases without actually dispersing. As a result of more higher income individuals, land degradation occurs more rapidly in the H region to accommodate for more people and greater needs.

Improved well-being and wealth for the lower income population will place greater demands on the environment, but that is not a reason to prevent development in lower income countries. As it stands, the current population numbers and resource use are not truly sustainable.

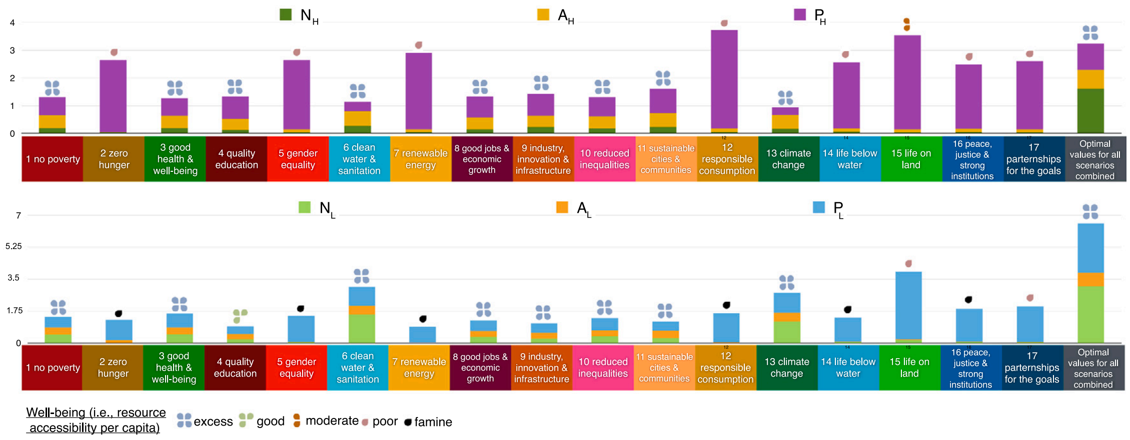

Fig. 5. 'Realistic' scenario long-term. Long-term proportion of land (natural (N_L, N_H) and agricultural (A_L, A_H)) and individuals (population (P_L, P_H)) in the higher income (H) and lower income (L) regions for the 'realistic' scenario. The population described here includes both higher income and lower income individuals within each region. The stacked bars show that well-being after 700 years, once the variables settle, is 'poor' or worse when there are more people than available land in the region. The number of scenarios showing a high population, poor well-being and degraded land increases to nearly half of all scenarios.

The future 'sustainable' population would have to be much smaller in order to maintain a high-consumption lifestyle. In this scenario, individuals make the choice of higher consumption lifestyles, with fewer children, gradually decreasing the population over the next 700 years. The exact values may not be realistic, however from the results we conclude that sustainability requires a proportional ratio of natural and agricultural land to human population size to promote well-being and maintain ecosystem services (Figs. 4,5). The proportion of agricultural land can exceed the proportion of natural land, but given the model assumptions that agricultural land and technology/development decline in the absence of natural land there is no scenario in which agricultural land exists long-term without natural land. Therefore, agricultural land would decline without natural land and ultimately lead to famine within the population.

3.4. Inequality

There is an overwhelming theme that arises when analyzing the goals: sustainability requires a change in power dynamics (i.e., inequality). In the model, power determines how much access each region and subpopulation within the region has to natural and agricultural resources and how the land is managed. The current system is heavily skewed against lower income countries ($power_L \ll power_H$, $R_L < R_H$), impacting income (i.e., $s_{i,j}(P,N,A,C,T)$), land management (i.e., $xdN_H(P,T) > xdN_L(P,T)$, $xdA_H(P,N,C,T) > xdA_L(P,N,C,T)$), and mobility (i.e., $R_{H,L} < avg(R_H) \Rightarrow d_{H,L}(P,N,A,C,T) \Uparrow$). This creates a positive feedback of inequality that leads to an undesirable future.

The model shows three ways in which the power ratio can be improved. First, a direct change in land access and management through policy intervention that promotes equal access between higher income and lower income regions, such as the case of SDG 10 Reduced Inequalities. Second, the access to resources may be redistributed to ensure equal distribution among income levels and individuals (SDG 2, Zero Hunger). Lastly, by increasing technology and development (e.g. SDGs 3,4,9,11), power intrinsically changes, as the lower income region improves living conditions and have greater capital to manage their own land.

3.5. Technology & development

The model uses a broad definition of technology and development, which includes innovation, infrastructure, education and income gains. The emphasis on technology and development shown here should be taken with a grain of salt, as Binswanger (2001) suggested that resource-saving and energy-saving technological progress will not be sufficient in order to make the economy sustainable because of the induced feedback in energy or resource demand, described as the rebound effect. Furthermore, rapid economic development without consideration for the environment and without proper infrastructure and waste management leads to severe environmental degradation (Tang et al., 2017), therefore the type of development, or the effect of technology may be more critical than the quantitative change. In order for technology and development to be effective tools, they need to take into consideration social and environmental needs.

This is where power dynamics are most evident — who gets to decide what rules are set and how they are enforced; how the economic incentives and disincentives are applied; and what norms and expectations are placed on people and organizations (Swinburn, 2019).

4. Conclusion

Realistically, in the long run the current population size and resource use are not sustainable with any one goal or combination of goals. Our work shows that over the next 70 years achieving at least a 'good' measure of well-being is possible for the majority of the global human population by targeting goals that promote health, education, public infrastructure and greater equality. Whether the long-term outcome is sustainable depends on goals that balance the ratio of people to nature. Here we describe two options for sustainability, such that the population and natural land are both maintained and the demands of the current and future populations are met without diminishing environmental integrity. First, consumption levels and land degradation must decline to provide ecosystem services for future generations, while maintaining the current population. Furthermore, a combination of social and environmental practices are needed to avoid feedbacks that can produce unintended consequences. This option seems highly unlikely, as consumption is on the rise and the benefits from 'green' technologies are ambiguous. Alternatively, sustainability can be achieved by maintaining a balance between people and land. The number of people needs to be proportional to the total combined area of natural and agricultural land. We find that the long-term sustainable population maintains a high-consumption lifestyle (i.e., excess well-being), through feedbacks that decrease fertility rates and increase longevity. This reduction in population, in addition to technology and development maintain natural and agricultural land, resulting in a sustainable system. Without drastic changes to technology, population size or consumption, the current system is not sustainable.

The model does not allow us to give precise recommendations or projections for sustainability, nor is the model intended to thoroughly evaluate the UN Sustainable Development Goals. Rather we aim to shed some light on sustainable development and highlight general weaknesses and strengths in our current practices that may hinder or help with the sustainability challenge.

Generally speaking, implementing policies to revive natural areas are too slow on their own to yield a sustainable future, whereas reducing inequality is essential to making strides towards sustainability. The results show that a minimum technology, innovation and social development increase in lower income regions or direct changes to inequality are required to promote sustainability, but the technology needs to work in tandem with environmental protection, otherwise development may cause severe environmental damage and jeopardize any sustainability efforts. Furthermore, given the short window of opportunity to improve well-being in the lower income regions, if actions to improve sustainability are postponed 50 years, then none of the SDGs provide a sustainable future for people or the environment.

In this paper, we identify some possible synergies, but we did not exhaust all the possibilities and we assume all goals are implemented at the same time. The 169 SDG targets and 232 indicators provide useful guidelines for sustainable development, but as others have suggested (Kubiszewski et al., 2022; Diaz-Sarachaga et al., 2018) achieving each target or specific indicators may be unnecessary or redundant. Given the overall simplicity of the model, many of the targets result in the same parameter changes. This simplicity allows us to see how many of the goals require increases in development (social & technological), decreases in natural land degradation, and the redistribution of resource accessibility. How these changes are implemented is specific to each region and economic group, which is one major advantage of the UN Sustainable Development Goals, but this also requires cooperation on time and spatial scales to be effective.

CRediT authorship contribution statement

Kirsten Henderson: Conceptualization, Methodology and analysis, Writing – original draft and revisions. **Michel Loreau:** Conceptualization, Revisions and editing Supervision, Funding acquisition.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Michel Loreau reports financial support was provided by TULIP Laboratory of Excellence. Michel Loreau reports financial support was provided by European Research Council.

Data availability

Data will be made available on request.

Acknowledgments

This work was supported by the TULIP Laboratory of Excellence (ANR-10-LABX-41) and was conducted within the framework of the BIOSTASES Advanced Grant, funded by the European Research Council under the European Union's Horizon 2020 research and innovation program (grant agreement No 666971). We thank Diego Bengochea for discussions on sustainable development.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.ecolmodel.2022.110164.

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