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# Unequal access to resources undermines global sustainability

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1 **RESEARCH PAPER**

2

3 **Unequal access to resources undermines global**  
4 **sustainability**

5 **Kirsten Henderson<sup>1</sup> | Michel Loreau<sup>1</sup>**

6 **1 | INTRODUCTION**

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

14 More often though the environment is valued for the productive assets (i.e. resources),  
15 which leads to inequality and poor land management. Inequality is driven by different land-  
16 use practices and investment choices that fail to distribute resources equally (Coomes et al.,  
17 2016). Inadequate distribution forces more land to be converted, which can lead to a cycle  
18 of poor land management, as well as social inequality and pushes development away from  
19 environmental sustainability (Hasegawa et al., 2019; Boyce, 1994; Cumming and von Cramon-  
20 Taubadel, 2018). Furthermore, there exists a positive feedback between power and wealth,

21 which reinforces inequality, such that in a finite system when one benefits and the other loses,  
22 the result of applying random processes is extreme inequality (Scheffer et al., 2017).

23 Modern practices are built on the idea that wealth and development of knowledge can  
24 continue infinitely (Cass and Mitra, 1991), which requires that the pace of population growth  
25 increases with social organization so that development does not stagnate (Bettencourt et al.,  
26 2007). If technological growth does not continue, economic expansion will increase the de-  
27 mand on the ecological system (Clow, 1998). However, Cumming and von Cramon-Taubadel  
28 (2018) found that economic development is not a precursor to environmental sustainability, as  
29 under the current two-economy system (i.e., high- and low-income) both economies are not al-  
30 lowed to continue developing or cannot simultaneously accumulate wealth (Cumming and von  
31 Cramon-Taubadel, 2018). Rather, the lower income regions supply the higher income regions  
32 with goods, resulting in the over-exploitation of resources and poor living conditions for the LI  
33 economies. Feedbacks between income and population growth push countries farther from  
34 sustainability and the development of countries is not sufficient to promote environmental sus-  
35 tainability. This begs the question as to whether reducing inequality (i.e., altering the access  
36 to resources), rather than economic development alone, is capable of breaking the feedback  
37 cycles in Cumming and von Cramon-Taubadel (2018)'s model that preclude sustainability.

38 When living conditions become undesirable, it becomes beneficial for individuals to move.  
39 Indeed, migration has been shown to allow individuals to inhabit less favourable environments  
40 through temporary dispersal (Holt, 2008) and even has the ability to reduce poverty by moving  
41 to regions with more opportunities or wealth (Adams Jr and Page, 2005). Sweden experienced  
42 mass movements of people in the 19th century, which has been attributed to poor resource  
43 availability and accessibility (Clarke and Low, 1992). The North of Sweden, where the land was  
44 less productive and the carrying capacity was minimal, experienced the greatest population  
45 exodus. In addition to poor resource availability, drought is a another factor in temporary  
46 and indefinite migration. However, the two are not independent as drought often leads to

47 diminished resources by altering the environment and agricultural practices. During the Dust  
48 Bowl of the 1930s in North America, and the severe droughts in Africa through the 1980s  
49 and 1990s, (McLeman, 2014) are classic examples of migration as the result of inauspicious  
50 environmental conditions. Migration can result from either of the two cases or a multitude  
51 of other factors, regardless the basic theory is that either the local conditions are insufficient,  
52 forcing people to leave, or the conditions elsewhere are comparatively better than the local  
53 conditions, attracting new individuals (Grigg, 1977).

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

68 It is clear that humans are dependent on ecosystem services and that poor living condi-  
69 tions lead to migration and unsustainable development, but what is less well understood is  
70 how social structures, as well as resource use in space and time alter the dynamics of a global  
71 socio-ecological system. Here we build and analyse a model to explore current and potential  
72 future land and social dynamics in space. We generate a model consisting of two regions with

73 inequality incorporated through differences in access to technology and resources. We com-  
74 pare the 'real world' model to a uniform one-region system, in addition to scenarios that alter  
75 income status within a region and dispersal between regions. Furthermore, we incorporate  
76 conservation and restoration practices in the two-region system with distinct populations and  
77 practices, hypothesizing that increasing the natural area can contribute to a sustainable and  
78 desirable future for humanity.

## 79 2 | BRIEF MODEL DESCRIPTION

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

90 The regions represent higher income and lower income economies and development struc-  
91 tures ( $j = L, H$ ), each with subpopulations that are also classified as higher income and lower  
92 income ( $P_{i,j}$ , where  $i = L, H$  represents the population income level, and  $j = L, H$  reflects  
93 the region income level). The higher income region refers to a GDP above the global average  
94 and the lower income region refers to a GDP below the global average, we have included a  
95 spreadsheet with this data in the appendix. The subpopulations LH and HL reflect the middle

96 income groups in the 'real world'. These groupings were derived from clear differences in the  
97 stages of the demographic transition, income, social norms, land-use practices, consumption  
98 habits and technological development between regions and populations classified as HI or LI.  
99 Kernel density plots are given in the appendix to show distinct groupings for higher and lower  
100 income regions, with more ambiguous differences between middle income groups. The four  
101 subpopulations in the model represent the spectrum of income groups globally, showing the  
102 variation in consumption levels, birth rates, death rates, research and development expendi-  
103 ture, and resource production. Equations and a full description of the model are provided in  
104 the appendix.

## 105 **2.1 | Human population**

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

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

118 Furthermore, individuals are able to move from one region to another by comparing the  
119 accessible resources in the foreign region with their own resource accessibility. In the model,

120 a sigmoidal curve is used to represent the relationship between resource accessibility and dis-  
121 persal.

## 122 2.2 | Land cover

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

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

138 Conversion from  $N_j$  to  $A_j$  depends on the demand ( $c_{V_j}$ ) from the population ( $P_j$ ) and tech-  
139 nology ( $T_j$ ), in each region. Progressive technology promotes increases in agricultural yield  
140 without the need for further land conversion. Therefore, the greater the technology variable,  
141 the lower the conversion rates. The foreign population in region  $\bar{j}$  also determines the rate  
142 of conversion from natural to agricultural land in region  $j$ , through the same processes as the  
143 local population  $j$ . The proportion of land in region  $j$  manipulated by the population in region

144  $\bar{j}$  is determined by the power ratio.

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

150 Restoration is a function of both natural and human processes that convert unused or de-  
151 graded land ( $U_j$ ) back into natural land ( $N_j$ ). The restoration scenario increases the rate of land  
152 actively being converted from  $U_j$  to  $N_j$  by the human population in region  $j$ . Conservation in  
153 the model refers to a fraction of natural land set aside, which provides individuals and the lo-  
154 cal environment with non-provisioning ecosystem services. Conservation occurs at a constant  
155 rate that is bound by the proportion of desired conserved land and already existing natural  
156 land.

### 157 2.3 | Technology & development

158 Technology and development are major drivers of population dynamics and therefore land  
159 management. Technology is include in the model through resource accessibility and power  
160 functions. It is estimated that higher income regions are more developed, in terms of education,  
161 medicine, machinery, etc. than lower income regions (The World Bank, 2019a; Kummu et al.,  
162 2018; Sarkodie and Adams, 2020; Sen and Laha, 2018). Therefore, we include two technology  
163 variables, one for each region ( $T_j, j = L, H$ ) with different growth rates. The technology growth  
164 curve is a function of population size and density, and the availability of natural resources (i.e.,  
165  $N_j$  and  $C_j$ ). Technology has been shown to increase with population density, however there  
166 becomes a point where the number of individuals exceeds the capacity of natural land and  
167 limits the future development of technology (Clow, 1998), thus giving making it hump-shaped



168 relationship.

169 Technology is a major determinant of power and resource accessibility – determining who  
170 will use what land, when, and how. We assume that technology builds upon itself, therefore  
171 the region with greater advances in technology has the potential to develop new technologies  
172 more quickly, akin to the power cycle described by Scheffer et al. (2017).

## 173 **2.4 | Resource acquisition**

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

## 180 **2.5 | Model analysis and simulations**

181 We first build a business as usual (BAU) model that uses historical trends from the last 260  
182 years to simulate current population and land dynamics. From 10 000 BCE to 1700 the popu-  
183 lation grew on average 0.04% per year and the proportion of land converted grew at less than  
184 1% (Max Roser and Ortiz-Ospina, 2013; Klein Goldewijk et al., 2011). The curves for both land  
185 change and population change follow the same exponential trends, both taking off after 1700;  
186 therefore, we assume that pre-Industrial Revolution data is similar to the early 1700s and is  
187 thus included implicitly in the model from data used on trends over the first half of the 1700s.  
188 The earlier dynamics were thoroughly explored in Henderson and Loreau (2019). We validate  
189 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 degraded or 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 an 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 respec-

216 tive subpopulation, regardless of their access to resources (i.e., acquired wealth). We also  
217 increased the rate of change between income groups, allowing individuals within each sub-  
218 population to transition more quickly between income groups. Finally, for the migration sce-  
219 narios, we prevented individuals from relocating to a different region and we doubled the rate  
220 of migration to see how allowing more or less people into foreign regions would impact the  
221 socio-ecological system.

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

225 The individuals in the population are assigned a well-being status based on the number  
226 of accessible hectares of resources per person ( $R$ ): famine is defined as  $R < 0.55ha/pers.$ ;  
227 poor well-being occurs when  $0.55 \geq R < 1ha/pers.$ ; moderate well-being is defined by  
228  $1 \geq R < 2ha/pers.$ ; good well-being is defined as  $2 \geq R < 5ha/pers.$ ; excessive well-being  
229 is equivalent to  $R \geq 5ha/pers.$  These values are based on the global ecological footprint of  
230 countries (Global Footprint Network, 2019) and the corresponding income group of the coun-  
231 try (details in population calculations and groupings in the appendix)

## 232 3 | RESULTS & DISCUSSION

### 233 3.1 | Business as usual scenario

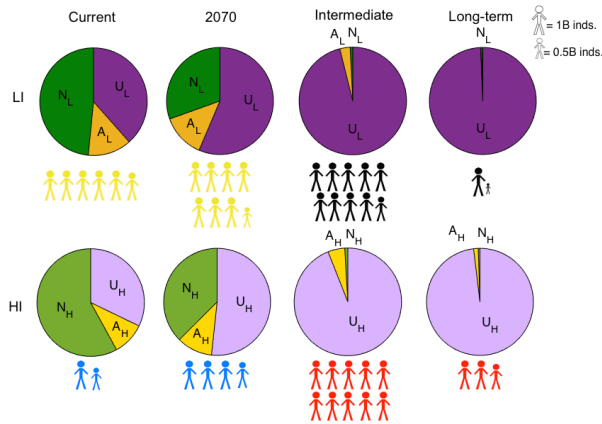
234 The model is able to regenerate observed human population and land cover patterns from ap-  
235 proximately 1750 using parameters estimated from historical data and theories on technology,  
236 demography and ecology (Henderson and Loreau, 2019). The simulations give current values  
237 of  $N_{L,H} \approx 0.5 * L_{L,H}$ ,  $A_L = 0.84$  Bha,  $A_H = 0.64$  Bha and the population size in each region ( $j$ )  
238 is  $P_L = 5.9B$ ,  $P_H = 1.4B$ . Furthermore, the model population projections fit within the 95 per-

239 cent prediction interval of the UN population numbers in 2070 (9.9 to 11.2B) from the United  
240 Nations Population Division (2019) – our higher income population in 2070 is 3.6B, which is  
241 on the upper end of the UN range for high- and upper-middle-income populations (2.75 to  
242 4.2B); and our lower income population is estimated to be 7.2B, on the high end of the UN  
243 range for low- and lower-middle-income populations (5.7 to 7.2B). In the majority of scenarios,  
244 the population is still growing slowly in the year 2100. Unlike the UN projections, the model  
245 simulations described here continue after 2100, after which the model shows major changes  
246 in population dynamics. These changes are driven by the spatial distribution of people and  
247 goods.

248 The model predicts three stages of population dynamics, based on resource accessibility  
249 (i.e., land cover and technology) and dispersal trends. The first 340 years (from approximately  
250 1760 until 2100) are governed by resource accessibility, the population grows without any  
251 impediments from natural land deficiencies. Thereby, many scenarios are similar over this  
252 time period.

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

262 Finally, in 2250, the population starts to decline, as technology has long since stagnated  
263 and resource availability declines below adequate levels to maintain the human population. In  
264 the long-term (i.e., 740 years, long-term dynamics), the BAU scenario leads to famine in the LI



**FIGURE 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.

265 region and poor well-being in the HI region. Both regions experience a population decline, as  
 266 a result of high death rates and little or no recruitment.

### 267 3.2 | Impact of technology

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

276 of comparison with our global two-economy system.

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

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

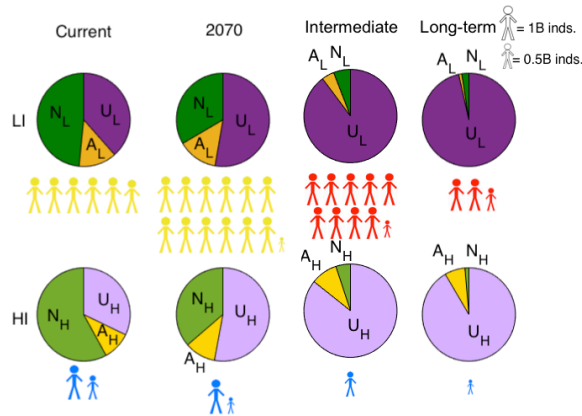
298       Even when lower income regions experience strides in technological and economic devel-  
299 opment, as is the case now, the result is greater environmental degradation. Model simulations  
300 show that countries develop into higher income groupings, thereby gaining a higher standard  
301 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 (1995)'s 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. Doubling the dispersal



**FIGURE 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.

326 rate shows no qualitative differences to the BAU scenario.

### 327 3.4 | Conservation scenario

328 In a seemingly counter-intuitive response, conservation in a region ( $j$ ) draws individuals to the  
 329 region ( $j$ ) from the foreign region ( $\bar{j}$ ). Conserved land,  $C_j$ , does not provide any provisioning  
 330 services to the human population, therefore it seems counter-intuitive that individuals would  
 331 be attracted to the region, but conservation is a symbol of a developed social structure and  
 332 therefore higher well-being (Ghimire and Pimbert, 2013). In the model, conservation allows  
 333 development to continue and therefore increases power. As such, the region with conserva-  
 334 tion experiences increases in growth and dispersal, as individuals from the no-conservation  
 335 region flow in, which changes resource accessibility. Initially, the fluctuations in resource ac-



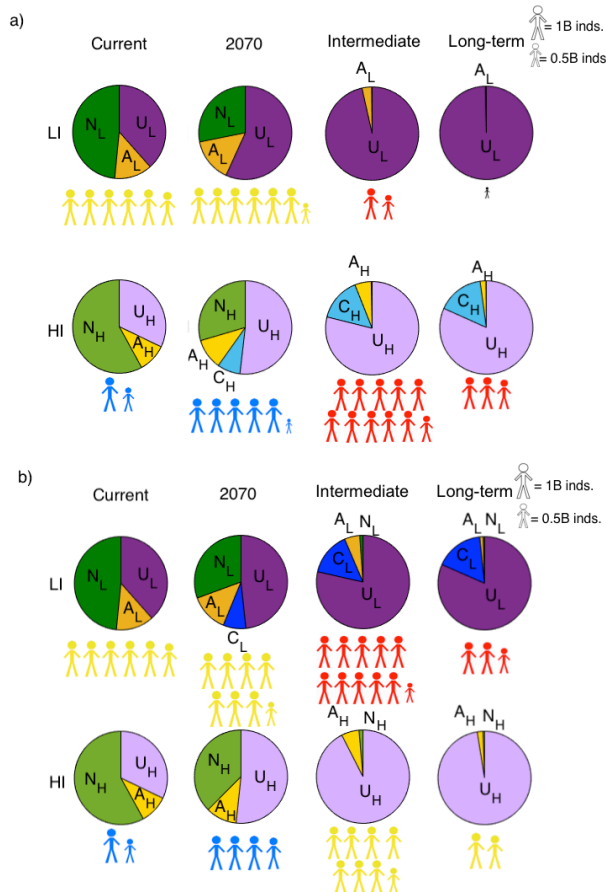
336 cessibility promote growth; however, as the population grows the resource accessibility per  
337 capita declines significantly and causes a decline in the population.

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

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

353 The sustained technology value in the LI region is greater ( $T_L = 3.3$ ). We interpret this  
354 as conservation bringing greater social development and innovation to the region, based on  
355 the theoretical relationship between environmental degradation and poverty, and thus the  
356 potential for environmental rehabilitation to improve production technologies and services  
357 (Ghimire and Pimbert, 2013). The simulated outcome of LI region conservation is optimistic  
358 and should be viewed as the best-case scenario, as it assumes conservation is applied with  
359 little behavioural spillover and positive technological improvements.

360 The one-region conservation scenario provides an interesting contrast to the two-region  
361 system. Conservation in the one-region system generates the greatest abundance of con-



**FIGURE 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.

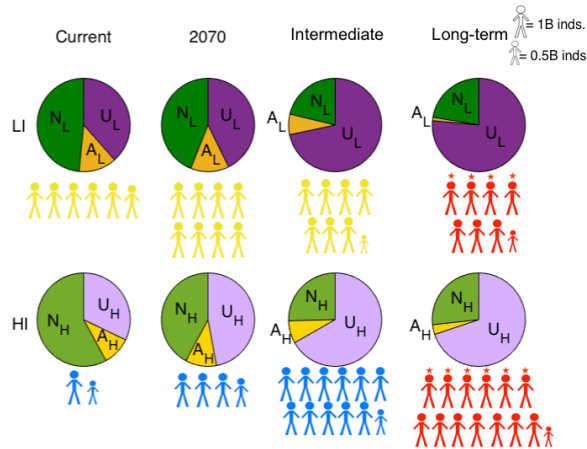
served natural land, while maintaining a good or better population well-being when technology and social structures are well-developed. In this scenario, conservation has no direct or indirect outcome on the human population, the land is merely shifted from unused to conserved nature. However, for populations 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 ( $N_{th}$ ).

385 Restoration has an impact on dispersal and income status. The higher income region con-  
386 tinues to enjoy high resource accessibility over a longer period of time. Furthermore, with  
387 restoration the size of the HI region increases, as whole countries become richer. Restora-  
388 tion in the lower income region improves the well-being and we infer from the model simu-  
389 lations and UN findings (UNnews, 2019) that the lower income region population uses these  
390 newfound resources to seek better opportunities in the HI region or transition to higher in-  
391 come countries once enough wealth is obtained. However, restoration does not solve social  
392 issues (i.e., inequality, over-population), it only delays the impact of environmental degradation,  
393 which causes larger population's with poor well-being and globally limited resources. In the  
394 intermediate stage (intermediate dynamics), the renewed resources from restoration pushes  
395 the population to extreme sizes, while maintaining the living standards (i.e.,  $W_L = moderate$ ,  
396  $W_H = excessive$ ), which ultimately places huge demands on the environment. The dispersal-  
397 driven stage of the model socio-ecological dynamics (second phase) in this scenario is delayed  
398 100 years beyond the onset observed in all other two-region scenarios. In the long-term, all  
399 populations look to dispersal as a means of accessing resources, only to find that resources  
400 are limited globally. As a result, in the long-term the access to resources declines per capita,  
401 as the population outgrows the ecological capacity of the global system.

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



**FIGURE 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 ( $W_L = \text{moderate}$ ,  $W_H = \text{excessive}$ ). After which, the population becomes too large ( $P_H = 67.3\text{B}$  inds.,  $P_L = 43.3\text{B}$  inds.) for the resource availability ( $N$  and  $A$ ) and the well-being declines to poor, globally. Stick figures with an asterisk represents 10B individuals, as seen in the long-term dynamics.

### 407 3.6 | Status scenario

408 Lastly, in a scenario in which individuals are not allowed to change income status, thereby  
 409 keeping access to resources limited in lower income populations (in both HI and LI regions),  
 410 there is little impact on the results. The number of individuals in each subpopulation changes;  
 411 however the population size, by region, remains the same (Fig. A2). The difference in well-  
 412 being is slight, yet there are no qualitative changes to the results. As there is no change in  
 413 population dynamics, the land cover remains the same compared to the BAU scenario.

### 414 3.7 | Comparison with the one-region system

415 The one-region system is much more stable than the two-region system. There are fewer feed-  
 416 backs in the one-region system, which means the outcome of each action is more deliberate

417 and achieves the desired goal. For example, the one-region case with restoration shows that  
418 restoration of natural land improves well-being (Fig. 5c), in addition to sustaining natural land  
419 at  $N = 3.3$  Bha.

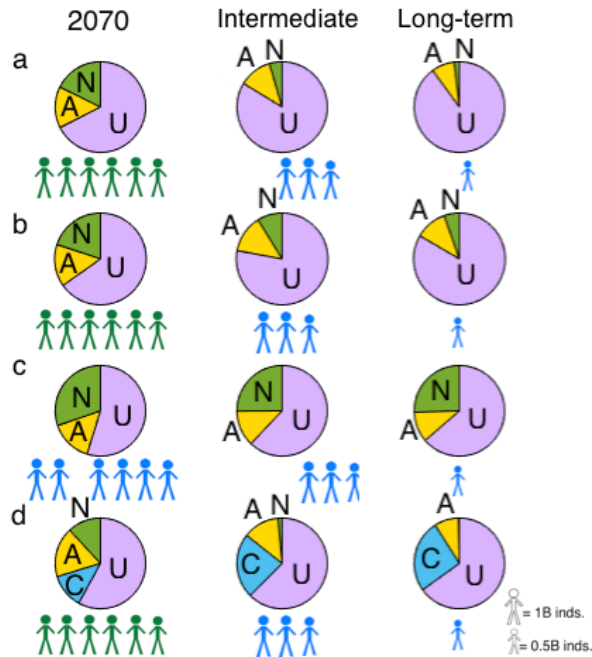
420 Unlike the two-region system, the one-region system maintains natural land ( $N$ ), smaller  
421 populations, and a continual state of well-being for all scenarios. The one-region system is  
422 strongly influenced by the rate of technological growth. Fast technological growth leads to a  
423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

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

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

## 432 4 | CONCLUSIONS

433 The complex interactions between land, people and technology make it difficult to predict the  
434 success of sustainable development policies. The multitude of feedbacks between humans,  
435 nature and development necessitates the use of a coupled socio-ecological system in order to  
436 adequately reflect our environmentally and socially diverse world. For example, restoration has  
437 the potential to promote higher sustained populations with improved well-being, yet we find  
438 that the multiple feedbacks between dispersal and resource accessibility drive the population  
439 towards growth at the expense of well-being, as individuals move to where resources are more



**FIGURE 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  $A$ .

440 accessible and growth is possible. However, this eventually exhausts all the resources leading  
441 to few accessible resources, a massive population, and poor well-being. Without inequality or  
442 the spatial distribution of people and goods, the outcome of land restoration would be entirely  
443 beneficial to humans and the environment.

444 In all model scenarios, it is evident that technology provides an advantage to higher income  
445 regions by allowing population's to access more resources and disperse more easily, conse-  
446 quently contributing to the poor well-being of those less fortunate.

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

461 The one-region case describes a system where neither people, nor resources can disperse.  
462 This hypothetical system gives a glimpse into a world with reduced inequality and more local  
463 land use. The one-region case maintains consistent well-being and results in slower depletion  
464 of agricultural and natural resources. In the one-region model simulations inequality still ex-  
465 ists within resource accessibility, but the technological and social development are the same.



466 By removing inequalities associated with resource distribution or inequalities that arise from  
467 distinct groupings of people with different behaviours and privileges, the greater the potential  
468 to promote a sustainable future.

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

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

491 We are a global society with different land use patterns, social inequality, and the move-

492 ment of people and goods. The spatial aspect of a global system with two distinct regions,  
493 allows for faster technological development, higher peaks in population size, and generally  
494 speaking lower population well-being. The unequal access to resources and differences in  
495 technological progress, including the development of social structures, education and infras-  
496 tructure, alter the outcome of natural and agricultural land sustainability and social policies.  
497 These scenarios do not include further degradation of natural land or agricultural land by way  
498 of climate change, changes in consumption, disease or civil unrest. We only look at the feed-  
499 backs between technology/innovation, human population dynamics and land cover. Even with-  
500 out such stochastic events or secondary effects, the scenarios show the rapid degradation of  
501 land and the counter-intuitive impact of well-intended policies. The potential for stochastic  
502 events to perturb the system could be enormous, considering the negative outcomes in a rel-  
503 atively ideal system. Future work will elaborate on the impact of land management and social  
504 equality on global socio-ecological sustainability.

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## 641 APPENDIX

### 642 Model in detail

643 The model represents a simplified global system with two regions classified by their income  
 644 group ( $j = L, H$ ) and each region consists of two subpopulations ( $i = L, H$ ). Individuals are  
 645 categorized as either lower or higher income subpopulations, within higher or lower income  
 646 regions ( $P_{i,j}, i = L, H, j = L, H$ ), similar to the model by Cumming and von Cramon-Taubadel  
 647 (2018).

648 The two regions are composed of natural land ( $N_j, j = L, H$ ), agricultural land ( $A_j$ ) and un-  
 649 used land ( $U_j$ ), which is the total land area ( $L_j$ ) minus  $A_j$  and  $N_j$ . Land-use practices include  
 650 local ( $j$ , such that  $j = L, H$ ) and foreign ( $\bar{j}$ , such that if  $j = L, \bar{j} = H$  or  $j = H$  and  $\bar{j} = L$ ) use of  
 651 land. Land dynamics include functions describing degradation ( $dN_j(P, T), dA_j(P, N, C)$ ), cross-  
 652 degradation ( $xdN_j(P, T), x dA_j(P, N, C)$ ), conversion ( $cv_j(P, T)$ ), restoration ( $rt_j(P, N, A, C)$ ) and  
 653 options for conservation ( $cs_j(N, C)$ ).

654 The human population is able to change income status within their own region given by  
 655 the functions  $s_{i,j}(P, N, A, C, T)$  and  $s_{\bar{i},j}(P, N, A, C, T)$ , where  $i$  is the population in either the  
 656 HI or LI subpopulations and  $\bar{i}$  is the opposite of  $i$ . Individuals are able to disperse from one  
 657 region to another, given by the functions  $\delta_{i,j}(P, N, A, C, T)$  and  $\delta_{i,\bar{j}}(P, N, A, C, T)$ . The growth  
 658 of each subpopulation varies significantly with their access to resources, which is described  
 659 by the function ( $g_{i,j}(P, N, A, C, T)$ ).

660 The higher income region initially has a higher overall income level, such that those in the  
 661 lower income subpopulation in the higher income region have a greater access to resources  
 662 than individuals in the lower income region. Similarly, the technological development in the  
 663 higher income region is initially faster than the lower income region. However, all the equations  
 664 are dynamic and have the ability to change. The rates of change are given by the following  
 665 differential equations:



$$\frac{dP_{i,j}}{dt} = (g_{i,j}(P, N, A, C, T) - s_{i,j}(P, N, A, C, T) - \delta_{i,j}(P, N, A, C, T)) \cdot P_{i,j} +$$

$$s_{i,j}^-(P, N, A, C, T) \cdot P_{i,j}^- + \delta_{i,j}^-(P, N, A, C, T) \cdot P_{i,j}^-,$$

$$\frac{dN_j}{dt} = (-dN_j(P, T) - x dN_j(P, T) - cv_j(P, T)) \cdot N_j + a_d A_j + rt_j(P, N, A, C) - cs_j(N, C) \cdot N_j,$$

$$\frac{dA_j}{dt} = (-dA_j(P, N, C, T) - x dA_j(P, N, C, T) - a_d) \cdot A_j + cv_j(P, T) \cdot N_j, \quad (\text{A.1})$$

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

$$\frac{dT_j}{dt} = \min(1, T_j) \cdot t_j \cdot \left( \frac{P_j^{0.5}}{\max(1, (P_j^{0.5} - (N_j + e_s C_j))^2)} \right)$$

$$\cdot \min(1, (\max(-0.001, (N_j + e_s C_j) - N_{th}))).$$

## Human population

Population growth rate ( $g_{i,j}$ ) is determined from the non-monotonic curve relating recruitment and mortality rates to resource accessibility ( $R_{i,j}$ ). The details of this theory are described in Henderson and Loreau (2019). The recruitment and mortality equations are modified to incorporate two distinct regions, as such the resource accessibility units are given in ha/ind. rather than Bha (Henderson and Loreau, 2019), which requires a calibration of the recruitment equation to maintain the characteristics of the curve. The curve shape is the same in both models, however the range is truncated here, which results in a sharper rise and decline for each hectare of accessible resource.

$$g_{i,j} = \frac{b \exp\left(\frac{-(2R_{i,j} - b_{th})^2}{2(R_{i,j})^{0.25}}\right)}{(R_{i,j})^2} - \frac{m_{max}}{1 + \exp(2R_{i,j} - m_{th})} + m_{min}. \quad (\text{A.2})$$

The maximum recruitment rate is given by  $b$ . There is a transition in social behaviours from survival mode (i.e., quantity) to thrive mode (i.e., quality) which occurs when resources reach a certain threshold of accessible resources ( $b_{th}$ ). The mortality rate is also threshold-dependent ( $m_{th}$ ), such that there is a sharp drop from maximum mortality ( $m_{max}$ ) when  $R_{i,j}$

685 reaches  $m_{th}$ . Unlike recruitment, mortality cannot equal zero, therefore  $m_{min}$  represents the  
686 minimum mortality rate.

687 Once a threshold amount of accessible resources ( $s_{H,j_{th}}, s_{L,j_{th}}$ ) is obtained, an individual can  
688 change status from higher income to lower income ( $s_{H,H}(P, N, A, C, T), s_{H,L}(P, N, A, C, T)$ ) or  
689 from lower to higher income ( $s_{L,L}(P, N, A, C, T), s_{L,H}(P, N, A, C, T)$ ).

$$s_{H,j}(P, N, A, C, T) = \frac{\psi_{H,j}}{1 + \exp(R_{H,j} - s_{H,j_{th}})^{0.5}}, \quad (\text{A.3a})$$

690

$$s_{L,j}(P, N, A, C, T) = \psi_{L,j} \cdot \exp(R_{L,j} - s_{L,j_{th}})^{0.5}, \quad (\text{A.3b})$$

691 where  $\psi_{i,j}$  is the status shift coefficient that creates a bias in status change. Status changes in  
692 association with resource accessibility ( $R_{i,j}$ ), however inequality in our social system makes it  
693 more difficult for lower income individuals break the poverty cycle (Payne, 2005). What we  
694 consider “higher income” occurs at  $R = 2\text{ha/ind.}$ ; however, it is more difficult to become higher  
695 income, therefore  $s_{L,j_{th}}$  is set at 2.5 ha/ind. When access to resources drops below 1.5 ha/ind.  
696 in the model, individuals have a moderate well-being, which is considered to be the case for  
697 lower income individuals, therefore  $s_{H,j_{th}}$  is set at 1.5 ha/ind. Once the resource access for in-  
698 dividuals in the HI subpopulation dips below 1.5 ha/ind., the individual becomes lower income.  
699 The values for  $s_{L,j_{th}}$  and  $s_{H,j_{th}}$  were estimated from the average global ecological footprint for  
700 each income group (details provided below in Population calculations and groupings section).  
701 Individuals are able to move from one region to another by comparing the resource accessibil-  
702 ity in the foreign region ( $avg(R_{\bar{j}})$ ) compared to the local resource accessibility ( $R_{i,j}$ ), where  $i$  is  
703 the income group ( $i, i = H, L$ ) and  $j$  is the region ( $j, j = H, L$ ). Individuals disperse to the region  
704 with greater resource accessibility according to the function:

$$\delta_{i,j}(P, N, A, C, T) = \frac{\delta_{i,j}}{\frac{N_j + \alpha C_j}{\max(P_j, 0.00001)}} \cdot \frac{avg(R_{\bar{j}})}{R_{i,j}}. \quad (\text{A.4})$$

705 The equation for dispersal was modified from Keegan (1995), where movement is a logistic  
706 equation reflecting the relationship between births, deaths and resources, and the dispersal  
707 equation in Potapov et al. (2014). Here, a sigmoidal curve is used to represent the relationship  
708 between resource accessibility and dispersal.

709 Not all individuals are able to disperse at the same rate, inequality and policies limit dis-  
710 persal, therefore the rate of dispersal ( $\delta_{i,j}$ , where  $i = L, H$ , subpopulation income status, and  
711  $j = L, H$ , the region) is different for each subpopulation. Individuals also take into considera-  
712 tion the fraction of natural land ( $N_j$ ) and conserved land ( $C_j$ ) per person ( $P_j$ ). More natural and  
713 conserved lands presumably mean greater well-being (Ghimire and Pimbert, 2013).  $\alpha$  changes  
714 the influence of conservation on migration.

## Technology & development

Technology presents a large unknown in terms of future potential to continue positive development. Generally, in the literature technology growth is represented by a sigmoidal curve (Henderson and Loreau, 2019). In the majority of cases, the technology output described here follows a sigmoidal trend (Fig. A1), but instead of imposing a threshold, it is the population density and natural land cover (both  $N$  and  $C$ ) that determine the threshold, which allows more dynamic output and variations in onset, steepness and duration of the technology transition. In the framework outlined by Galor and Weil (2000), technological progress depends on population size and human capital. We argue that it is more plausible to assume that technological change depends on population density, as population density facilitates communication and exchange, increases the size of markets and generates demand for innovation (Klasen and Nestmann, 2006).

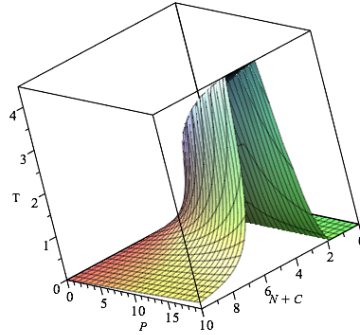
We used historical data to calibrate the higher and lower income technology/development variables and differential equations. The technology and development growth rate up until present should lie between economic growth rate, which has grown at the same pace (Motesharrei et al., 2016) and technological growth, measured by advances in computer processing and inventions, which is 10 times faster than human population growth.

In the model, technology/development is a major driver of population dynamics via resource accessibility. It is estimated that higher income regions are more developed than lower income regions, in terms of education, medicine, machinery, etc. (The World Bank, 2019a). Therefore, we include two technology/development variables, one for each region ( $T_j, j = L, H$ ) with different growth rates ( $t_j$ ). The technology growth curve is a function of population size (i.e.,  $P_j = P_{H,j} + P_{L,j}$ , where  $j$  is the region, density (i.e.,  $\frac{(P_j)^{0.5}}{\max(1, ((P_j)^{0.5} - (N_j + e_s C_j))^2)}$ ), and 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 ( $N_{th}$ ) (Clow, 1998). Conserved land provides ecosystem services, minus provisioning services, therefore only a fraction is useful for technological development, given by  $e_s$ .

Technology and development are major determinants of power and resource accessibility – determining who will use what land, when, and how. We assume that technology/development builds upon itself, therefore the region with more technology and more structured development has the potential to develop new technologies more quickly, hence the term  $\min(1, T_j)$ .

Technological innovation does not create new human capabilities nor production processes, it only finds new ways to tap into and harness existing natural processes and energy flows (Clow, 1998). To continue economic growth indefinitely, technological innovation has to continue on a coordinated and indefinite basis. If not, economic expansion will place greater demands on the environment and cause more ecological disruption; as a result, one quickly runs into limitations on production arising from the inability of the Earth to supply resources and waste absorption. Therefore, we assume there is an ecological threshold in the development of technology ( $N_{th}$ , eqns. A.1 & A.6). There is no such thing as indefinite improvement in technological efficiency nor indefinite ability to tailor ecosystems to deliver more resources or absorb and recycle more wastes.

In terms of cost-benefit analysis, many have suggested that technology and resource prices



**FIGURE A1** Non-monotonic technology curve that is density-dependent ( $\frac{P}{N}$ ) and nature-dependent ( $N, C$ ).

757 can only prolong resource accessibility within certain environmental and social limits (Mudd,  
 758 2010; Prior et al., 2012; Schandl and West, 2010). Hence, the use of a density-dependent  
 759 technology curve (fig. A1). Below is a simplification of the density- and nature-dependent  
 760 technology equation.

$$\frac{P^{0.5} \min(1, \max(-0.001, N + e_s C - N_{th}))}{\max(1, (P^{0.5} - N - e_s C)^2)} \quad (\text{A.5})$$

## 761 | Resource acquisition

$$\text{power}_j = \frac{P_j^{0.5}}{P_{0j}} \cdot \frac{T_j^{0.5}}{T_j} \quad (\text{A.6})$$

762 Power ( $\text{power}R_j$ ) refers to the share of resources the population, in each region, ( $P_j$ ) can  
 763 access. Foreign access to resources is simply  $1 - \text{power}R_j$ . For example, the higher income  
 764 region exerts more power, therefore controls the majority of land in their own region ( $j$ ), yet  
 765 still has access to a significant share in the foreign region ( $\bar{j}$ ). This share of land is given by the  
 766 power ratio equation:

$$\text{power}R_j = \min\left(0.99, 2 \frac{\text{power}_j}{\text{power}_j + \text{power}_{\bar{j}}}\right) \quad (\text{A.7})$$

767 The power dynamics for agriculture are the same as for natural land.

768 Resource accessibility per person is a function of the resources available ( $N_j, A_j$ ) and how  
 769 much access each individuals has to these resources through power and technology. It is as-

770 summed that technology/development ( $T_j$ ) determines the production yield and the ability to  
771 acquire the available resources.

$$R_{i,j} = \frac{(N_j + A_j) \cdot powerR_j + (N_{\bar{j}} + A_{\bar{j}}) \cdot (1 - powerR_j) \cdot T_j}{P_j}. \quad (\text{A.8a})$$

772 The power dynamics can drop the resource accessibility to unrealistic proportions. There-  
773 fore, when  $R_{i,j} < 1$  the resource accessibility is scaled according to the famine state ( $R = 0.55$ ),  
774 resources ( $N_j, C_j, A_j$ ), technology ( $T_j$ ) and people ( $P_j$ ).

$$R_{i,j} = \frac{0.55 \cdot \min(1, (\max(0.00001, (N_j + e_s C_j) - N_{th}))^{0.5}) + T_j^{0.5} (N_j + A_j)^{0.5}}{\max(0.5, P_j)^{0.5}}. \quad (\text{A.8b})$$

775 For the minority subpopulation in each region (when  $i \neq j$ ), we assume an unequal access to  
776 resources. Despite the same technology and development, the access is not distributed equally  
777 throughout the region. We scale the resource accessibility as follows,  $R_{L,H} = R_{H,H} \cdot 0.65$  and  
778  $R_{H,L} = R_{L,L} \cdot 1.6$ , according to GINI data from OECD (2019); The World Bank (2019b).

## 779 | Land dynamics

780 The composition is classified given FAO data on the eleven global land cover layers. Agricul-  
781 tural land ( $A_j$ ) is composed entirely of croplands, which occupies 12.6% of current land cover.  
782 Natural land ( $N_j$ ) describes the broadest range of land cover, including grasslands, herbaceous  
783 vegetation, mangroves, shrub-covered areas, sparse vegetation, tree-covered areas, for a total  
784 of 59.3%. Finally, the unused land describes the remaining land cover, artificial surfaces, bare  
785 soils, snow and glaciers, and inland water bodies (28.1%) (Food and Agriculture Organization  
786 of the United Nations, 2019).

## 787 | Natural land

788 The degradation and consumption of natural land in each region ( $j = L, H$ ) depends on the  
789 population size within each region ( $P_j$ ), the demand and degradation of resources ( $dN_j$ ) and  
790 the proportion land under control of population ( $powerR_j$ ),  $P_j$ .

$$dN_j(P, T) = powerR_j^{0.5} \cdot dN_j \cdot P_j. \quad (\text{A.9})$$

791 In both, degradation and cross-degradation, the square root of power is used to determine  
792 the proportion of land used by each region, as the impact of degradation can extend beyond  
793 the land under question and percolate to other patches (Kun et al., 2019). Furthermore, the  
794 ecosystem services from one area are beneficial to the adjacent areas, therefore reducing the

795 natural land area can reduce the resilience of the surrounding area. For example, pest control  
 796 in wheat crops benefits from natural predators and as Woodcock et al. (2016) explain the spill-  
 797 over of natural pest control services declined with distance from the crop edge.

798 The remaining proportion of land not used by the local individuals ( $1 - powerR_j$ ) gets con-  
 799 sumed and degraded by the individuals from the other region ( $P_j$ ). In what is termed cross-  
 800 degradation:

$$xdN_j(P, T) = (1 - powerR_j)^{0.5} \cdot xdN_j \cdot P_j. \quad (A.10)$$

801 The coefficient for cross-degradation and consumption,  $xdN_j$ , is assumed to be smaller  
 802 than  $dN_j$ . The values assigned to the coefficients are given in Table A1.

803 Conversion of natural land ( $N_j$ ) to agricultural land ( $A_j$ ) is necessary to supply the current  
 804 and future populations with adequate food. The equation is given by

$$cv_j(P, T) = \frac{cv_j \cdot powerR_j^{0.5} \cdot P_j + xcv_j \cdot (1 - powerR_j)^{0.5} \cdot P_j}{(1 + T_j)}. \quad (A.11)$$

805 Agriculture is part of the global trade network and as such agricultural production in one  
 806 region is likely to be consumed by another region. Conversion depends on the demand from  
 807 each region  $cv_j$  (local) and  $xcv_j$  (foreign) and what share of the land each region is able to ma-  
 808 nipulate ( $powerR_j$  and  $1 - powerR_j$ ). Furthermore, technology allows the yield to improve  
 809 without increasing land cover. Hence, when technological development ( $T_j$ ) increases, conver-  
 810 sion ( $cv_j(P, T)$ ) of  $N_j$  to  $A_j$  declines.

811 Restoration is both the natural and human process of converting unused or degraded land  
 812 ( $U_j$ ) back into natural land ( $N_j$ ).

$$rt_j(P, N, A, C) = (rN + rH \cdot P_j) \cdot \max(0, L_j - N_j - A_j - C_j). \quad (A.12)$$

813 The rate of natural land restoration ( $rN$ ) is the inverse time required to return  $U_j$  back  
 814 into a natural space. Human land restoration is another model scenario, used to analyse the  
 815 active process of returning degraded land to a natural state. Therefore,  $rH$  is the constant  
 816 rate of restoration per person ( $P_j$ ). A minimal restoration is expected in the business as usual  
 817 scenario, such that  $rH = rN$ .

818 Conservation in the model refers to a fraction of land set aside for non-provisioning ecosys-  
 819 tem services.

$$cs_j(N, C) = cs \cdot \rho \cdot \frac{L_j}{N_j + C_j} \cdot \min(1, P_j). \quad (A.13)$$

820 The goal of conservation is to maintain a certain proportion of natural land ( $C_j$ ). Therefore,  
 821 natural land ( $N_j$ ) is set aside and continually maintained, so long as there are people to govern  
 822 the conserved land,  $\min(1, P_j)$ . The conservation of natural land ( $C_j$ ) is a model scenario, where  
 823 a proportion of land ( $\rho$ ) is set aside and maintained at a rate of  $cs \cdot L_j / (N_j + C_j)$ .

## Agricultural land

The majority of newly converted agricultural land ( $A_j$ ) area is derived from natural land ( $N_j$ ), leading to degradation of  $N_j$ . It has also been shown that agricultural production improves with surrounding natural land area and that degradation is intensified when there is a lack of supporting ecosystem services (Bennett et al., 2009; Braat and De Groot, 2012). Therefore, agricultural degradation is a function of the degradation rate ( $dA_j$ ) and ecosystem service influence:

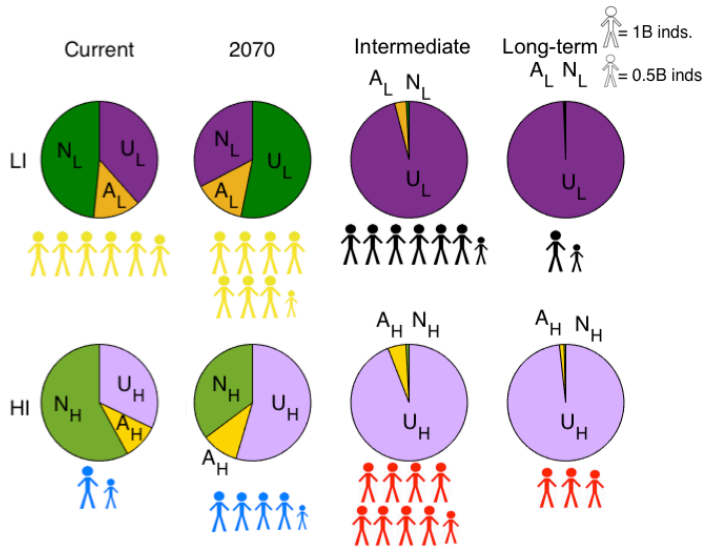
$$dA_j(P, N, C, T) = P_j \cdot powerR_j^{0.5} \cdot \left( \frac{dA_j \exp(-(N_j + C_j))}{p_{es} \cdot L_j} + dA_{min} \right) - a_d. \quad (A.14)$$

Degradation is impacted by regulating services, it has been shown that natural land provides essential assets that increase the yield, diminish pests and provide numerous benefits to agricultural land (Swinton et al., 2007). Therefore, degradation is intensified when the natural land ( $N_j$ ) and conserved land ( $C_j$ ) area do not represent the proportion  $p_{es}$  of the entire land area. From studies on the benefits of pollination (Morandin and Winston, 2006) on agriculture and improved insect diversity and pest control in complex agriculture systems (Bianchi et al., 2006; Söderström et al., 2001), the required proportion of land for the flow of ecosystem services and production ( $p_{es}$ ) is estimated at 0.3 of the region ( $L_j$ ). As the population ( $P_j$ ) grows, so does the consumption of agriculture goods and degradation. The regional population exerts a proportion of the degradation, which is represented by  $powerR_j^{0.5}$ . Even if there are sufficient supporting services there will still be a minimal rate of agricultural degradation ( $dA_{P_{min}}$ ), as a result of consumption and modern agricultural practices and urbanization (Azadi et al., 2011; Southgate et al., 1990; Smetanová et al., 2019). In addition to human degradation of agricultural land, natural degradation occurs as a result of soil erosion at a rate approximately 3 to 8 times slower than human-caused soil erosion, hence  $a_d$  is set to 0.0001/yr (Nearing et al., 2017).

Agricultural land is further consumed and degraded by the foreign population ( $P_{\bar{j}}$ ) in the region  $j$  ( $j = L, H$ ;  $\bar{j} = H$  if  $j = L$  and  $\bar{j} = L$  if  $j = H$ ). Cross-degradation is determined by the proportion of land used by foreign entities ( $(1 - powerR_j)^{0.5}$ ).

$$xA_j(P, N, C, T) = P_{\bar{j}} \cdot (1 - powerR_j)^{0.5} \cdot \left( \frac{xA_j \cdot \exp(-(N_j + C_j))}{es \cdot L_j} + xA_{P_{min}} \right) - a_d. \quad (A.15)$$

Cross-degradation shares the same characteristics as degradation, except the rate of degradation ( $xA_j$ ) reflects the demands from the foreign region. The minimal cross-degradation ( $xA_{P_{min}}$ ) is also dependent on the demands from the foreign region.



**FIGURE A2** No status shift – land and population patterns. The land and population dynamics are unchanged from the BAU scenario. The population size ( $P_L$  and  $P_H$ ) are the same, the subpopulations are different, however that is not evident here. The well-being is qualitatively unchanged. The  $P_L$  transitions from moderate (yellow) to famine (black), while the  $P_H$  transitions from excessive (blue) to poor (red). The land cover is similar to the BAU scenario, where natural land ( $N_L$ ,  $N_H$ ) and agricultural land ( $A_L$ ,  $A_H$ ) are negligible.

### 853 | Additional results

#### 854 | Status

855 Globally, the population is becoming wealthier. Therefore, accelerating the movement of indi-  
 856 viduals through income status, allows more individuals to move to the higher income popula-  
 857 tion, which decreases the number of individuals in the lower income population. This is often  
 858 seen in rural-urban transitions, such that when individuals move from rural to urban regions,  
 859 fertility decreases (Jensen and Ahlburg, 2004). However, in this scenario there is no change  
 860 to the long-term resource accessibility or well-being to support the shift in population income  
 861 levels, therefore the trend is similar to business as usual (BAU) scenario. In the case of no sta-  
 862 tus shift (Fig. A2), the overall population in each region remains the same as the BAU scenario.  
 863 In both cases, the collapse of resource accessibility is too strong to be overcome by shifts in  
 864 income status.

#### 865 | Technology

866 The model suggests that technology is more than three times greater in the HI region than in  
 867 the LI region. This is in range of the Human Development Index (HDI), where the countries  
 868 with the greatest HDI (i.e., Norway, Switzerland, Australia) have HDI values that are 2.8 times  
 869 greater than countries with the lowest values (i.e., Niger, Central African Republic) (United



870 Nations Development Programme, 2019). The HDI considers education, income and life ex-  
871 pectancy, all of which are considered components of our technology variable. Technology and  
872 population are intricately linked, which is evidenced through the multiple scenarios evaluated.  
873 Technological development is promoted by the number of individuals; however, when there  
874 are too many people and natural land is limited, this impedes technology growth. The non-  
875 monotonic resource curve (Fig. A1) suggests that technology can either help the population  
876 grow, if the well-being is in the moderate state or worse, otherwise the population decreases,  
877 if the population well-being is good or above, based on theory on the demographic transition  
878 (Henderson and Loreau, 2019).

### 879 | Conservation

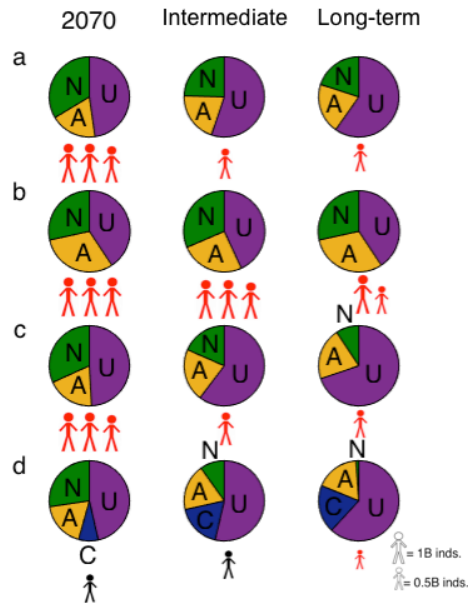
880 Conservation in either region, always benefits the HI population more than the LI population;  
881 however, conservation in the LI region encourages the development of technology and im-  
882 proves well-being compared to the business as usual scenario. Individuals in the HI region  
883 benefit from little competition for resources in their own region and take resources from the  
884 LI region, where the LI increase in technology staves off famine in the LI region.

### 885 | Restoration

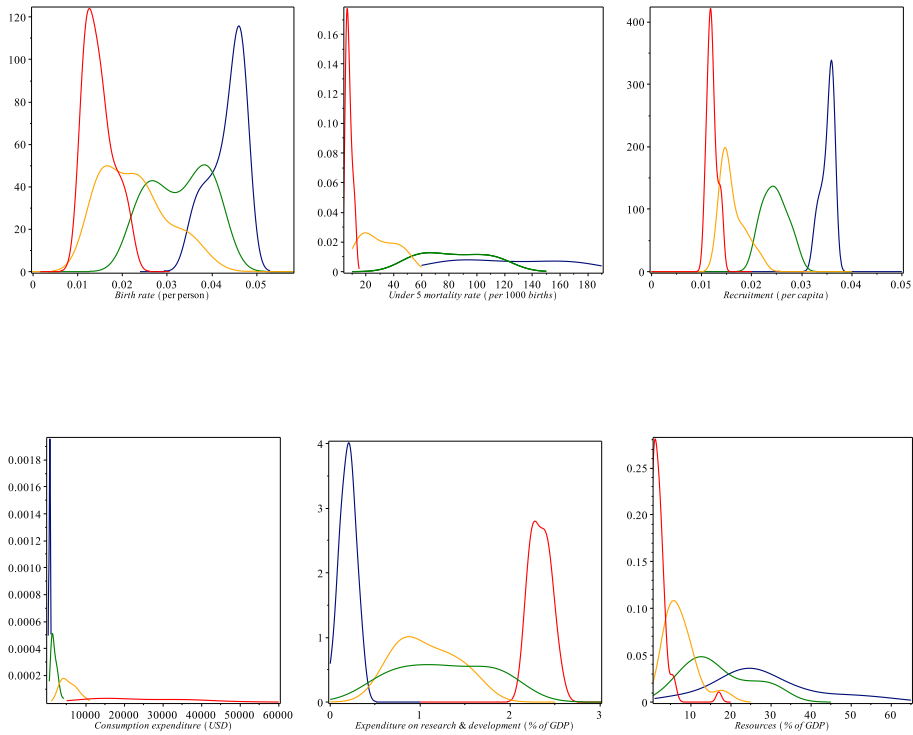
886 Restoration in a specific region (i.e., 1 of the 2 regions) results in similar trends to conservation  
887 in a specific region. Natural land and agricultural land are sustained in the region with restora-  
888 tion and the population disperses to the region with natural land restoration. In the higher  
889 income region, the population is very high (37B inds.) and the land area is minimal ( $N = 1$  Bha  
890 and  $A = 0.2$  Bha), causing a poor well-being in the region with restoration. In the lower income  
891 region, restoration causes unrealistically high population numbers (>200B inds.), as result of  
892 the positive feedback between people and technology, with adequate natural land. In both  
893 cases, the region without restoration becomes non-existent in terms of land and people in the  
894 long-term.

### 895 | One-region

896 If the one-region system were to follow a low-tech scenario, what could be considered a world  
897 without the industrial revolution, the population would remain low and in a poor state (Fig. A3).  
898 Here land management policies can either help, minimally, or harm the population. Restora-  
899 tion provides slightly more resources to the population, which increases resource accessibility  
900 enough to reproduce more, but not enough to improve well-being (Fig. A3b). Conservation,  
901 initially decreases the well-being of the human population, by limiting the access to resources  
902 until the population declines sufficiently to reach a poor human well-being and sustainable  
903 land cover (Fig. A3d). In all the scenarios, some form of natural land is maintained, either  
904 conserved or accessible, and agricultural land area is consistent over the years.



**FIGURE A3** One-region (low-tech), all scenarios – land and population patterns. a) BAU - In the one-region, low-tech case, the population does not grow quickly, in 320 years the  $P$  increases by 1.8B. The slow growth is due to a lack of accessible resources, all individuals have a poor (red) well-being, except in the conservation scenario. The population size is between 4 times and 34 times smaller than BAU two-regions ( $P = 2.8$  in 2070,  $P = 0.5$  in 2250,  $P = 0.3$  in 2750). Significant fractions of natural land ( $N$ ) and agricultural land ( $A$ ) are maintained over time, yet  $N$  still declines ( $N = 4.3$  Bha in 2070,  $N = 2.6$  Bha in 2750) and  $A$  increases by 0.2 Bha. b) Restoration - A higher  $P$  is maintained over time, with restoration. There is also more  $N$  and  $A$  throughout the simulations. c) No status - The population size ( $P$ ) and well-being ( $W$ ) is similar to the BAU scenario. There is a decline in  $N$  from 4.1 Bha to 1.2 Bha, while  $A$  remains constant. d) Conservation - Conservation reduces the the population size ( $P < 0.3B$  inds.) and well-being ( $W = \text{famine}$ ), immediately after application. Once population declines to  $\approx 0.1B$ , resource accessibility per person returns to  $W = \text{poor}$ .



**FIGURE A4** Kernel density plots to show the differences between high and low-income groups. The x-axis represents a global development indicator and the y-axis represents the calculated density. Each plot shows the range of values for each income group, as classified by the World Bank Group, over the last 60 years. There are clear clustering patterns that distinguish low-income countries from high-income countries, while the upper and lower middle-income countries lie in the middle and overlap with all income groups. The data for research expenditure in low-income and lower middle-income were sparse; therefore the lower middle-income group was generated using data for East Asia and Pacific (excluding high-income countries) and the low-income countries was calculated as an average of low-income countries with consistent data (Madagascar, Burkina Faso and Uganda). The plots were generated using data from the World Bank Group in Maple.

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## Population calculations and groupings

The information here was used to set the subpopulations. Data is from 2010 for population size and GDP for each country given by the World Bank Group (The World Bank, 2019a). Countries with a GDP per capita greater than 20 000 USD are classified as  $P_{HH}$  in our model; between 10 000 and 20 000 USD are classified as  $P_{LH}$ ; between 5 000 and 10 000 USD are classified as  $P_{HL}$ ; and below 5 000 USD are classified as  $P_{LL}$ . These groupings were used as guidelines for the model simulations, for example the model simulations for population numbers were compared to the 2010 values to validate the model. These groupings also provided the basis for the model assumptions and kernel density plots. When compared to the World Bank Group classification, the bounds set in our model classification are higher on average than the World Bank, but the population within the regions of higher income and lower income remain the same.

We also include the ecological footprint of each country and an average footprint per income group. The ecological footprint is measured in global hectares, which includes water bodies. In our model we do not include water, therefore we reduce the resource accessibility ( $\approx$  ecological footprint) to account for the absence of water bodies. However, we maintain that  $R_{HH} \approx 1.35 \cdot R_{LH}$  and  $R_{HL} \approx 1.62 \cdot R_{LL}$ , as indicated by the Global Footprint Network (2019).

## Series Nam Country Na 2010 [YR20 Population

## Ecological Footprint (gha)

GDP per ca  British Virgi ..		29152		
GDP per ca  Channel Isl: ..		165385		
GDP per ca  Curacao ..		157980		
GDP per ca  French Poly ..		273124		
GDP per ca  Gibraltar ..		33736		
GDP per ca  Korea, Dem ..		25183833		
GDP per ca  New Caledc ..		272400		
GDP per ca  Sint Maarte ..		38825		
GDP per ca  Somalia ..		13797201		
GDP per ca  St. Martin ( ..		35858		
GDP per ca  Syrian Arab ..		17997408		
GDP per ca  Not classifi: ..		..		
GDP per ca  Monaco	150585,45	37718	P_HH	
GDP per ca  Liechtenste	141200,38	37470		
GDP per ca  Luxembour	104965,31	569604		12.9
GDP per ca  Bermuda	88207,328	65239		7.5
GDP per ca  Norway	87693,79	5188607		5.5
GDP per ca  Switzerland	74605,775	8282396		4.6
GDP per ca  Cayman Isl:	73350,785	61724		5.8
GDP per ca  Isle of Man	69766,521	83234		
GDP per ca  San Marino	68496,361	33272		
GDP per ca  Qatar	67403,16	2565710		14.4
GDP per ca  Denmark	58041,398	5683483		6.8
GDP per ca  Sweden	52817,441	9799186		6.5
GDP per ca  Macao SAR	52253,155	602085		
GDP per ca  Australia	52022,126	23815995		6.6
GDP per ca  Netherland	50950,034	16939923		4.8
GDP per ca  Ireland	48715,177	4701957		5.1
GDP per ca  Faroe Islan:	48530,234	48051		
GDP per ca  United Stat	48466,823	#####		8.1
GDP per ca  Canada	47450,318	35702908		7.7
GDP per ca  Singapore	47236,96	5535002		5.9
GDP per ca  Austria	46858,043	8642699		6.0
GDP per ca  Finland	46459,973	5479531		6.3
GDP per ca  Japan	44507,676	#####		4.5
GDP per ca  Belgium	44141,878	11274196		6.3
GDP per ca  Greenland	43988,332	56114		
GDP per ca  Iceland	43024,924	330815		
GDP per ca  Germany	41531,934	81686611		4.8
GDP per ca  France	40638,334	66593366		4.4
GDP per ca  Virgin Islan:	40043,19	107710		
GDP per ca  Andorra	39736,354	78011		
GDP per ca  United King	39435,84	65128861		4.4
GDP per ca  Kuwait	38577,382	3835591		8.6
GDP per ca  Italy	36000,52	60730582		4.4
GDP per ca  Brunei Dar:	35269,553	414907		4.2
GDP per ca  United Aral	33893,304	9262900		8.9
GDP per ca  New Zealar	33692,011	4595700		4.7
GDP per ca  Hong Kong	32549,998	7291300		
GDP per ca  Cyprus	30818,48	1160985		3.7

GDP per ca Guam	30700,434	161853		
GDP per ca Israel	30693,593	8380100		4.9
GDP per ca Spain	30502,72	46444832		4.0
GDP per ca Bahamas, T	28443,408	374206		3.7
GDP per ca Greece	26917,759	10820883		4.3
GDP per ca Puerto Rico	26435,749	3473166		
GDP per ca Aruba	23512,603	104341		6.5
GDP per ca Slovenia	23509,543	2063531		5.1
GDP per ca Portugal	22498,691	10358076		4.1
GDP per ca Korea, Rep.	22086,953	51014947		6.0
GDP per ca Malta	21107,364	445053		5.8
GDP per ca Turks and C	21028,408	35981		
GDP per ca Bahrain	20722,137	1371851		8.6
GDP per ca Czech Repu	19808,071	10546059	P_LH (under 20	5.6
GDP per ca Oman	19281,166	4267348		6.8
GDP per ca Saudi Arabi	19262,548	31717667		6.2
GDP per ca Equatorial (	17272,01	1168568		1.9
GDP per ca Slovak Repu	16727,291	5423801		4.2
GDP per ca Trinidad an	16683,355	1370328		8.4
GDP per ca Barbados	16056,117	285324		3.8
GDP per ca St. Kitts anc	15508,617	51203		
GDP per ca Northern M	14804,247	55780		
GDP per ca Estonia	14784,381	1315407		7.1
GDP per ca Croatia	13923,637	4203604		3.9
GDP per ca Venezuela,	13825,358	30081829		
GDP per ca Hungary	13113,526	9843028		3.6
GDP per ca Antigua anc	13049,257	93566		4.3
GDP per ca Chile	12808,035	17969353		4.3
GDP per ca Poland	12599,534	37986412		4.4
GDP per ca Libya	12064,781	6418315		
GDP per ca Uruguay	11992,017	3412009		
GDP per ca Lithuania	11953,938	2904910		5.6
GDP per ca Latvia	11344,693	1977527		6.4
GDP per ca Brazil	11286,243	#####		
GDP per ca Seychelles	10804,684	93419		2.8
GDP per ca Russian Fec	10674,997	#####		5.2
GDP per ca Turkey	10672,389	78529409		3.4
GDP per ca Argentina	10385,964	43131966		3.4
GDP per ca American S	10271,225	55812		
GDP per ca Palau	10219,928	17665		
GDP per ca World	9540,9048	7,341E+09		
GDP per ca Mexico	9271,3982	#####	P_HL (under 10	2.6
GDP per ca Kazakhstan	9070,4883	17542806		5.5
GDP per ca Malaysia	9040,5663	30270962		2.9
GDP per ca Gabon	8840,7307	1947686		2.3
GDP per ca Suriname	8255,7969	559143		3.0
GDP per ca Romania	8209,9195	19815481		3.1
GDP per ca Costa Rica	8141,9131	4847804		2.7
GDP per ca Panama	8082,0285	3968487		2.3
GDP per ca St. Lucia	8037,473	179126		2.3
GDP per ca Mauritius	8000,3764	1262605		3.5
GDP per ca Lebanon	7756,7441	6532678		3.3

GDP per ca  South Afric:	7328,6156	55386367		3.2
GDP per ca  Grenada	7257,7566	109599		2.9
GDP per ca  Middle East	7174,0977	#####		
GDP per ca  Maldives	7076,6624	454915		
GDP per ca  Dominica	6967,2452	71183		2.4
GDP per ca  Bulgaria	6843,2669	7177991		3.4
GDP per ca  Montenegr	6682,2812	622159		3.7
GDP per ca  Iran, Islami	6603,2123	78492215		3.2
GDP per ca  Botswana	6434,8157	2120716		2.7
GDP per ca  Colombia	6326,5495	47520667		2.0
GDP per ca  St. Vincent	6292,7898	109148		
GDP per ca  Belarus	6181,3999	9489616		4.0
GDP per ca  Azerbaijan	5842,8058	9649341		2.1
GDP per ca  Serbia	5735,4229	7095383		3.0
GDP per ca  Cuba	5730,3548	11324781		1.8
GDP per ca  Dominican	5555,3909	10281680		
GDP per ca  Namibia	5324,617	2314904		
GDP per ca  Peru	5082,3548	30470734		2.2
GDP per ca  Thailand	5076,343	68714511		2.5
GDP per ca  Nauru	4921,1191	12475	P_LL (under 5000 per capita)	
GDP per ca  Jamaica	4704,0545	2891021		1.6
GDP per ca  Iraq	4657,2804	35572261		1.7
GDP per ca  Bosnia and	4635,5178	3429361		3.7
GDP per ca  Ecuador	4633,5904	16212020		1.7
GDP per ca  China	4550,4536	1,371E+09		3.6
GDP per ca  North Mac	4542,8997	2079328		2.9
GDP per ca  Algeria	4480,7245	39728025		2.4
GDP per ca  Turkmenist	4439,2004	5565287		5.3
GDP per ca  Paraguay	4355,9349	6688746		2.9
GDP per ca  Belize	4270,7996	360933		5.4
GDP per ca  Eswatini	4168,5052	1104044		1.9
GDP per ca  Tunisia	4141,9764	11179949		2.2
GDP per ca  Albania	4094,3621	2880703		2.0
GDP per ca  Jordan	3690,1133	9266575		2.1
GDP per ca  Timor-Leste	3656,9522	1196302		0.5
GDP per ca  Fiji	3652,5274	868627		3.1
GDP per ca  Angola	3587,8838	27884381		1.0
GDP per ca  Samoa	3566,3624	193513		
GDP per ca  Tonga	3553,2206	100781		3.4
GDP per ca  Cabo Verde	3378,2549	524743		1.4
GDP per ca  Kosovo	3283,4835	1801800		
GDP per ca  Georgia	3233,2959	3725276		2.1
GDP per ca  Armenia	3218,3727	2925553		1.9
GDP per ca  Indonesia	3122,3628	#####		1.7
GDP per ca  Guyana	3033,2477	767432		3.4
GDP per ca  Tuvalu	3022,2888	11099		
GDP per ca  El Salvador	2983,2427	6325124		2.1
GDP per ca  Vanuatu	2966,8571	271130		
GDP per ca  Ukraine	2965,1424	45154029		2.9
GDP per ca  Micronesia,	2885,4459	108895		
GDP per ca  Marshall Isl	2876,995	57439		
GDP per ca  Morocco	2839,9252	34663603		1.7

GDP per ca  Guatemala	2825,484	16252429	1.9
GDP per ca  Congo, Rep	2809,695	4856095	
GDP per ca  Sri Lanka	2799,6489	20970000	1.5
GDP per ca  Egypt, Arab	2644,817	92442547	1.8
GDP per ca  Mongolia	2643,2929	2998439	7.7
GDP per ca  West Bank	2354,126	4270092	
GDP per ca  Nigeria	2292,4452	#####	1.1
GDP per ca  Bhutan	2258,1831	727876	4.5
GDP per ca  Philippines	2124,0568	#####	1.3
GDP per ca  Moldova	1958,1337	3554108	1.7
GDP per ca  Bolivia	1955,4616	10869730	3.2
GDP per ca  Papua New	1949,3525	8107775	
GDP per ca  Honduras	1904,3465	9112916	1.6
GDP per ca  Uzbekistan	1634,3121	31298900	1.9
GDP per ca  South Suda	1535,7082	10715658	1.5
GDP per ca  Kiribati	1516,8119	110930	
GDP per ca  Nicaragua	1503,8704	6223240	1.8
GDP per ca  Sudan	1489,8769	38902950	1.2
GDP per ca  Zambia	1489,4591	15879361	0.9
GDP per ca  India	1357,5637	1,31E+09	1.2
GDP per ca  Djibouti	1343,2687	913993	2.4
GDP per ca  Yemen, Re	1334,7848	26497889	0.7
GDP per ca  Vietnam	1317,8907	92677076	2.1
GDP per ca  Comoros	1315,2148	777424	1.2
GDP per ca  Ghana	1298,437	27849205	2.0
GDP per ca  Solomon Isl	1290,3988	603118	2.4
GDP per ca  Cameroon	1285,2617	23298368	1.4
GDP per ca  Senegal	1278,9778	14578459	1.1
GDP per ca  Mauritania	1241,4288	4046301	2.3
GDP per ca  Cote d'Ivoire	1211,9303	23226143	1.2
GDP per ca  Lesotho	1199,9518	2059021	1.4
GDP per ca  Lao PDR	1140,5992	6741164	1.9
GDP per ca  Sao Tome a	1094,7106	199432	1.7
GDP per ca  Pakistan	987,40972	#####	0.8
GDP per ca  Myanmar	979,05163	52680726	1.7
GDP per ca  Kenya	951,68796	47878336	1.0
GDP per ca  Zimbabwe	948,33185	13814629	1.1
GDP per ca  Chad	891,69882	14110975	1.5
GDP per ca  Kyrgyz Rep	880,03778	5956900	1.7
GDP per ca  Gambia, Th	860,63787	2085860	1.0
GDP per ca  Cambodia	785,50228	15521436	1.4
GDP per ca  Bangladesh	781,15359	#####	0.9
GDP per ca  Benin	758,43508	10575952	1.4
GDP per ca  Tajikistan	749,55271	8454028	0.9
GDP per ca  Tanzania	743,40378	51482633	1.2
GDP per ca  Mali	709,58196	17438778	1.6
GDP per ca  Guinea	672,4244	11432088	1.6
GDP per ca  Eritrea	667,74418	..	0.5
GDP per ca  Haiti	665,62742	10695542	0.7
GDP per ca  Uganda	622,49885	38225453	1.1
GDP per ca  Nepal	592,4011	27015031	1.1
GDP per ca  Rwanda	582,69412	11369071	0.8



GDP per ca  Burkina Fas	575,44645	18110624	1.2
GDP per ca  Guinea-Bis:	557,63213	1737202	1.5
GDP per ca  Afghanistar	543,30304	34413603	0.7
GDP per ca  Togo	533,50879	7323158	1.1
GDP per ca  Liberia	513,4457	4472230	1.1
GDP per ca  Central Afri	487,94538	4493170	1.2
GDP per ca  Malawi	478,66859	16745303	0.7
GDP per ca  Madagasca	471,95921	24234088	0.9
GDP per ca  Mozambiqu	471,18169	27042002	0.8
GDP per ca  Sierra Leon	401,835	7171914	1.2
GDP per ca  Niger	347,34304	20001663	1.7
GDP per ca  Ethiopia	341,55411	#####	1.0
GDP per ca  Congo, Den	334,02157	76244544	0.7
GDP per ca  Burundi	234,23565	10160030	0.7

Data from database: World Development Indicators  
 Last Updated: 03/18/2020

GDP per ca| High incom 39173,973 1,191E+09