General Certificate of Education
Advanced Level Examination
June 2013

Science in Society SCIS4/PM

Unit 4 Case Study

Preliminary Material

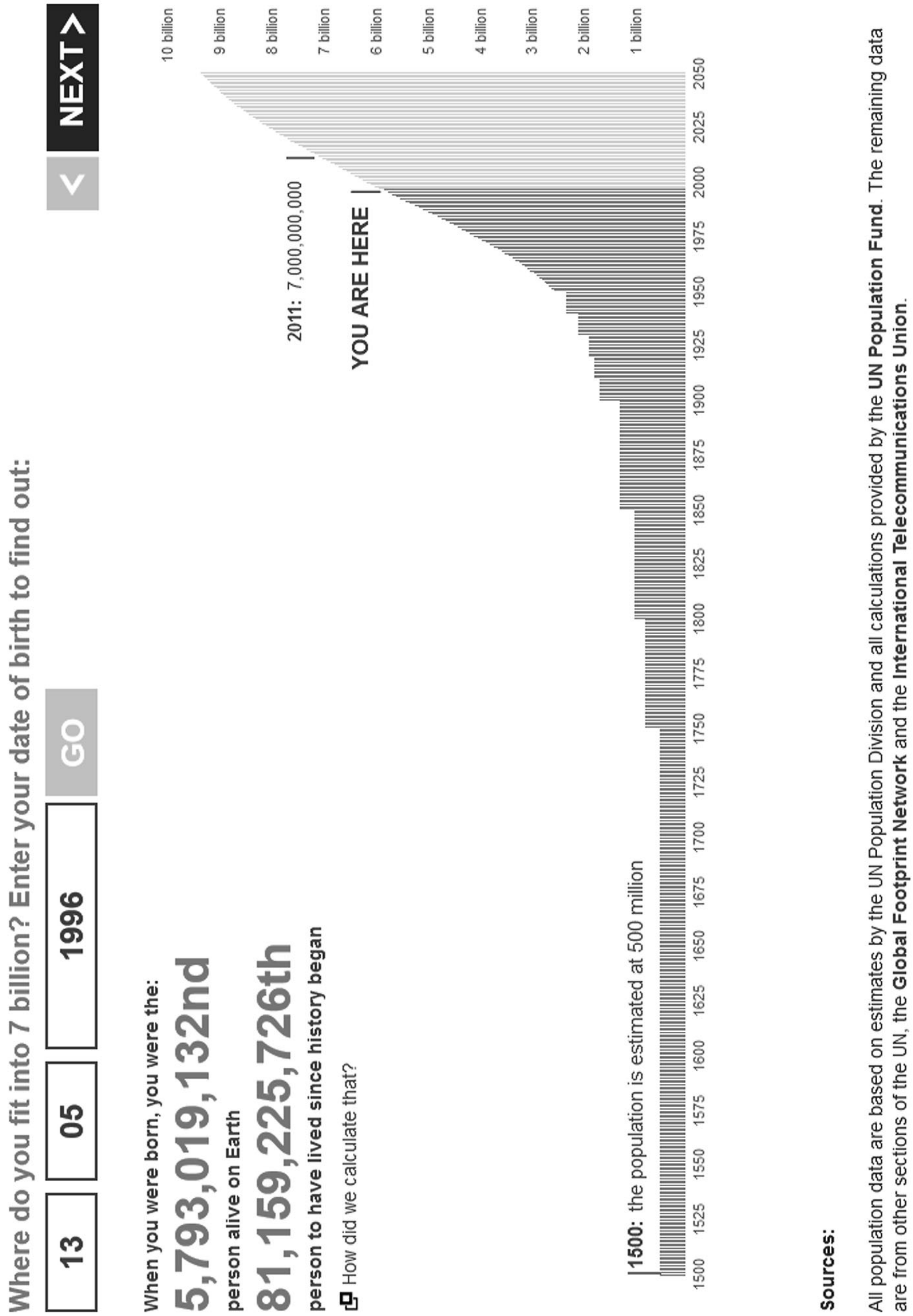
- This Source Material should be opened and issued to candidates on or after 1 May 2013.
- A clean copy of the Pre-released Source Material will be provided at the start of the Unit 4 examination.

A

Information

- This case study source material consists of extracts from five sources (**A–E**) on the subject of global population.
- This material is being given to you in advance of the Unit 4 examination to enable you to study the content of each extract in preparation for questions based on the material in the examination. Consider the scientific explanations and the ideas about how science works that are involved, as well as the issues raised in the sources.
- You may write notes on this copy of the case study source material, but you will not be allowed to bring this copy, or any other notes you may have made, into the examination room. You will be provided with a clean copy of this case study source material, together with one additional source: **Source F**, at the start of the Unit 4 examination.
- You are not required to carry out any further study of the topic than is necessary for you to gain an understanding of the ideas described and to consider the issues raised. You are not required to understand any detailed **science explanations** beyond those outlined in **Sources A–E** and those in the *Science in Society* specification.
- It is suggested that a minimum of three hours detailed study is spent on this pre-release material.

Source A: Screenshot taken from *www.bbc.co.uk/news/world-15391515* on 4 January 2012



Source B: Adapted from United Nations press release, 3 May 2011

World Population to reach 10 billion by 2100 if Fertility in all Countries Converges to Replacement Level

1 The current world population of close to 7 billion is projected to reach 10.1 billion in the next ninety years, reaching 9.3 billion by the middle of this century, according to the 2010 Revision of World Population Prospects, the official United Nations population projections prepared by the Population Division of the Department of Economic and Social Affairs, which is being launched today. Much of this increase is projected to come from the high-fertility countries, which comprise 39 countries in Africa, nine in Asia, six in Oceania and four in Latin America.

2 **Small variations in fertility can produce major differences in the size of population in the long run.** This must be considered when developing a suitable model to produce population projections. The projections reported here assume a medium level of worldwide fertility. The projection for 2050 is more certain than for 2100 because people who will be 40 years and older in 2050 are already born. According to the projection, it will take 13 years to add the eighth billion, 18 years to add the ninth billion and 40 years to reach the tenth billion.

3 **Current fertility levels vary markedly among countries.** Today, 42 per cent of the world's population lives in low-fertility countries, that is, countries where women are not having enough children to ensure that, on average, each woman is replaced by a daughter who survives to the age of procreation. Another 40 per cent lives in intermediate-fertility countries where each woman is having, on average, between 1 and 1.5 daughters, and the remaining 18 per cent lives in high fertility countries where the average woman has more than 1.5 daughters.

4 **The highest potential for future population growth is in high-fertility countries.** Between 2011 and 2100, the projection is that the population of the high-fertility countries would more than triple, passing from 1.2 billion to 4.2 billion. During the same period, the population of the intermediate-fertility countries would increase by just 26 per cent, from 2.8 billion to 3.5 billion, while that of the low-fertility countries would decline by about 20 per cent, from 2.9 billion to 2.4 billion (**Figure 1**).

5 **By the turn of the century, only the population of high-fertility countries would still be increasing.** According to the projection, in 2095-2100 the populations of both the low-fertility countries and the intermediate-fertility countries would be declining at a rate of approximately 0.3 per cent per year. In sharp contrast, the population of the high-fertility countries would still be increasing at a rate of 0.5 per cent per year.

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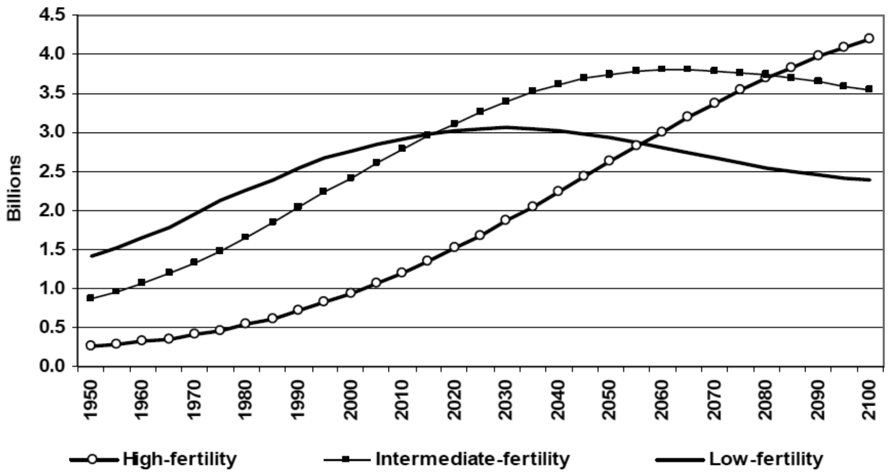
Figure 1 Population for countries grouped by fertility level, medium variant, 1950-2100



6 **These projections hinge on the assumptions made about the future evolution of fertility**. In the 2010 Revision, a new model was used to derive the future path of fertility. The model was based on the fertility trends estimated for all countries of the world for the period 1950 to 2010. The model was then tested and modified using the 2008 Revision data. In this process, account is taken of past fertility trends in a given country plus the past experience of all other countries in the world. The model was used to generate 100,000 possible paths for future fertility for each country and the median values of those paths determined the actual fertility path used. The model incorporated the additional assumption that, over the long run, replacement-level fertility would be reached (a level which, in low-mortality countries, is close to 2.1 per children per woman).

7 **Life expectancy is projected to increase in the three groups of countries considered**. In 2005-2010, average life expectancy at birth was lowest among the high-fertility countries, at 56 years, mainly because many of them have generalized HIV/AIDS epidemics. Nevertheless, given the advances made in reducing the spread of the disease and the expansion of antiretroviral treatment, the projections assume a continued decline in mortality rates from HIV/AIDS as well as from other major causes of death. Therefore, the expectation of life among high-fertility countries rises to 77 in 2095-2100. Globally, life expectancy is projected to increase from 68 years in 2005-2010 to 81 in 2095-2100.

Source C: Adapted from *www.unfpa.org*

A global initiative for all humanity

BACKGROUND AND PARTICIPATION OVERVIEW

By the close of 2011, the global population will have reached 7 billion. A world of 7 billion has implications on sustainability, urbanization, access to health services and youth empowerment – however, it also offers a rare call-to-action opportunity to renew global commitment for a healthy and sustainable world.

7 Billion is a challenge

Already, too many people suffer from poverty, discrimination, and violence. Conflicts and weather-related disasters are forcing people to flee their homes. Climate change is exacerbating food and water shortages. As more and more people join those of us already here, solving existing challenges will become increasingly more urgent – and new challenges will arise that demand the best in each of us.

7 Billion is an opportunity

Never before has the world nurtured so many talented, creative, educated people. Never before has humanity been so interconnected. We are now part of a global community where actions taken in one country or region can have an immediate impact on other parts of the world. We have yet to realize the vast human potential among women and girls – who comprise half the world's population – and the energy and talents of some two billion young people.

7 Billion is a call to action

This milestone provides an occasion to recognize and celebrate our common humanity and diversity. It is also a time to demonstrate our shared responsibility to care for each other and our planet. Ensuring the well-being of current and future generations will require unprecedented global cooperation. Individuals can make a difference by uniting through social networks, popular culture and the shared values reflected in international agreements. In a world of 7 Billion people, incremental actions will create exponential results.

7 Billion Actions **is a platform for individuals, businesses, governments, NGOs, media and academia to contribute to a better world for all people. It is an opportunity to showcase stories, connections and actions.** ***7 Billion Actions*** **will shine a bright light on the good works being done by many and encourage more to join. It also will serve as a springboard to generate collective actions that can make a huge difference for present and future generations.**

Turn over ▸

Context/Background

The status quo is not sustainable. We must evolve away from ever-widening income and consumption disparities towards meeting basic needs, reducing inequities, and shifting to cleaner energy and technology.

Many people are living longer and healthier lives, and couples are choosing to have smaller families. But 215 million women in developing countries who would like to plan and space their children lack access to effective contraception. Too many young people lack education, training and employment. Too many women are denied equal opportunity.

To create a sustainable and peaceful world, we must invest wisely. By investing in health and education and moving to a green economy, we can improve the well-being of people and our planet. As lives improve, population growth tends to stabilize.

Platform for Partnership

You are one of 7 Billion. Every individual and organization has a unique role and shared responsibility to address issues that affect us all.

For Individuals, *7 Billion Actions* is about shared commitment.

We are all connected. We all must recognize, and embrace, our individual and collective capacity to change and improve the world. It takes individual action to produce institutional change. Each of us can commit, in whatever way we can, to address the challenges and pursue the opportunities that a world of 7 billion presents.

For Government, *7 Billion Actions* is about shared leadership.

The challenges and opportunities of 7 Billion will be addressed by countries with skilled and healthy workers, strong commitment to research and technology and efficient ways to move people, goods and information. Government at all levels (national, regional and local), share responsibility to support organizations and individuals working to improve society. Governments can work together to guide and shape our collective understanding of what is important, to break down barriers that impede critical progress, and to enable innovation that benefits the world. Sound government leadership can propel human progress.

For Businesses, *7 Billion Actions* is about shared value.

Businesses can use their influence to create economic returns in ways that also create value for society. ‘Shared value’ is not just social responsibility or philanthropy, it is a new way to measure success by adopting sustainable practices and policies that produce value over the long term. Companies that create shared value enhance their own competitiveness while advancing the economic and social conditions in the communities in which they operate. Through financial contributions or in-kind donations, companies can become official Sponsoring Partners of *7 Billion Actions*.

Key sectors for business in relation to 7 Billion include:

Health: Health is everyone's business. Better health improves productivity. Major advances continue to improve public health dramatically, often at a very low cost. And corporate innovation and distribution systems have made a huge difference. But more progress is needed: 1,000 women still die every day from treatable complications of pregnancy and childbirth, millions of people living with HIV remain untreated, and there is high unmet need for family planning. Companies can work with government and other institutions to foster well-being for current and future generations. The benefits to individuals and communities will be immediate and sustainable.

Food & Water: Food security and access to clean water is everyone's business and the foundation for life. Yet one billion people today lack access to clean water. Together we can identify opportunities to improve the quantity, quality, and accessibility of the food we eat and the water we drink. By using our ingenuity we can meet the challenge to deliver healthy food and clean water for everyone.

Technology: Innovation is everyone's business. Scientific breakthroughs – from telecommunications and computing to advances in medicine, neuroscience and renewable energy – abound and are paving the way for social and economic transformation. But the wealth of ideas and technologies are not being harnessed as effectively as they could to improve human well-being and build a sustainable future. Together we can direct innovation to address global challenges.

Education, Skills and Livelihoods: In our competitive global economy, creating opportunity and increasing productivity is everyone's business. Developing better systems to educate adolescents and young people and develop their skills encourages healthier lifestyles and larger dreams for the future. Together we can equip current and future generations with the skills and confidence to build a sustainable society.

For NGOs, *7 Billion Actions* is about shared responsibility.

NGOs can play a variety of roles in helping to improve the state of the world, including serving as a bridge between business, government and civil society; connecting the policy makers to the grassroots; bringing practical solutions to the table; calling their peers to account; and acting as the voice for the voiceless, who are often left out of decision-making processes. NGOs must engage, with other institutions and sectors, in practical projects that stretch everyone's visions and capacities. NGOs must bring their expertise in a range of areas and an understanding and connection to specific communities and audiences that other groups can't access.

For Media, *7 Billion Actions* is about shared perspective.

Like NGOs, media play a critical role in holding institutions accountable to the public and elevating public discourse. The media has a responsibility to provide accurate, timely and relevant information about the world we live in. Solid information and analysis, from a multitude of credible voices, can build collective wisdom. The media can clarify issues and reinforce our understanding of interconnections and interdependencies that define today's world. 7 Billion presents a compelling opportunity for media to explore the complexities, contradictions and challenges of demographic trends, their impacts, and spur action.

For Academia, *7 Billion Actions* is about shared understanding.

Education and research are fundamental to the success of efforts to improve society. The aptitudes and abilities that contribute to a sustainable world can be cultivated through formal and informal education. We can encourage individuals to share their insights and ideas, to participate in discourse and decision-making, and to raise awareness of the need for solidarity and social responsibility. Academia can spark ideas, conversations and actions related to a world of 7 Billion.

Source D: Edited article from *www.guardian.co.uk* by Juliette Jowit, 30 October 2011

Population is not the problem

Population policies have little impact on the way a minority of humans use the Earth's resources

The birth of a baby is usually an occasion for joy. The arrival, however, of the 7 billionth person in the next few days is being awaited with growing trepidation about the devastating impact of humans on the planet. Environmentalists are arguing in circles about who or what is to blame: the total number of people; or the amount of water, food, mineral ores or clean air each demands. Professor Paul Ehrlich … likens the environmental impact to the area of a rectangle: one side is the size of population, the other their consumption.

Although Ehrlich's rectangle is a neat illustration, the population "problem" for the environment is more accurately described as two rectangles, each representing the number of people on the vertical and their lifestyles on the horizontal: one tall skinny quadrant encompasses billions of people who use very little of Earth's resources; the other a much shorter, extraordinarily long one for the minority of humans who use the vast majority of natural wealth. The World Bank estimates, for example, that the richest fifth of the world has more than three-quarters of the income; the poorest fifth just 1.5%.

Given that populations are barely stable and sometimes falling in most of the rich world, population policy would inevitably have to make noticeable inroads into the tall-skinny many/poor rectangle. Assuming such policies were successful – and excluding the widely unacceptable coercion of China's one child policy or India's mass sterilisations in the 1970s, persuading people to have fewer babies has proved very tricky – the overall reduction in combined environmental impact would be very small.

The more troubling issue, though, is that this calculation assumes that as the tall-skinny rectangle gets shorter, it does not get wider. Experience, however, suggests that … it will get fatter.

Across time and geography, countries that have reduced birth rates have got richer and so more consumptive: rising incomes, better health and education give men and women the confidence that more of their children will survive into adulthood and help support their families; and as birthrates fall governments can spend more on each person's health, education and jobs, feeding a virtuous cycle of economic development and slowing population growth.

It would be interesting to see a proper assessment of the point at which the benefit of having fewer people consuming is offset and then increasingly dwarfed by their greater consumption. There are some telling pointers. Comparison … of the CIA World Factbook data for countries' birthrates and average purchasing power of each person shows a pretty strong correlation between the two.

Statisticians are quick to point out that because two things appear to be linked does not mean one causes the other, but on-the-ground evidence suggests rising affluence and declining fertility rates are inextricable. Time after time descriptions of countries that have successfully reduced population growth show how they have grown notably richer at the same time, even if they are not exactly well-off: Guatemala in central America, Bangladesh in south-east Asia, and … South Korea.

At the same time, study after study shows environmental damage rises – so far almost always perpetually – with income, and often more steeply as developing countries begin to industrialise. Most dramatically, these forces appear to have come together in China, whose one-child policy – albeit with massive state investment and rapid expansion of the market economy – has coincided with the country's rise to become the world's second biggest economy (and, incidentally, the biggest emitter of greenhouse gas pollution).

Technically speaking, of course, population campaigners are right: environmental degradation can be helped by reducing the number of people and what they use. Population policies are best left to those focusing on poverty and women's rights. For environmentalists, talk of too many people is a dangerous distraction for campaigners and consumers, too many of whom will find it a convenient excuse to ignore the more pressing need for changes to what and how we spend our growing riches.

Source E: abridged version of an article from Ecological Modelling journal.

Harvesting the sun: New estimations of the maximum population of planet Earth

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a b s t r a c t

The maximum population, also called Earth's carrying capacity, is the maximum number of people that can live on the food and other resources available on planet Earth. Previous investigations estimated the maximum carrying capacity as large as about 1 trillion people under the assumption that photosynthesis is the limiting process. Here we use a present state-of-the-art dynamic global vegetation model with managed planetary land surface, Lund-Potsdam-Jena managed Land (LPJmL), to calculate the yields of the most productive crops on a global 0.5° × 0.5° grid. Using the 2005 crop distribution the model predicts total harvested calories that are sufficient for the nutrition of 11.4 billion people. We define scenarios where humankind uses the whole land area for agriculture, saves the rain forests and the boreal evergreen forests or cultivates only pasture to feed animals. Every scenario is run in an extreme version with no allowance for urban and recreational needs and in two soft versions with a certain area per person for non-agricultural use. We find that there are natural limits of the maximum carrying capacity which are independent of any increase in agricultural productivity, if non-agricultural land use is accounted for. Using all land planet Earth can sustain 282 billion people. The save-forests-scenario yields 150 billion people. The scenario that cultivates only pasture to feed animals yields 96 billion people. Nevertheless, we should always have in mind that all our calculated numbers for the carrying capacity refer to extreme scenarios where humankind may only vegetate on this planet. Our numbers are considerably higher than the general median estimate of upper bounds of human population found in the literature in the order of 10 billion.

1. Introduction

Human carrying capacity (K) describes the number of human beings that can be supported on a sustainable basis in a given area (or on the whole Earth) within natural resource limits and by human choices concerning social, cultural and economic conditions. K is not fixed and can be altered for example by technology. While there is a general agreement about the existence of a certain limit of population size (i.e. K) the estimates have varied from about 1 billion to 1000 billions. It is useful to differentiate between biophysical and social K. The biophysical K is the maximum population that can be supported by the resources of planet Earth at a given level of technology. The social K is the sustainable biophysical K within a given social organization. The social K is always less than the biophysical as it accounts also for the quality of life. Carrying capacity may be one of the most important concepts in environmental sciences today. Like sustainability, carrying capacity can be applied to almost any human–environment interaction, at any scale, and it has the additional advantage of providing quantitative results – something that according to Sayre (2008) is so far missing for sustainability. On the other hand Schellnhuber et al. (2004) published a comprehensive book about quantitative sustainability science and also discussed its relation to carrying capacity. These authors state that at least two factors have to be taken into account for estimating the human carrying capacity: the first factor is the totality of ecological services the Earth system can provide ("supply side"), the second factor is the totality of ecological human needs according to judicious minimum standards ("demand side"). The supply side can be provided by Earth-system analysis for sustainability, while the demand side has to be estimated by proposing new principles for global stewardship.

Already in the 17th century Antoni van Leeuwenhoek estimated the carrying capacity of the Earth as 13.4 billion people. He found this number by multiplying his estimate of the population of Holland (1 million people) with his estimate of the ratio of Earth's inhabited land area to Holland's area (13,400). In the 19th century, Justus von Liebig formulated his Law of the Minimum. He found that the addition of a single fertilizer will increase crop yield only if a particular soil can deliver all the other necessary nutrients. Using Liebig's Law of the Minimum, K will be constrained by whatever survival resource is in shortest supply. Examples for such limiting factors considered in other studies are food supply, water supply, energy availability or the area of land required to grow food, timber and other forest products. Liebig's law assumes that K is strictly proportional to the limiting factor and neglects interactions among different factors.

In this study we are interested in the maximum carrying capacity (K) – that is, the maximum number of people that can live on Earth. This number was estimated by De Wit (1967). In his basic model the maximum potential terrestrial photosynthetic productivity (with no allowance of cities, recreation, optimal soil minerals, and water) is enough for about 1 trillion people. It is evident that such an approach lacks realism, and can be considered as an "academic game". Such estimations of K are based on a Genghis-Khan-behaviour of the anthroposphere, i.e. a species that spreads out abrasively over the whole planet. A Genghis-Khan-species would use the whole net primary production (NPP) for its energy and food demands.

doi:10.1016/j.ecolmodel.2011.03.030

Turn over ▶

Actually, the value of 1 trillion people for K calculated by De Wit (1967) is not the largest number given in the scientific literature. Kleiber (1961) calculated K from the constraint that all the carbon contained in the Earth were embodied in people that contain about 12 kg of carbon per person. His value of about 1.6×10^{21} kg for the terrestrial carbon content is about twice the currently accepted value and leads to the conclusion that the maximum carrying capacity cannot exceed about 10^{20}. We should have in mind that these 10^{20} people would have to live by cannibalism alone. A second estimation of Kleiber (1961) is based on the assumption that solar radiation is the only factor to limit plant growth and that enough algae to feed a person for a year can be grown on 1 m^2. Assuming that about 480×10^{12} m^2 can be used for algae production he arrives at a maximum carrying capacity of 480 trillion people. Another spectacular estimation of K was published by Fremlin (1964). He estimated the maximum population of a future high technology society from the condition that the removal of heat by black body radiation to space is the sole limitation. In this case about 10^{16} people could live on the future Earth in about 800–1000 years from now. . . . We will use De Wit's (1967) estimation of about 1 trillion people for the maximum carrying capacity. . . .

Besides the studies on carrying capacity a similar question has been addressed in studies on global food production under the present state and future scenarios for global change, in particular concerning future population growth.

The model of De Wit (1967) was a state-of-the-art model for the time of its publication and also for many years after that. Nevertheless, from a present point of view there are a lot of shortcomings that can be overcome with the help of present-day modelling tools. One example of these shortcomings is the approach to divide the Earth's surface into 13 latitude intervals of 10° and to take the properties at the middle latitude of each row as characteristic, independent of the geographic longitude. Therefore, we try to repeat the estimations of K with a present day state-of-the-art dynamic global vegetation model with managed planetary land surface, Lund-Potsdam-Jena managed Land (LPJmL). LPJmL simulates biophysical and biogeochemical processes as well as productivity and yield of the most important crop types worldwide. In this way, LPJmL as a dynamical model contains interactions between different potential limiting factors (e.g. food supply is a function of water supply, climate, and land use) and is more realistic than simulations based on photosynthetic capacity that is only constrained by radiation and temperatures in 10° latitude intervals.

In the next section we describe details of the calculation of De Wit (1967) and present some new analytical extensions; in Section 3 we specify the LPJmL-model; results are presented in Section 4, and we discuss additional constraints in Section 5 like water consumption, nutrients, crop protection, energy, and land use. Concluding remarks are drawn in Section 6.

2. Harvesting the sun: photosynthesis in plant life

The title of this section was the title of a symposium where De Wit probably for the first time discussed the question "How many people can live on Earth if photosynthesis is the limiting process?" (De Wit, 1967). His aim was to calculate the kilograms of carbohydrate produced per hectare of land surface per year assuming only radiation and temperature as the constraining factors. He considered a hypothetical crop that is able to convert 50% of the photosynthetic energy into harvested yield. A further reduction factor of 50% takes into account that not the whole yield of carbohydrates is usable for human consumption because of losses, etc. In this way one quarter of the potential biomass assimilation is the net carbohydrate available for human consumption. Furthermore, he used the relation that one gram of net carbohydrate eaten supplies about four kilocalories of energy. For the average nutritional requirement of a single person with vegetarian diet he assumed 2740 kcal per day (i.e. about 1 million kcal per year). This value is an average value compared to the average Indian's diet of about 2100 kcal per day and 3500 kcal per day per person in the United States. Our choice is comparable to the present world average calorie consumption per person of 2803 kcal per day. The maximum number of people on Earth, i.e. the maximum carrying capacity K, is calculated from the product of productive area (A) and the harvest per unit of this area (h) divided by the average nutritional requirement of a single person (n):

$$K = A\frac{h}{n} \qquad (1)$$

De Wit's (1967) estimates of the human population that could be fed from the calories produced on Earth are shown in Table 1. This table also contains a column that takes into account the effect that every person needs about 750 m^2 for urban use and recreation (houses, highways, parks, etc.) not available for agriculture. This number of 750 m^2 was derived from the region between Boston and Washington, DC, which covered a metropolitan area of 27,500 km^2 and was occupied by 37 million people at that time.

The maximum possible number of people on Earth of 1022 billions, i.e., about one trillion (Table 1) is reduced to 146 billions (column 5) if one reserves 750 m^2 per person for urban use and recreation. Duplicating the non-agricultural used area to 1500 m^2 per person lowers the maximum population to 79 billions (Table 1, bottom line). We may represent the effect of non-agricultural used area per person (B) by extending equation (1) in the following way:

$$K = A\frac{h}{n} - KB\frac{h}{n} \qquad (2)$$

$$K = \frac{A(^h/_n)}{1 + B(^h/_n)} \qquad (3)$$

Eq. (2) is constructed in such a way that the non-agricultural used area is subtracted from the productive area according to the number of people in every 10° latitude interval. This is in conformity with the fact that agriculture is located where also most of the people live, e.g. near to rivers. This equation allows us to estimate the effect of yield increase for example by new management practices (MPs). In human history new MPs have led to continuous increases in agricultural productivity. In order to access the potential of yield increases to increase in K we have to find the limit of equation (3) when h goes to infinity:

Table 1

Estimates of the Earth's carrying capacity.

North latitude (°)	Land surface (100 million hectares)	Number of months above 10 °C	Number of people (billions)	
			No allowance for urban and recreational needs	750 m^2 per person for urban and recreational
70	8	1	10	5
60	14	2	30	11
50	16	6	95	17
40	15	9	136	18
30	17	11	151	20
20	13	12	105	16
10	10	12	77	11
0	14	12	121	17
−10	7	12	87	9
−20	9	12	112	11
−30	7	12	88	9
−40	1	8	9	1
−50	1	1	1	1
Total	132		1022	146

$$\lim_{h\to\infty} K = \frac{A}{D} \quad (4)$$

Eq.(4) shows that in the case of very efficient agriculture the carrying capacity is only determined by the ratio of the total productive area A and the non-agricultural used area (per person) B. Assuming A as 132 million km^2 and B as 750 and 1500 m^2 we find a limiting carrying capacity of 176 billion and 88 billion, respectively. These are comparable to the numbers of 146 billion and 79 billion reported by De Wit (1967) (see Table 1), which means that his estimates are based on the assumption of very efficient agricultural production.

The calculated Earth's plant production is called gross primary prodution (GPP). GPP has to be converted to net primary production (NPP) by subtracting autotrophic respiration that a plant needs for its own metabolism. In this way, NPP is the net amount of carbon assimilated in a given period by vegetation that can be transferred from plants to higher trophic levels. De Wit's (1967) estimation of Earth's annual potential carbohydrate production corresponds to a NPP of 200 billion tons of carbon, representing a more than three-fold increase of the NPP of currently prevailing vegetation, NPP_{act}. According to Haberl et al. (2007) the human alternations of photosynthetic production in ecosystems and harvest of products of photosynthesis can be referred to as "human appropriation of net primary production (NPP)" or HANPP. They found an aggregate global HANPP value of 15.6 PgC/yr (Note 1) or 23.8% of potential NPP. Also today, agricultural productivity (NPP) can exceed that of natural vegetation in intensively managed and especially in irrigated agricultural areas. Nevertheless, De Wit's estimation of K is of principal academic interest. Our new and more realistic estimation accounts for additional constraints that have not been considered by De Wit: irrigation water availability and length of the growing period.

Note 1: Petagram Carbon (PgC) equals 10^{15} gC, or 1 billion metric ton C, or 3.67 billion metric ton CO_2.

Table 2
Energy content of harvest for the 11 crop functional types and pasture.

	Dry matter fraction	Energy content of moist matter in kcal/g
Wheat	0.88	3.34
Rice	0.87	2.80
Maize	0.88	3.56
Millet	0.88	3.40
Pulses	0.90	3.41
Sugar beet	0.24	0.70
Cassava	0.35	1.09
Sunflower	0.93	3.08
Soybean	0.90	3.35
Groundnut	0.94	4.14
Rapeseed	0.92	4.94
Pasture	0.25	1.05

3. Model description

3.1. The LPJmL-model

LPJmL is a process-based ecosystem model which simulates the growth, production and phenology of 9 plant functional types (representing natural vegetation at the level of biomes); and of 11 crop functional types (Table 2) and managed grass. Carbon fluxes (gross primary production, auto- and heterotrophic respiration) and pools (in leaves, sapwood, heartwood, storage organs, roots, litter and soil) as well as water fluxes (interception, evaporation, transpiration, soil moisture, snowmelt, runoff, discharge) are modelled accounting explicitly for the dynamics of natural and agricultural vegetation. For example, carbon and water fluxes are directly linked to vegetation patterns and dynamics through the linkage of transpiration, photosynthesis and plant water stress. The phenology and management dates (sowing and harvest) of the different crop types are simulated dynamically based on crop-specific parameters and past climate experience, allowing for adaptation of varieties and growing periods to climate change. All processes are modelled at a daily resolution and on a global 0.5° × 0.5° grid. At sowing, photosynthesis in LPJmL starts on the basis of leaf area index supplied from seed reserves. The daily assimilation by photosynthesis is allocated to four carbon pools:

Turn over

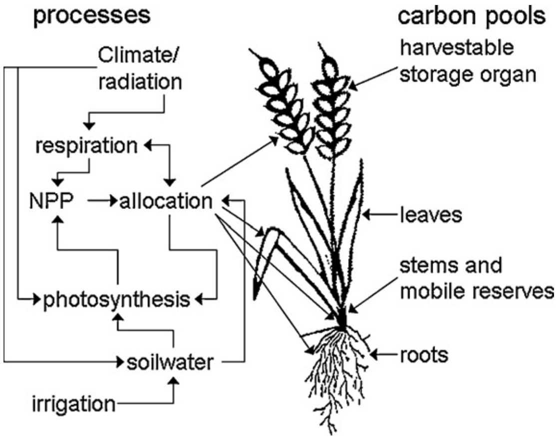

Fig. 1. Sketch of the processes involved in the calculation of plant biomass and the partitioning to 4 carbon pools in LPJmL. Only the harvestable storage organ is considered a source of food here. Arrows indicate energy, carbon or water fluxes. NPP = net primary production.

leaves, roots, harvestable storage organs (e.g. grains for cereals), and a pool representing stems and mobile reserves. At harvest only the biomass fraction of the storage organs is considered for calculating the calorific density. The processes involved in the calculation of the harvested carbon are sketched in Fig. 1.

The suitability of the model for vegetation/crop and water studies has been demonstrated before by validating simulated phenology and yields, river discharge, soil moisture, evapotranspiration and irrigation water requirements.

. . .

3.2. Model setup

For this analysis we simulated crop yields of each of the 11 crop types and pasture implemented at each location (0.5° grid cells) on the entire land surface and chose the crop yielding the highest caloric productivity. Therefore land use is determined algorithmically and not prescribed. Crop types considered and their caloric contents are displayed in Table 2. We assume intensive agricultural practices for all crops in order to compute maximum productivity, irrespective of actual intensity patterns. Rotational constraints are disregarded here, as are area requirements for infrastructure, so that all the area within a grid cell can be used for the production of the most productive crop. There are a lot of very productive regions, especially in the tropics, where double or even triple cropping systems are possible: rice-wheat in Northwest India, wheat-maize in the northern China Plain, rice-rice in Vietnam/ Thailand, etc. At the regional scale, the highest cropping intensity (1.35 crop cycles per year) is found in Eastern Asia. All areas under the same climate could not support the same cropping intensity, because we must account for the availability of water as many of these multiple cropping systems are irrigated. In Asia, for example, a significant part of the water used for irrigation relies on the rivers filled by the melting of the Himalayan glaciers or on ground-water use, and not all areas on the globe under a similarly warm and sub-humid climate may take so much water from the rivers or from underground. We assume that the annual production of single-cycle cropping systems, as simulated by LPJmL, are doubled in regions where (a) the crop cycle is shorter than half a year and (b) growth is not limited by temperatures.

We base our numerical experiments on averaged yield data simulated by LPJmL for the period 1996–2005 driven by Climate Research Unit. . . . We select in each grid cell the crop with the maximum energy-based crop yield on the whole available land area with a minimum thaw depth of one meter and irrigation limited by available river discharge.
In the case of pasture we assume that 1/10 of the calories of the grass fed to animals reach humans as animal products (De Wit, 1967).

In order to test our version of LPJmL we start the numerical experiments with the 2005 land-use patterns and crop distribution. The carrying capacity is calculated under the assumption that all harvested crops are used directly for human nutrition. Only grass is used as fodder for animals.

3.3. Scenario descriptions

The most extreme scenario is the experiment with no allowance for urban and recreational needs and with cultivation of all productive land. We call this the extreme Genghis-Khan-scenario. Under this premise we have to include all available land including remote areas, where the harvested carbon exceeds some critical threshold excluding desert areas and high-mountain areas. Furthermore all scenarios are based on local production and consumption patterns without any trade. In the soft Genghis-Khan-scenarios we allow 750 and 1500 m^2 per person for non-agricultural use, respectively.

The next scenario is based on the hope that humankind will not realize the Genghis-Khan-scenarios but will preserve at least the tropical and the boreal evergreen forests. In particular tropical forests play a major role in biodiversity conservation and their deforestation would strongly influence climate, an effect that up to now is not taken into account in the Genghis-Khan-scenarios. In the save-forests-scenarios we exclude the areas where the potential natural vegetation as simulated by LPJmL is dominated by tropical evergreen or boreal evergreen plant functional types (PFTs) from agricultural use, irrespective of whether these forests are currently still existent.

For a third scenario, the Burger-scenario, we assume that humankind cultivates only pasture on all the available area and the grass is used to feed animals. In this way we can calculate the maximum carrying capacity in a world where humankind subsists only from animal products. Actually, most of the animals in industrial agriculture are fed on crops (soybean, maize, etc.) and only partially on grass. On the other hand, the use of crops as fodder for animals lifts the humankind to the 3rd trophical level lowering the maximum carrying capacity due to energy-transfer-loss. The only exception is grass that cannot be used as an aliment for humans.

4. Results

As a first step the LPJmL model has been applied for the real land-use-patterns from the year 2005. . . . The total harvested calories are sufficient for the nutrition of 11.4 billion people with an annual nutritional requirement per capita of 1 million kcal per year. Our result is about two times higher than the actual human population. This results from the facts that a large part of actual harvested crops are used as fodder for animal production and the difference between the caloric value of animal feeds and the caloric value of consumed animal products by humans.

For the extreme Genghis-Khan-scenario, we find that main yields result from sugar beets, maize, wheat, and pulses. The harvested calorific density shows that with the exception of deserts, high mountains and high latitudes the nearly complete continental area is used for agriculture with typical values between 2000 and 3000 kcal/m^2 yr. In Table 3 we compare our results of the number of people in every latitudinal band with the results of De Wit (1967). Our extreme Genghis-Khan-scenario allows for a maximum population of 282 billion people which is considerably less than the one trillion by De Wit (1967). The soft Genghis-Khan-scenarios lower the maximum population to 89 billion and 54 billion people, respectively. The results for the Genghis-Khan-scenarios with a crop distribution by choosing the crop type with the maximum energy yield for each grid cell may appear rather unrealistic compared to actual present day cropping patterns. In fact, the dominant crops worldwide are wheat, maize and rice, both for use as staple food as well as cash-crops, because small grains are easier to store and to trade than root crops, at least fresh and because caloric content is not the only production objective. Therefore, we have recalculated the crop distribution for the extreme Genghis-Khan-scenario by selecting the crop type with maximum yield only out of the three present day most important crop types: wheat, maize, rice and pasture. The results are shown in Table 3. Comparison of this more constrained simulation with the extreme Genghis-Khan-scenario reveals only small deviations. This is because the caloric yields (kcal/m^2 yr) of the different crop types considered here are often very similar, even though this is not necessarily true in terms of biomass.

The results for the save-forests-scenario are presented in Table 3 in a similar way as for the Genghis-Khan-scenario. We find that under the extreme save-forests-scenario, 57 million km^2 (43%) are reserved for nature conservation, which lowers the maximum carrying capacity from 282 billion to 150 billion people. This reduction by 47% is close to the reduction in available land (57%), indicating that the above-average productivity of tropical forests is largely counterbalanced by the below-average productivity of boreal forests. In this scenario, sugar beets, maize, wheat, and cassava are the most important cultivation types. The soft versions of this scenario (reserving 750 or 1500 m^2 per person for non-agricultural use) lower the maximum population to 51 billion and 31 billion, respectively.

In the extreme Burger-scenario about 96 billion people could exist on our planet only from animal products (Table 3).

Table 3

Comparing estimates of the Earth's maximum human population to the results of LPJmL.

North latitude (°)	Number of people (billions)									
	No allowance for urban and recreational needs					750 m^2 per person for urban and recreational needs				
	De Wit	LPJmL – Genghis K.	LPJmL – save-forests	LPJmL – Burger	LPJmL – wmr[a]	De Wit	LPJmL – Genghis K.	LPJmL – save-forests	LPJmL – Burger	LPJmL – wmr[a]
70	10	1.7	0.4	0.2	1.7	5	0.7	0.2	0.2	0.7
60	30	14.5	2.6	3.4	13.4	11	6.2	1.1	2.6	6.0
50	95	37.9	17.6	9.6	29.2	17	13.0	5.7	6.4	11.9
40	136	35.8	27.8	8.9	30.5	18	12.1	9.6	5.7	11.5
30	151	22.3	21.2	6.2	21.4	20	8.5	8.1	3.7	8.4
20	105	13.4	7.9	6.6	11.8	16	4.6	3.0	3.5	4.3
10	77	28.1	11.1	12.1	26.1	11	7.8	3.8	5.9	7.7
0	121	40.1	6.1	17.4	37.0	17	10.0	1.6	7.5	9.7
−10	87	37.3	15.2	14.3	32.1	9	9.4	3.7	6.6	9.0
−20	112	27.1	17.6	10.8	22.7	11	8.5	6.0	5.4	8.1
−30	88	15.8	15.4	4.9	12.3	9	5.6	5.5	2.7	5.0
−40	9	6.0	6.0	1.7	4.6	1	1.7	1.7	1.0	1.6
−50	1	1.5	1.5	0.3	1.4	1	0.5	0.5	0.2	0.5
Total	1022	281.5	150.4	96.4	244.2	146	88.6	50.5	51.4	84.4

[a] LPJmL-wmr is a Genghis-Khan-scenario, but only with the three currently most important crop types (wheat, maize and rice) plus pasture.

Turn over ▶

This number is reduced to 51 billion and 36 billion, respectively, in the soft versions of the Burger-scenario.

5. Discussion

The results presented within this paper are theoretical and do not account for all limitations and problems associated with this very intensive land use. This concerns in particular water consumption, nutrients, crop protection, energy, and land-use patterns.

Water consumption: In case of irrigation, the model computes the amount of water that would be available from the rivers under the assumption of no water extraction for other purposes (e.g. industrial, households, and drinking water for animals and humans). With our estimation of carrying capacity, a higher population would also use more water for industrial and household purposes, reducing the amount available for irrigation. On the other hand, some regions withdraw their irrigation water from ground water reserves, which are not taken into account in this study. Certainly, a technological increase in the efficiency of water use for both industry and agriculture is theoretically possible. Another problem associated with irrigation is that intensive irrigation in many semi-arid areas has led to severe salinisation problems. In some cases, degraded soils must be abandoned. We do not account for any soil degradation processes (and the related loss of production potential) in such vulnerable irrigated places.

Nutrients: Both De Wit's (1967) estimations as well as our calculations do not account for limitations in nutrients, in particular nitrogen and phosphorus. This implies the unlimited availability of fertilizer. While nitrogen can principally be supplied in sufficient amounts, phosphorus is available in limited supply only, even though these resources may last for more than a century. We can estimate the phosphorus demand for our extreme Genghis-Khan-scenario. Our calculated total vegetation carbon of 56.6 Gt corresponds to 0.28 Gt phosphorus which is more than an order of magnitude lower than the estimated phosphorus resources of 13 Gt. Nevertheless, phosphorus would be a limiting resource in a non-sustainable management without recycling. The phosphorus content in the harvested crops is about 0.15 Gt per year. Therefore, the estimated phosphorus resources given above would last for 86 years.

Crop protection: The strategy of large-scale planting of only the most productive crop is very simplistic as it defies classical agronomic experience. In most farming systems, crops are rotated following 2–4 year cycles, which leads to better soil quality and reduces pests and diseases. In all places on the planet where mono-cultures occur, the natural fertility of soils is diminished and the crops are becoming less resistant against illness. These systems are still productive if sustained by large amounts of agrochemical inputs, like industrial fertilizer, pesticides, fungicides, and herbicides.

Energy: Beside the associated pollution problems (water quality, toxic elements sometimes present in various parts of the food chain) and large amounts of greenhouse gas emissions (especially N_2O), this is a very energy-demanding system. With respect to the diminution of fossil fuels, and as bioenergy plantations are excluded from this study (land use for food only), this system will be energetically sustainable only if significant progress is achieved within the renewable energy sector.

Land-use patterns: We assume that food production is local, i.e. that people live where their calories are being produced. This causes an over-proportional use of productive land for non-agricultural purposes in the soft versions of our scenarios, consistent with the historic development of land-use patterns, where settlements mainly emerged in fertile areas. If we would allow for transportation of food then areas needed for housing, industries and recreation could be allocated to the least productive areas. In that case, the soft versions of our scenarios would be much closer to their corresponding extreme versions. The potential to reduce agricultural area demand by concentrating agricultural production in the most productive areas in the world, irrespective of existing settlement patterns, is equally large for present-day production systems.

The assumption of up to 250 km^2 large monocultures is certainly an undesirable agricultural production system in many respects, as it disregards environmental and social side-effects but optimizes the food provision only. Due to the abilities of the model used, we here consider single crop systems without crop rotations and multiple cropping systems only. It is, however, possible to allow for a more diverse crop mix and thus reduce the agro-chemical input requirements, without compromising the carrying capacity in a strong way. As shown in Table 3, the carrying capacity changes only slightly if the model is forced to select from wheat, maize and rice only. This indicates that the energy yield per unit area is not mainly determined by the crop planted, but by environmental conditions. It also shows that results are largely insensitive to possible distortions in cropping patterns that result from crude global-scale crop-variety parameterizations. The dominance of pulses at around 55° N, for example, has only little effects on the carrying capacity of these latitudinal bands. Results change by ~1% if pulses are replaced by wheat in this area.

The save-forests-scenarios would additionally allow for sustainable use of forests for food production not considered in our estimates. The shifting cultivation methods of traditional communities within the tropical forests can be sustainable food production systems if cropping cycles are not too long (1–3 years) and regeneration periods are not too short (10–30 years). Naturally this implies very low population densities. Various authors have estimated the carrying capacity under sustainable traditional shifting cultivation to fall between 10 and 30 persons per km^2. The natural distribution of the tropical rain forests in our simulation is around 37 million km^2. So we can estimate that between 0.37 and 1.11 billion people could live sustainably within "conserved" tropical forests, i.e. without any damageable destruction. However, this is 2–3 orders of magnitude lower than the 158 billion of the save-forests-scenario.

The temperature constraints of boreal forests did not allow for establishing such shifting cultivation techniques. However, the prehistorical hunter and gatherer techniques can sustain a very sparse human population density in boreal forests. Estimates are around 1 person per km^2, although there are much higher estimates for specific places (e.g. along the North American Northwest Coast). Assuming this value of 1 person per km^2, we can feed about 20 million people in such a way within the boreal forest area of our save-forests-scenario. In comparison to the overall carrying capacity this is totally insignificant.

6. Conclusions

Our estimation of maximum carrying capacity is related to the pioneering work of De Wit (1967) who assumed radiation- and temperature-limited photosynthesis as the limiting factor. Using an actual process-based crop model we find that the extreme results of De Wit (1967) are reduced by a factor of about 4. Nevertheless, these results do not take into account many constraints discussed in the previous section. Therefore our new estimation for the carrying capacity can be considered as an “academic game” approach. The availability of land for agricultural production and diet patterns are the major determinants of the carrying capacity. If land is excluded from agricultural use, either for nature conservation or recreational/ industrial purposes, the carrying capacity is reduced roughly by a factor of 2–5. Nevertheless, these numbers are still much higher than the median estimates for K in the range of 7.7–12 billion. Our estimates for K in the range of 31.1–281.5 billion (Table 3) correspond to a situation where humankind can only vegetate on our planet.

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