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Unequal access to resources undermines global sustainability

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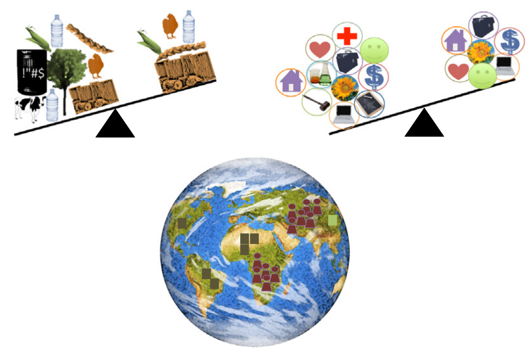
HIGHLIGHTS

- Inequality in resource accessibility favours higher peaks in population growth.
- Large, unequal populations and dwindling natural land lead to poor well-being.
- Two distinct economies foster unequal development and reinforce unsustainable practices.
- Dispersal of people and goods undermines restoration and conservation.

GRAPHICAL ABSTRACT



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ABSTRACT

Within a global society there exist various land use patterns, inequality, and the movement of people and goods. The various practices and behaviours associated with our current society raise questions about the future sustainability of the human population and the natural environment. We derive a simplified model of the global socio-ecological system in an effort to explore the connections between human well-being and land resources, specifically looking at resource accessibility, conservation initiatives and human migration between two economically diverse regions. We find that the spatial aspect of a global system with two distinct regions allows for faster development of technology, higher peaks in population size, greater natural land degradation, and generally speaking lower population well-being in the long-term. The unequal access to resources and differences in technological progress, alter the outcome of land management (i.e., conservation) and social behaviours (i.e., migration). We conclude that any socio-ecological management practices should be conscientious of the diversity in land access, population size, population well-being and development within the global society, as the potential for unintended consequences is high.

1. Introduction

Goodhart's Law states that "when a measure becomes a target, it ceases to be a good measure" (Chrystal et al., 2003). This statement is particularly relevant to our global socio-ecological and economic system, where the pursuit of well-being and economic growth can cause people to overlook other aspects of life, such as biodiversity and ecosystem services. Therefore, efforts to promote environmental sustainability and population 'well-being' need to consider the entirety of the socio-ecological system, as ecosystem services are essential to wealth, well-being, and sustainability (Costanza et al., 2014).

More often though the environment is valued for the productive assets (i.e. resources), which leads to inequality and poor land management. Inequality is driven by different land-use practices and investment choices that fail to distribute resources equally (Coomes et al., 2016). Inadequate distribution forces more land to be converted, which can lead to a cycle of poor land management, as well as social inequality and pushes development away from environmental

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sustainability (Hasegawa et al., 2019; Boyce, 1994; Cumming and von Cramon-Taubadel, 2018). Furthermore, there exists a positive feedback between power and wealth, which reinforces inequality. In a finite system when one benefits and the other loses the result of applying random processes is extreme inequality (Scheffer et al., 2017).

Modern practices are built on the idea that wealth and development of knowledge can continue infinitely (Cass and Mitra, 1991), which requires that the pace of population growth increases with social organization so that development does not stagnate (Bettencourt et al., 2007). If technological growth does not continue, economic expansion will increase the demand on the ecological system (Clow, 1998). However, Cumming and von Cramon-Taubadel (2018) found that economic development is not a precursor to environmental sustainability, as under the current two-economy system (i.e., high- and low-income) both economies are not allowed to continue developing or cannot simultaneously accumulate wealth (Cumming and von Cramon-Taubadel, 2018). Rather, the lower income regions supply the higher income regions with goods, resulting in the over-exploitation of resources and poor living conditions for the LI economies. Feedbacks between income and population growth push countries farther from sustainability and the development of countries is not sufficient to promote environmental sustainability. This begs the question as to whether reducing inequality (i.e., altering the access to resources), rather than economic development alone, is capable of breaking the feedback cycles in Cumming and von Cramon-Taubadel's (2018) model that preclude sustainability.

When living conditions become undesirable, it becomes beneficial for individuals to move. Indeed, migration has been shown to allow individuals to inhabit less favourable environments through temporary dispersal (Holt, 2008) and even has the ability to reduce poverty by moving to regions with more opportunities or wealth (Adams and Page, 2005). Sweden experienced mass movements of people in the 19th century, which has been attributed to poor resource availability and accessibility (Clarke and Low, 1992). The North of Sweden, where the land was less productive and the carrying capacity was minimal, experienced the greatest population exodus. In addition to poor resource availability, drought is a another factor in temporary and indefinite migration. However, the two are not independent as drought often leads to diminished resources by altering the environment and agricultural practices. During the Dust Bowl of the 1930s in North America and the severe droughts in Africa through the 1980s and 1990s are classic examples of migration as the result of inauspicious environmental conditions (McLeman, 2014). Migration can result from a multitude of factors, regardless the basic theory is that either the local conditions are insufficient, forcing people to leave, or the conditions elsewhere are comparatively better than the local conditions, attracting new individuals (Grigg, 1977).

Among the many social factors that influence dispersal — policy, family, job opportunities (Gonzalez et al., 2008) — income inequality can have the largest impact, both directly and indirectly. As mentioned above inequality leads to greater land degradation, and severe land degradation forces people to disperse. This phenomenon is more likely to affect low-income individuals, for which agriculture is the main income source (Levy and Patz, 2015). However the paradox of migration is that the cost is too high for the poor to disperse (Black et al., 2011) and the wealthy do not benefit from dispersing (Towner, 1999). If people are unable to move and the or land is degraded, they will inevitably experience poor well-being and become embroiled in a poverty-trap (Barbier and Hochard, 2016). Human migration has been a mainstay in human society, yet in recent years the number of migrants from less developed regions to more developed regions has been on the rise, which contributes significantly to population growth in certain regions (UN Population Division, 2019). Furthermore, the number of refugees and asylum seekers is the highest it has ever been and this trend is expected to continue without conflict resolution and improved local environmental conditions (Black et al., 2011).

It is clear that humans are dependent on ecosystem services and that poor living conditions lead to migration and unsustainable development, but what is less well understood is how social structures, as well as resource use in space and time alter the dynamics of a global socio-ecological system. Here we build and analyse a model to explore current and potential future land and social dynamics in space. We generate a model consisting of two regions with inequality incorporated through differences in access to technology and resources. We compare the 'real world' model to a uniform one-region system, in addition to scenarios that alter income status within a region and dispersal between regions. Furthermore, we incorporate conservation and restoration practices in the two-region system with distinct populations and practices, hypothesizing that increasing the natural area can contribute to a sustainable and desirable future for humanity.

2. Brief model description

Cumming and von Cramon-Taubadel (2018) modelled the relationship between differing economies (e.g., Human Development Index 1 (HDI1) regions and HDI4 regions) and distinct practices, which is supported by empirical data showing that there are two groups of individuals with distinct demography, development structures, and consumption patterns (Oswald et al., 2020). We provide further support for a two-economy global structure in an analysis of The World Bank (2019) data (details in the Appendix). We use this idea of distinct economies with distinct practices and apply it to an ODE model of global land management and population growth (Henderson and Loreau, 2019). We modified the Henderson and Loreau model to incorporate two regions, movement of people and goods, and inequality. The model simulates a simplified global system with two regions and two subpopulations within each region.

The regions represent higher income and lower income economies and development structures ($j = L, H$), each with subpopulations that are also classified as higher income and lower income ($P_{i,\,j}$, where $i = L, H$ represents the population income level, and $j = L, H$ reflects the region income level). The higher income region described here refers to a GDP above the global average and the lower income region refers to a GDP below the global average, we have included a spreadsheet with this data in the Appendix. The subpopulations LH and HL reflect the middle income groups in the 'real world'. These groupings were derived from clear differences in the stages of the demographic transition, income, social norms, land-use practices, consumption habits and technological development between regions and populations classified as HI or LI. Kernel density plots are given in the Appendix to show distinct groupings for higher and lower income regions, with more ambiguous differences between middle income groups. The four subpopulations in the model represent the spectrum of income groups globally, showing the variation in consumption levels, birth rates, death rates, research and development expenditure, and resource production. Equations and a full description of the model are provided in the Appendix.

2.1. Human population

The population growth function, which takes into consideration recruitment and adult mortality rates, is dependent on resource accessibility (ha/pers., which is calculated as a function of technology and land capacity). When population growth is plotted against resource accessibility we see a non-monotonic curve that increases initially with resources and then declines as resource accessibility surpasses the basic needs level. The details of this theory are described in Henderson and Loreau (2019).

Resource accessibility also moderates the rate at which individuals change income status. Once an accessible resource threshold (ha/ind.) is crossed – determined by World Bank income classifications (The World Bank, 2019) and the ecological footprint of each country (Global Footprint Network, 2019) – individuals can become higher income or lower income. The shift in status increases exponentially with resources, when individuals shift from lower to higher income; and the shift in status decreases logistically from higher to lower income.

Furthermore, individuals are able to move from one region to another by comparing the accessible resources in the foreign region with their own resource accessibility. In the model, a sigmoidal curve is used to represent the relationship between resource accessibility and dispersal.

2.2. Land cover

The two regions are composed of natural land (N_j), where natural land describes 'semi-natural' and natural land, such as grasslands, tree-covered areas, shrub-covered areas (the full list of natural land areas, as described by the FAO, is provided in the Appendix); agricultural land (A_j), which is referred to as croplands by the FAO; and unused land (U_j), which is the total land area (L_j) minus A_j and N_j. Unused land describes all land that is not agricultural or natural, such as urban, degraded land, and minimally productive land (i.e., glaciers, barren land). Land-use practices include local and foreign use of land, such as degradation and cross-degradation, agricultural conversion, restoration (human and natural regeneration) and the option to include conservation.

The degradation and consumption functions for N_j and A_j ($j = L, H$) are linearly dependent on the population size, the demand for resources and the share of land used by the local population. The share of the land used is determined by the power the region wields, which is a function of technology and population size. The remaining proportion of land not used by the local (j) individuals may be consumed and degraded by individuals from the foreign region ($\bar{j}$, where $\bar{j}$ is the opposite of j, such that if $j = L, \bar{j} = H$ and vice versa).

Conversion from N_j to A_j depends on the demand (cv_j) from the population (P_j) and technology (T_j), in each region. Progressive technology promotes increases in agricultural yield without the need for further land conversion. Therefore, the greater the technology variable, the lower the conversion rates. The foreign population in region $\bar{j}$ also determines the rate of conversion from natural to agricultural land in region j, through the same processes as the local population j. The proportion of land in region j manipulated by the population in region $\bar{j}$ is determined by the power ratio.

Additionally, agricultural production has been shown to benefit from surrounding natural land area (Bennett et al., 2009; Braat and De Groot, 2012). Therefore, agriculture degradation is modelled as a function of consumption and ecosystem services (i.e., natural (N_j) and conserved natural land (C_j)). Ecosystem services buffer the effects of agricultural land degradation, as reflected in the model by an exponentially decreasing function (details in the Appendix).

Restoration is a function of both natural and human processes that convert unused land (U_j) back into natural land (N_j). The restoration scenario increases the rate of land actively being converted from U_j to N_j by the human population in region j. Conservation in the model refers to a fraction of 'preserved' natural land, which provides individuals and the local environment with non-provisioning ecosystem services. Conservation occurs at a constant rate that is bound by the proportion of desired conserved land and already existing natural land.

2.3. Technology & development

Technology and development are major drivers of population dynamics and therefore land management. Technology is included in the model through resource accessibility and power functions. It is estimated that higher income regions are more developed, in terms of education, medicine, machinery, etc. than lower income regions (The World Bank, 2019; Kummu et al., 2018; Sarkodie and Adams, 2020; Sen and Laha, 2018). Therefore, we include two technology variables, one for each region (T_j, $j = L, H$) with different growth rates. The technology growth curve is a function of population size and density, and the availability of natural resources (i.e., N_j and C_j). Technology has been shown to increase with population density, however there becomes a point where the number of individuals exceeds the capacity of natural land and limits the future development of technology (Clow, 1998), thus making it a hump-shaped relationship.

Technology is a major determinant of power and resource accessibility – determining who will use what land, when, and how. We assume that technology builds upon itself, 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).

2.4. Resource acquisition

Resource accessibility controls societal feedbacks in the system, but it is also determined by numerous variables, making it the nucleus of our model. Resource accessibility per individual is dependent on the power wielded by their region (a combination of technological development and population size, details in the Appendix), the availability of agricultural and natural resources, the ability to acquire such resources, and the potential to enhance production yield with technology.

2.5. Model analysis and simulations

We first build a business as usual (BAU) model that uses historical trends from the last 260 years to simulate current population and land dynamics. From 10,000 BCE to 1700 the population grew on average 0.04% per year and the proportion of land converted grew at less than 1% (Max Roser and Ortiz-Ospina, 2013; Klein Goldewijk et al., 2011). The curves for both land change and population change follow the same exponential trends, both taking off after 1700; therefore, we assume that pre-Industrial Revolution data is similar to the early 1700s and is thus included implicitly in the model from data used to describe trends over the first half of the 1700s. The earlier dynamics were thoroughly explored in Henderson and Loreau (2019). We validate our findings with data from the World Bank Group given in the Appendix. The ODE model was run through MATLAB using odesolver 113. Parameter values, initial conditions and a range of scenario parameters are given in the Appendix.

We then apply alternative land management practices (i.e., conservation in the LI region, conservation in the HI region, restoration) and social policies (i.e., migration, income status) to current trends and simulate the results over 740 years. After 740 years the results reach a sustained value, however we are unable to calculate an analytic equilibrium, as the model contains 12 variables. Furthermore, when discussing population dynamics, the short-term, transient dynamics are generally of greatest interest (Ezard et al., 2010). However, we run the model long-term 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. We want to make clear that the projections and stages of demographic and land management transitions are susceptible to different timescales, we refer to the socio-ecological dynamics in terms of present to 2100, intermediate dynamics and long-term dynamics.

The restoration scenario involves the active conversion of unused land (U_j) back into natural land (N_j) by the local population (P_j, includes both subpopulations within the region j). The BAU scenario maintains minimal restoration rates, while the restoration scenario models rates between 50 and 100 times the natural rate of restoration. By contrast, conservation is used to describe natural land (N_j) being set aside – taking N_j and maintaining it in the conserved state (C_j), such that individuals and land cover are provided with non-provisioning services, but the land is unavailable for harvest or manipulation. We vary the rate of conservation in a effort to find a link between sustainability and conserved land (parameter details are given in the Appendix). Conservation is applied to the LI region alone, the HI region alone, and both regions together. The conservation scenario increases the proportion of land set aside in a conserved state (between 5 and 30% of natural land).

The no status change scenario looks at the impact of keeping individuals in their respective subpopulation, regardless of the their access to resources (i.e., acquired wealth). We also increased the rate of change between income groups, allowing individuals within each subpopulation to transition more quickly between income groups. Finally, for the migration scenarios, we prevented individuals from relocating to a different region and we doubled the rate of migration to see how allowing more or less people into foreign regions would impact the socio-ecological system.

In addition, we compare the two-region system with four subpopulations to a one-region system with two subpopulations to understand the role of the spatial distribution of land and people in the dynamics of our global system.

The individuals in the population are assigned a well-being status based on the number of accessible hectares of resources per person (R): famine is defined as $R<0.55 ha/pers.$; poor well-being occurs when $0.55 \geq R<1 ha/pers.$; moderate well-being is defined by $1 \geq R<2 ha/pers.$; good well-being is defined as $2 \geq R<5 ha/pers.$; excessive well-being is equivalent to $R \geq 5 ha/pers$. These values are based on the global ecological footprint of countries (Global Footprint Network, 2019) and the corresponding income group of the country (details in population calculations and groupings in the Appendix).

3. Results & discussion

3.1. Business as usual scenario

The model is able to regenerate observed human population and land cover patterns from approximately 1750 using parameters estimated from historical data and theories on technology, demography and ecology (Henderson and Loreau, 2019). The simulations give current values of $N_{L,\ H} \approx 0.5{*}L_{L,\ H}$, A_L=0.84 Bha, A_H=0.64 Bha and the population size in each region (j) is P_L=5.9B, P_H=1.4B (Fig. 1). Furthermore, the model population projections fit within the 95% prediction interval of the UN population numbers in 2070 (9.9 to 11.2B) from the UN Population Division, 2019 – our higher income population in 2070 is 3.6B, which is on the upper end of the UN range for high- and upper-middle-income populations (2.75 to 4.2B); and our lower income population is estimated to be 7.2B, on the high end of the UN range for low- and lower-middle-income populations (5.7 to 7.2B). In the majority of scenarios, the population is still growing slowly in the year 2100. Unlike the UN projections, the model simulations described here continue after 2100, after which the model shows major changes in population dynamics. These changes are driven by the spatial distribution of people and goods.

The model predicts three stages of population dynamics, based on resource accessibility (i.e., land cover and technology) and dispersal trends. The first 340 years (from approximately 1760 until 2100) are governed by resource accessibility, the population grows without any impediments from natural land deficiencies. Thereby, many scenarios are similar over this time period.

However, afterwards the access to resources changes the spatial distribution of individuals, as natural land deficiencies accumulate in both regions. At this stage (2100–2250, intermediate dynamics), dispersal becomes the main driver of global system dynamics. Resource accessibility and other drivers in the model are still at work, but the dispersal rates increase significantly and allow us to identify a new stage of socio-ecological dynamics. The subpopulations are reconfigured into different income groups and regions as a result of the feedbacks between resource accessibility and dispersal, which causes a second wave of population growth. This alters technological development and degradation patterns, which ultimately impacts population growth and well-being.

Finally, in 2250, the population starts to decline, as technology has long since stagnated and resource availability declines below adequate levels to maintain the human population. In the long-term

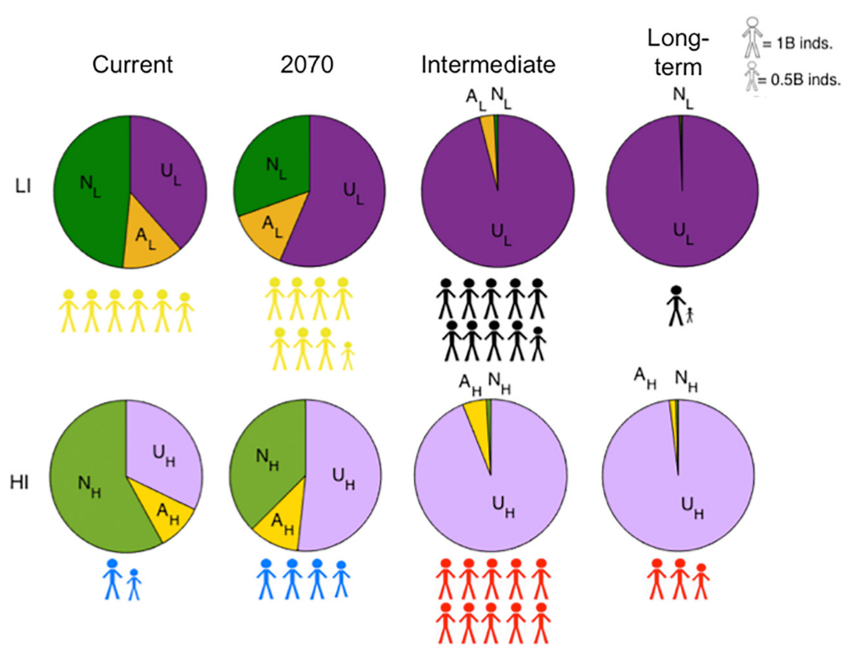

Fig. 1. Business as usual scenario – land and population patterns. Currently natural land occupies the greatest area in both regions (N_L, N_H), followed by unused land (U_L, U_H) and approximately 10% agricultural land (A_L, A_H). In 2070, agricultural land area increases slightly, but the majority of converted natural land becomes degraded (U_L, U_H). In the long-term, U_L and U_H remain, with negligible fractions of N_L, N_H, A_L and A_H, resulting in a population collapse. The population peaks well after 2100 (P=19.8B, P_L=9.8B, P_H=10B), while the well-being peaks in 2070 (W_L = *moderate*, W_H = *excessive*). One stick figure represents 1B individuals and shrunken stick figures represent fractional billions. The well-being (W_L, W_H) is determined by the accessible resources per person (ha/pers.): yellow = moderate well-being, blue = excessive, black = famine, red = poor.

(i.e., 740 years, long-term dynamics), the BAU scenario leads to famine in the LI region and poor well-being in the HI region. Both regions experience a population decline, as a result of high death rates and little or no recruitment.

3.2. Impact of technology

The major differences between the two regions (higher income and lower income), in the model, can be attributed to the population recruitment rates combined with technological development and social investment in each region, which ultimately determine power and resource accessibility. In general, technology allows the population to sustain a high well-being lifestyle, which contributes to a declining recruitment rate and leads to minimal population numbers with high well-being. This cycle continues so long as there is continuous technological development and reduced inequality. There is only one scenario for which this is true, the one-region/high-tech scenario (Fig. 5), yet this is a hypothetical scenario used for the purpose of comparison with our global two-economy system.

The higher income region has a technological advantage over the lower income region that ensures the HI region has a greater well-being and more access to resources than the LI region. However, lower income populations produce people power and without the flow of people from the LI region to the HI region, technological development curtails in the higher income region. The model suggests that it is difficult for the lower income region to match the technological development of the higher income region, especially considering that resources from the LI region are being used by the HI region. Two distinct economies drive the system further away from sustainability, yet promotes development, at least in the higher income region, and maintains inequality.

Model simulations suggest that technological development plateaus in 2070, if there is no change in land management practices or population dynamics, as a result of declining natural land. In turn resource accessibility declines, which reduces well-being while population continues to grow, in the short-term. Societies are trapped in the middle of the demographic transition (Bongaarts, 2009) or the Malthusian Regime described by Galor and Weil (2000), which promotes growth at the expense of well-being. In the long-term, both well-being and population numbers decline, as there is no technological growth and negligible resources. We can extrapolate from these results that environmental degradation results in economic and societal collapse. The future of technological development and innovation represents a large unknown, with respect to if and when output will stagnate and whether the results will be overwhelmingly positive or negative for the socio-ecological system as a whole. However, we do not believe technology is a panacea for inequality and environmental degradation.

Even when lower income regions experience strides in technological and economic development, as is the case now, the result is greater environmental degradation. Model simulations show that countries develop into higher income groupings, thereby gaining a higher standard of living at the expense of natural land and ecosystem services. Technology can lead to greater environmental degradation, for example an increase in agricultural production efficiency may increase demand and result in further land degradation (Alcott et al., 2012). Furthermore, there exists a positive feedback loop, in which the higher income subpopulation of the LI region seeks opportunities in the higher income region, leaving the lower income subpopulation with few resources that are primarily exported to higher income regions. This is consistent with Richardson's (1995) work suggesting that globalization leads to a rise in inequality.

3.3. Impact of dispersal

Dispersal is another key driver of the socio-ecological system. The model clearly shows that population dispersal alters technological development, degradation patterns, and growth patterns. As mentioned above the second stage of the population trends simulated in this model is governed by dispersal. Individuals disperse in response to insufficient resource accessibility, whether relative or real (UNnews, 2019). From model simulations we infer that individuals seek better opportunities, which results in short-term increases in resource accessibility and growth. In the long-term, mass dispersal leads to homogeneously poor well-being, if there is no change in consumption habits. We deduce that dispersal temporarily masks or dilutes feedbacks between resource accessibility and population dynamics. As a result, dispersal encourages populations to grow beyond resource accessibility at the regional level by allowing individuals to move and access more resources elsewhere.

Without dispersal from one region to another (Fig. 2), the population in the higher income region shrinks (P_H<0.1B in 2750). There is not enough replacement growth within the HI region and without input from the lower income region the population is small and declining. The direct effect of not allowing individuals to move from one region to the other is a decline in population numbers: one from excessive well-being and no population regeneration (HI region); the other from poor living conditions and high mortality rates (LI region). Doubling the dispersal rate shows no qualitative differences to the BAU scenario.

3.4. Conservation scenario

In a seemingly counter-intuitive response, conservation in a region (j) draws individuals to the region (j) from the foreign region ($\bar{j}$). Conserved land, C_j, does not provide any provisioning services to the human population, therefore it seems counter-intuitive that individuals would be attracted to the region, but conservation is a symbol of a developed social structure and therefore higher well-being (Ghimire and Pimbert, 2013). In the model, conservation allows development to continue and therefore increases power. As such, the region with conservation experiences increases in growth and dispersal, as individuals from the no-conservation region flow in, which in turn changes resource accessibility. Initially, the fluctuations in resource accessibility promote growth; however, as the population grows the resource accessibility per capita declines significantly and causes a decline in the population.

In the higher income region, when conservation is applied (Fig. 3a), the natural land cover (N_j, natural land that is available to individuals for provisioning services) is similar to the BAU scenario, however the amount of degraded or unused land declines (U_j) by at least 1 Bha. Conservation in the higher income region prevents land from being degraded within the region but there is a rebound effect that causes greater degradation in the lower income region and reduces the resource accessibility of the LI population. This impacts the lower income population that remains in the LI region, reducing well-being until a famine state is reached.

When conservation is applied to the lower income region (Fig. 3b) there remains a minimal quantity of natural land (N_L, N_H) and agricultural land (A_L, A_H), in both regions over the long-term. There is less emigration out of the LI region in this scenario, which results in a greater LI population and lower HI population compared to the BAU scenario. With more individuals in the LI region there is a reduction in global consumption rates, as LI individuals consume less than HI individuals. Less consumption leads to slower rates of land degradation, which also increases population well-being in both regions ($W_L = poor$, $W_H = moderate$), when compared to the BAU scenario.

The sustained technology value in the LI region is greater (T_L=3.3). We interpret this as conservation bringing greater social development and innovation to the region, based on the theoretical relationship between environmental degradation and poverty, and thus the potential for environmental rehabilitation to improve production technologies and services (Ghimire and Pimbert, 2013). The simulated outcome of LI region conservation is optimistic and should be viewed as the best-

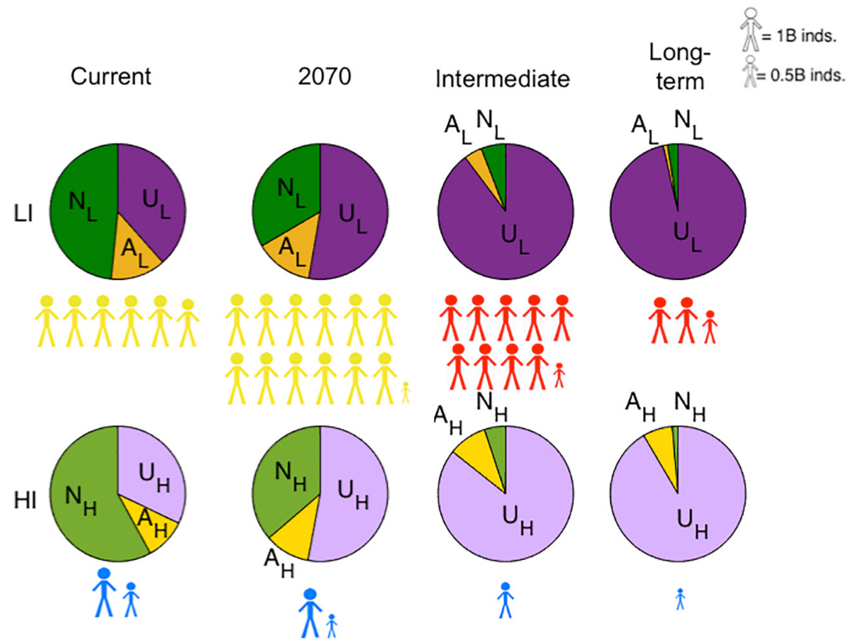

Fig. 2. No-dispersal scenario – land and population patterns. The population in the HI region (P_H) is low compared to the BAU population at all stages, where P_H<0.1B inds. exist with excessive well-being (blue), 0.46 Bha of agricultural land (A_H) and minimal natural land (N_H<0.1 Bha) in the long-term. Over the entirety of the simulations well-being is excessive, although technology is stagnant, there are fewer people with a high standard of living, which reduces land degradation. The population in the LI region more than doubles between now and 2070 (P_L=12.1B inds.), maintaining a moderate well-being (yellow). However, as resource accessibility diminishes, so does the population size (from a lack of resources) and well-being. In the long-term, there are 2.5B inds. with a poor well-being and a sliver of natural land remains until 2750 (N_L=0.16 Bha). The no-dispersal scenario does not allow individuals to move and impedes development of the region (i.e., countries do not change economic status), for which LI individuals are disproportionately impacted.

case scenario, as it assumes conservation is applied with little behavioural spillover and positive technological improvements.

The one-region conservation scenario provides an interesting contrast to the two-region system. Conservation in the one-region system generates the greatest abundance of conserved natural land, while maintaining a good or better population well-being when technology and social structures are well-developed. In this scenario, conservation has no direct or indirect outcome on the human population, the land is merely shifted from unused to conserved nature. However, for populations that are highly dependent on the local environment, and often cannot disperse for social or economic reasons, conservation policies can restrict access to resources and reduce the local population's well-being (Cazalis et al., 2018). For example, small-scale subsistence farmers in Nepal, with minimal income or technology may experience detrimental consequences from strict conservation policies (Brown, 1998). This is consistent with the one-region, lower income/low-tech, conservation scenario from the model (Fig. A3 in the Appendix). By contrast conservation designed to help subsistence farmers has benefited yields in Ethiopia (Bekele, 2005), similar to the simulated two-region conservation scenario in this model.

3.5. Restoration scenario

Restoration increases natural land (N_L, N_H) and agricultural land (A_L, A_H) area in both regions (Fig. 4). Unlike most scenarios, restoration maintains N until the final stage (N_L=1.34 Bha, N_H=1.74 Bha). With an increase in land cover there is an increase in resource accessibility, which allows the population (P_L, P_H) to grow throughout the intermediate and long-term stages. Restored natural land also allows technological development and innovation to continue (T_L, T_H). However, this relatively unchecked population growth in both regions leads to very high populations (P_L=43.4B, P_H=67.3B) with a poor well-being, in the long-term. Technology reaches a maximum of T_L=6.9 and T_H=24.5, the highest of all scenarios. The land is continuously converted back to natural land, which prolongs the period of time before technology is limited by the imposed natural land threshold (N_{th}).

Restoration has an impact on dispersal and income status. The higher income region continues to enjoy high resource accessibility over a longer period of time. With restoration the HI region expandse, as whole countries become richer. Restoration in the lower income region improves the well-being and we infer from the model simulations and UN findings (UNnews, 2019) that the lower income region population uses these newfound resources to seek better opportunities in the HI region or transition to higher income countries once enough wealth is obtained. However, restoration does not solve social issues (i.e., inequality, over-population), it only delays the impact of environmental degradation, which causes larger population's with poor well-being and globally limited resources. In the intermediate stage (intermediate dynamics), the renewed resources from restoration pushes the population to extreme sizes, while maintaining the living standards (i.e., W_L = *moderate*, W_H = *excessive*), which ultimately places huge demands on the environment. In this scenario, the dispersal-driven stage of the model (second phase) is delayed 100 years beyond the onset observed in all other two-region scenarios. In the long-term, all populations look to dispersal as a means of accessing resources, only to find that resources are limited globally. As a result, in the long-term the access to resources declines per capita, as the population outgrows the ecological capacity of the global system.

Dispersal also subverts attempts to restore natural land and improve well-being. If population growth or degradation stagnated over the intermediate dynamics, well-being would improve globally and restoration would be beneficial to natural land recovery and population dynamics, as is the case in the one-region scenario (Fig. 5c). However, without a change in habits and inequality, restoration encourages rapid growth and poor well-being, long-term.

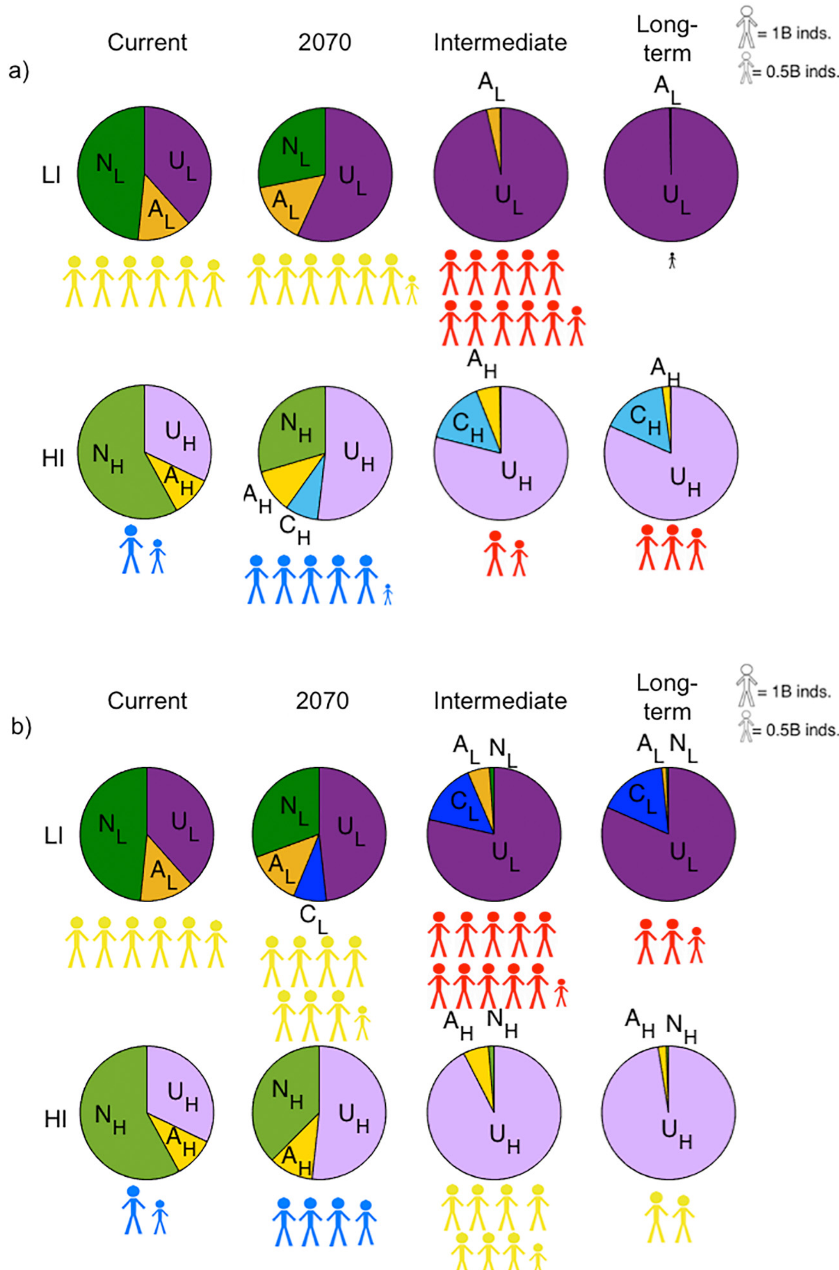

Fig. 3. a) HI Conservation – land and population patterns. Conservation entails setting aside a proportion of natural land for ecosystem services, excluding provisioning services (C_H). C_H eclipses natural land, as remaining N_H becomes C_H. C_H maintains more agricultural land over the simulations (A_H=0.13 Bha), but has no impact on the land dynamics of the LI region (N_L, A_L). Conservation in the HI region reduces the natural land area in the LI region and induces a famine state (W_L, black). Initially, the population in the HI region increases as land is conserved rather than degraded, but then declines in the long-term from a lack of resources. The LI population experiences mass emigration as HI region conserves land (discussed in detail in the text). b) LI Conservation – land and population dynamics. Conservation in the lower income region reduces the long-term unused land fraction (U_L) by replacing it with conserved land (C_L). Natural land (N_L, N_H) and agricultural land (A_L, A_H) are slightly higher than the BAU scenario. Both populations in the HI and LI regions have a higher well-being compared to the BAU scenario in the long-term ($W_H = moderate$, $W_L = poor$). There is less emigration from the LI region when conservation is implemented, which results in lower HI population and reduced land degradation.

3.6. Status scenario

Lastly, in a scenario in which individuals are not allowed to change income status, thereby keeping access to resources limited in lower income populations (in both HI and LI regions), there is little impact on the results. The BAU system is already significantly unequal, therefore by further constraining the LI subpopulations' efforts to improve their standard of living there is little impact on the qualitative results. The number of individuals in each subpopulation changes; however the population size, per region, remains the same (Fig. A2). The difference in well-being is slight, yet there are no qualitative changes to the results. As there is no change in population dynamics, the land cover remains the same compared to the BAU scenario.

3.7. Comparison with the one-region system

The one-region system is much more stable than the two-region system. There are fewer feedbacks in the one-region system, which means the outcome of each action is more deliberate and achieves the desired goal. For example, the one-region case with restoration shows that restoration of natural land improves well-being (Fig. 5c), in addition to sustaining natural land at N=3.3 Bha.

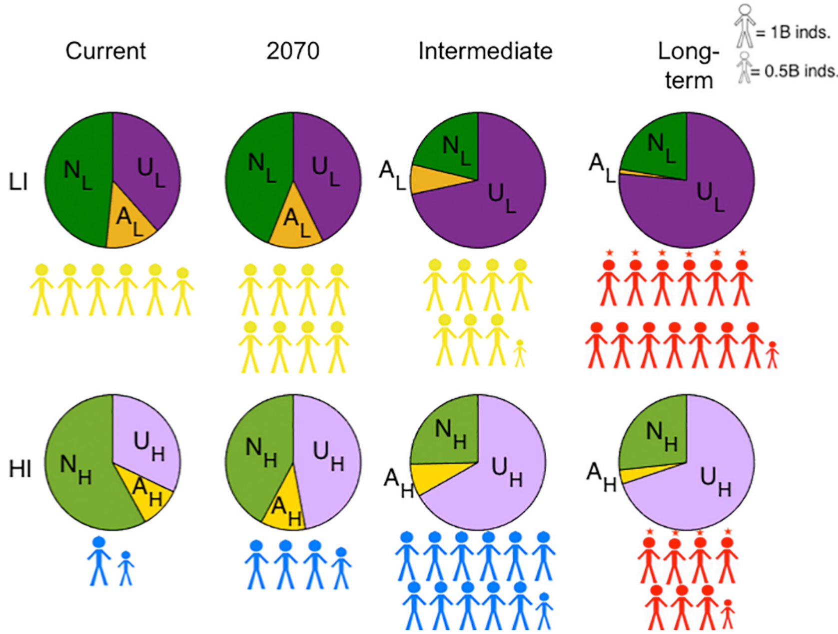

Fig. 4. Restoration – land and population patterns. Restoration increases the sustained area of natural land ($N_L \approx 1.3$, $N_H \approx 1.7$) by increasing the active conversion of unused land into natural land. The increase in natural land sustains technological development in the model, which drives an increase in population size, in both regions. The population well-being is maintained at its current state for over 200 years (W_L = moderate, W_H = excessive). After which, the population becomes too large (P_H=67.3B inds., P_L=43.3B inds.) for the resource availability (*N* and *A*) and the well-being declines to poor, globally. Stick figures with an asterisk represent 10B individuals, as seen in the long-term dynamics.

Unlike the two-region system, the one-region system maintains natural land (*N*), smaller populations, and a continual state of well-being for all scenarios. The one-region system is strongly influenced by the rate of technological growth. Fast technological growth leads to a higher income scenario with excessive well-being, whereas slow technological growth leads to mostly poor well-being populations with less than 3B individuals globally (Fig. A3).

Status change makes no qualitative difference (Fig. 5b). The population is all higher income already, so preventing the movement of individuals between income groups has little impact.

The long-term population and land projections of our model are not necessarily realistic predictions, but they give an indication of the trends that can be expected for business as usual practices and alternative scenarios. Who is using what resources and in which regions has a major impact on the outcome of the business as usual model and the alternative scenarios. People and land-use shape recruitment, mortality and dispersal patterns.

4. Conclusions

The complex interactions between land, people and technology make it difficult to predict the success of sustainable development initiatives. The multitude of feedbacks between humans, nature and development necessitates the use of a coupled socio-ecological model system in order to adequately reflect our environmentally and socially diverse world, otherwise key factors may be overlooked. For example, restoration has the potential to promote higher sustained populations with improved well-being, yet we find that the multiple feedbacks between dispersal and resource accessibility drive the population towards growth at the expense of well-being, as individuals move to where resources are more accessible and growth is possible. However, this eventually exhausts all the resources leading to few accessible resources, a massive population, and poor well-being. Without inequality or the spatial distribution of people and goods, the outcome of land restoration would be entirely beneficial to humans and the environment.

In all model scenarios, it is evident that technology provides an advantage to higher income regions by allowing population's to access

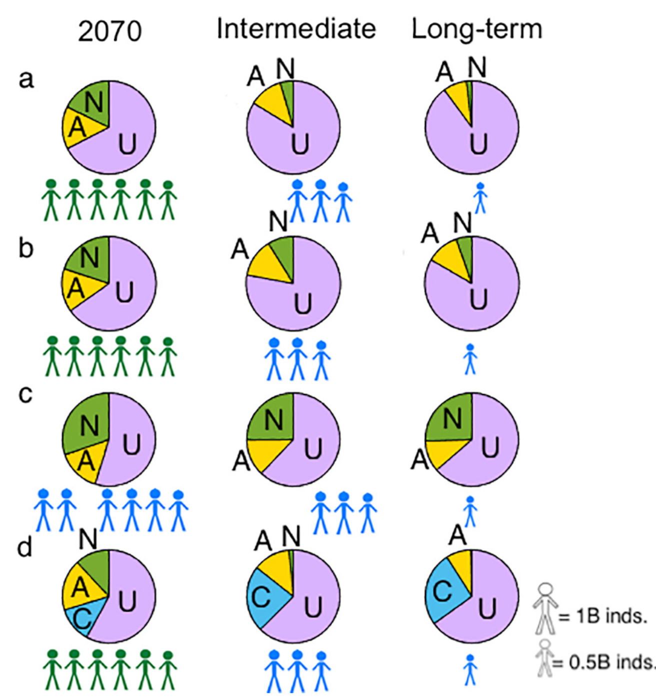

Fig. 5. One-region (high-tech), all scenarios – land and population patterns. a) BAU – In the one-region scenario, there is no dispersal of goods or people, but there is still inequality. When technological development is rapid, all individuals have a good (green) or excessive (blue) well-being. The population size is smaller than two regions (*P*=7.5 in 2070, *P*=2.8 in 2250, *P*=0.4 in 2750). b) No status – There are no qualitative changes to the human population dynamics. There is however more natural land (*N*) and agricultural land (*A*) throughout the simulations. c) Restoration – Restoration increases human well-being, maintaining excessive well-being throughout the simulations. There are over 3 Bha of sustained *N* and 1.4 Bha of sustained *A*. The population size (*P*) is similar to the BAU scenario, but with more resources, hence the greater well-being. d) Conservation - Conservation results in all natural land (*N*) being maintained as conserved land (*C*). Only a fraction of *C* provides ecosystem services necessary for human activities. However, the population is low and therefore can be maintained by the minimal services from *C* and agricultural production from *A*.

more resources and disperse more easily, consequently contributing to the poor well-being of those less fortunate.

After a brief period of bridging the gap between income disparity, inequality is on the rise again, which alters the access to resources per capita and ultimately impacts sustainable development and the average global well-being. In our model, there are multiple layers of inequality in the global, two-region system – differences in technological development, education, infrastructure etc.– which reinforce power dynamics and keep the higher income population thriving, often at the expense of the lower income population. It was not possible in the scenarios we evaluated to have equal technological development in both regions. Inequality is a major impediment to sustainable development and improved well-being. From the model we conclude that any effort to reduce land degradation, promote conservation or implement natural land restoration first needs to ensure adequate access to resources for all. There will always be inequality, but policy-makers should focus on reducing the gap, as inequality not only threatens societal well-being, but also impacts the environment and development, both locally and globally. We have just touched the surface of inequality here. Future work will take a more complete look at inequality and differences in consumption.

The one-region case describes a system where neither people, nor resources can disperse. This hypothetical system gives a glimpse into a world with reduced inequality and more local land use. The one-region case maintains consistent well-being and results in slower depletion of agricultural and natural resources. In the one-region model simulations there is still unequal access to resources, but the technological and social development variables are the same. By removing inequalities associated with resource distribution or inequalities that arise from distinct groupings of people with different behaviours and privileges, the greater the potential to promote a sustainable future.

Moreover, the land management scenarios simulated in the one-region environment indicates more or less the desired goal of each land action. The model results suggest that the movement of people and goods can undermine well-intended actions and can lead to confusion or dissociation with the environment. That is not to say dispersal should be limited, as there are numerous benefits to human migration, such as technological development, economic stimulus and cultural diversity (Damelang and Haas, 2012). There are also numerous social factors to consider that are beyond the scope of this paper. Simply, the fact that individuals can move and make decisions based on resource accessibility, necessitates more forethought when it comes to land policies, and consumption practices. Dispersal plays a major role in undermining policies and conservation in our model by masking feedbacks from the environment and delaying sustainable practices. Therefore, it is crucial to gain a better understanding of migration behaviours, the motivations for migration and how individuals adapt to their new environment.

The business as usual scenario provides a grim outlook on human well-being. Natural land conservation is one potential avenue for improving the long-term well-being of the human population and the natural environment; however, land patterns are strongly interlinked with social patterns. Dispersal in the model is driven by the amount of natural land and conserved land, which act as a proxy for greater ecosystem services and higher well-being. The extent of this influence may be over emphasized in the model and we are unable to say for certain that these are realistic patterns of movement with conservation, but it does raise further questions about spatial interactions between people and nature. This suggests that the success of conservation in our current global system, with inequality, migration and global trade is highly susceptible to the spatial dynamics of society.

We are a global society with different land use patterns, social inequality, and the movement of people and goods. The spatial aspect of a global system with two distinct regions, allows for faster technological development, higher peaks in population size, and generally speaking lower population well-being. The unequal access to resources and differences in technological progress, including the development of social structures, education and infrastructure, alter the outcome of natural and agricultural land sustainability and social policies. These scenarios do not include further degradation of natural land or agricultural land by way of climate change, changes in consumption, disease or civil unrest. We only look at the feedbacks between technology/innovation, human population dynamics and land cover. Even without such stochastic events or secondary effects, the scenarios show the rapid degradation of land and the counter-intuitive impact of well-intended policies. The potential for stochastic events to perturb the system could be enormous, considering the negative outcomes in a relatively ideal system. Future work will elaborate on the impact of land management and social equality on global socio-ecological sustainability.

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CRediT authorship contribution statement

Both ML and KH conceived of the project idea and contributed to the final version of the manuscript. ML provided critical feedback and funded the project. KH gathered the data, analysed the data, ran the model simulations and wrote the first draft of the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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