Sustainable Population in the Time of Climate Change

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Emma Engström, Malcolm Fairbrother, Karim Jebari,
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Institute for
Futures Studies

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Foreword

I'm pleased to present the report from the research project "Sustainable population in the time of climate challenge" which has been made possible through a generous grant from the Global Challenges Foundation (GCF). This has been quite a unique project. The research questions in the call by GCF were of a very wide scope and could not be addressed through any obvious or well-accepted method in a single discipline. We therefore had to take a genuinely interdisciplinary approach and develop novel approaches that allowed us to investigate the questions from several angles.

Our research team is composed of researchers in climate science, demography, economics, philosophy, psychology, sociology, and technology studies. All of our subprojects involved researchers from two or more of those disciplines, working with methods that cross the boundaries of academic disciplines. An illustrative example, to just take one, is our study of emerging food technologies, presented in section 6. It is about agriculture, it is authored by a philosopher and a scholar of technology, and it uses a backcasting method from futures studies. The result is an innovative and insightful study of this crucial aspect of sustainable population levels.

On behalf of the whole research team, I would like to thank the GCF for funding this high risk, high yield research project. It is rare to find financial support for research which addresses big bold questions in such a novel and interdisciplinary way. The results speak for themselves. The work presented in this report is of the highest quality, developing new ways of researching some of the most challenging questions of the future, and breaks new ground in various areas. It will for sure stimulate further research in the area.

Gustaf Arrhenius, Principal Investigator

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Contents

Executive Summary

This report presents the findings of our research project, "Sustainable population in the time of climate change", which was funded from November 2021 to November 2023. The project studied what level of global population is sustainable, under two broad headings. The first was the size of a sustainable population, and its dependency on economic, technological, and environmental factors. The second was population policy, where we investigated both the possibilities of policy to affect fertility and popular support for population policies.

Our headline results are as follows. The study of sustainable population size returned widely varying maxima, from 3.6–28.6 billion, with some reason for favoring lower estimates in that range. We find a broadly linear dependence between population size and environmental impact. However, our study of emerging agricultural technologies offers room for optimism, as they have the potential to feed a population slightly larger than today's sustainably, given certain preconditions. Population policy may not be required to reduce population, given currently falling fertility rates. Our study of popular attitudes did not find that individuals who are more worried about climate change have fewer (or more) children of their own, although most people in Sweden do think environmental considerations should influence decisions to have children.

The project was composed of several overlapping lines of inquiry, pursued relatively independently. This report therefore presents an array of linked but distinct perspectives on our research questions, offering insight into the topic of a sustainable global population. The report is structured in sections corresponding to sub-projects, with the authors of each section listed below. This structure was chosen to reflect our team's diversity of perspectives and approaches. We now describe those contents in more detail.

The first issue tackled by this report is the expected trajectory of global population, and whether overpopulation is a problem. This is important because it is implicit in many studies of population policy and work on sustainable population levels. Section 1 presents our view on global population growth. We give a summary of the current knowledge of population growth, summarize current UN population forecasts and reasonable expectations on how the human population will continue to grow, and when it may eventually stabilize, and even decrease. Demographic trends already underway are enough, in our view, to ensure that continued rapid population growth is not a concern. How much population will decline is a matter of internal debate for our team. Section 2 presents a view on which population may decline rapidly. Around two-thirds of the global population live in a country with a fertility rate that is below replacement level. The forces leading to low replacement seem unlikely to go away, and current high fertility countries are trending down. If global fertility rates land and stay significantly below replacement, we may see the exponential decay of global population size.

In Sections 2 and 3 we note that population policy, and indeed endogenous population decline, is not a solution to climate change. This is broadly because population changes are too slow to have an impact on the timeline required to mitigate climate change (which we take to be the next 50 years). Nonetheless, others have suggested that population policy be used to achieve environmental gains. Section 3 considers how this might be achieved ethically. We criticize a proposal which we call the "Arable Land Principle". In our view, it places undue focus on national-level population targets, and we find it to be both descriptively and morally inadequate. Instead, we propose that a sensible ethical approach must be holistic in its consideration of economic and environmental factors, and should take into account the possibility of trading in duties to reduce population.

We also studied public attitudes to environmental issues and population. Section 4 presents the results of two studies we conducted. In the first, we find that many people link environmental protection to childbearing decisions. Most people in Sweden think environmental considerations should influence decisions to have children, and that global population growth is a problem. However, we did not find that individuals who are more worried about climate change have fewer (or more) children of their own. In our second study, we find that most people would prefer a future world with a smaller number of people leading very high-quality lives, over a future with a larger population and greater total but lower average well-being.

Our investigation of the size of a sustainable population and its dependence on economic, technological, and environmental factors is contained in sections 5 and 6.

Section 5 describes a novel IPAT-based study of two environmental issues—climate change and human land use, studied using three different methods each. IPAT refers to an influential equation, I=PAT, linking the key variables of Impact, Population, Affluence and Technology. We are particularly interested in the relationship between population and environmental impacts and, broadly speaking, we find support for population acting as a linear scalar factor for environmental challenges. We also used the three IPAT-based methods to calculate a maximum population size, assuming we do not exceed the environmental impact levels of 2020. The three methods produce widely varying answers, from 3.6–28.6 billion. The low end of that range is generated by the literature's favored model, lending some support to lower expectations for sustainable population size. On the other hand, our study of emerging agricultural technologies lends some support to higher figures in that range, as we discuss below.

Section 6 describes how emerging technologies in agriculture might enable us to sustainably feed more people globally. The methodology of the study is backcasting, which involves specifying a goal and then assessing the potential of certain technologies to achieve that goal. The end-goal we selected is a 50% increase in food production, which we believe would be enough to eliminate hunger and allow for a larger global population in 2100. Three technologies were studied: vertical farming for vegetables and some fruits, C4 photosynthesis for grains, and realistic substitutes for meat and dairy products. The goal was to identify the environmental potential of each, as well as its enablers and drivers of success. The focus on technological change allows us to see what is possible with this lever alone. The key finding is that, if these three proposed technologies are widely adopted, and carbon-free energy is available, food production is projected to be climate neutral by 2100. We studied benefits to other planetary boundaries, including eutrophication, freshwater use, and land use. Some behavior change is required for these benefits to be realized, especially around the acceptability of GMOs and our cultural attachment to meat and dairy. Additionally, a key technological enabler for vertical farming is cheap and abundant fossil-free electricity.

1. Global Population Growth

Martin Kolk, Gustaf Arrhenius, Malcolm Fairbrother, Joe Roussos

What is at stake?

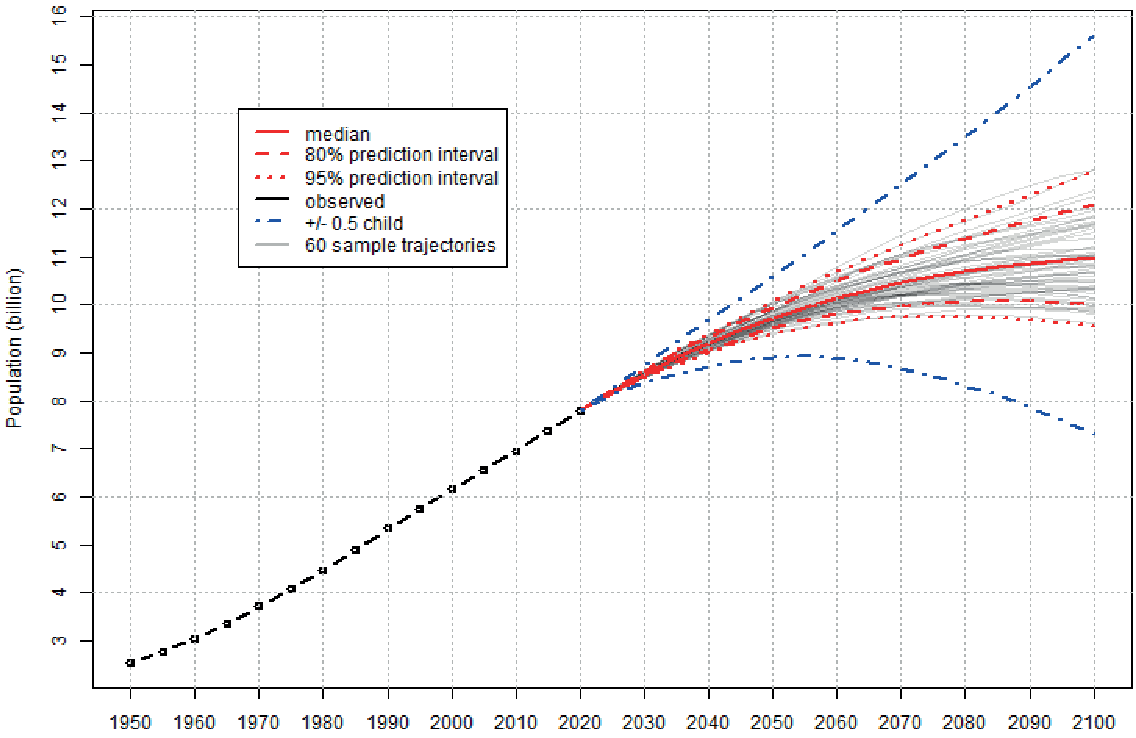
The total human population has increased dramatically from around 1.6 billion in 1900 to nearly 8 billion today, and it is forecast to continue growing over the course of the 21st century. A larger human population will—all else equal—place greater stress on most ecological systems and may have adverse consequences for human welfare.

A large population may contribute to and interact with other global catastrophic risks, e.g., those related to large-scale species extinction, desertification, and the collapse of valuable ecosystems. A rapidly growing human population may itself threaten human welfare and in particular may reduce the welfare of future generations. If the global population grows more quickly than societies can adapt, we and future generations may be confronted with very difficult trade-offs, and irreparable harm to the biosphere. As such, population growth may contribute to the "destruction of humanity's long-term potential" (Ord, 2020), making it an existential risk in a weak sense. It is not, however, an existential risk in its strict sense: a risk "…that threatens the premature extinction of Earth-originating intelligent life…" (Boström, 2013).

Global population growth is likely to be regionally imbalanced, concentrated in poorer countries. This means that negative externalities of population growth will also be concentrated in poorer countries. That a growing share of the world population in the least well-off countries may contribute to future political challenges such as conflicts and global inequality, which in turn may lead to migration from poorer countries.

How much do we know?

Demographers and government agencies have reliable information on population statistics and can make high-quality forecasts for the near future. We can be nearly certain that the human population will grow significantly over this century. The UN 2022 Population Prospects have a median forecast of 9.7 billion people for 2050 and a bit over 10 billion for 2100. Since a significant part of current population growth is due to the young age structure of the global population, these forecasts are rather certain and the UN gives an 80% confidence interval of around 9.5–10 billion for 2050 and around 9–11.5 billion for 2100, though forecasts are changing over time and other organizations make different forecasts. The global population has grown from around 1.7 billion in the 1900s, to nearly 8 billion today, a period of unprecedented rapid growth. The growth rate for the total human population peaked at around 2% per year in the 1960s and is around 1% today. The growth rate is forecasted to decline to the point where there is no growth in around 2100. Most of the future population growth will take place in Sub-Saharan Africa, while most of the growth since the 1950s took place in Asia.



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United Nations, DESA, Population Division. *World Population Prospects 2019*. http://population.un.org/wpp/

Figure 1. World: Total population.
This figure shows estimates and probabilistic projections of the total world population, based on projections of total fertility and life expectancy at birth. The lines represent the probabilistic median, and 80 and 95 per cent prediction intervals, as well as the (deterministic) high and low variants.

Most of our uncertainty about future population growth is related to childbearing. There are two major factors whose impact is not yet known: 1) the speed of fertility declines in Sub-Saharan Africa, and 2) future fertility trajectories in middle-income countries in Asia (particularly India and China). Fertility decline in Sub-Saharan Africa has previously been slower than in historic forecasts, though on the other hand the world has several recent historical examples of very rapid fertility decline (e.g. in East and Southeast Asia). China currently has very low fertility of around 1.3 children per woman, and fertility is rapidly falling in India. Whether the large Asian countries will have childbearing levels comparable to current southern European countries around 1.1 to 1.4 children on average, or more comparable to the higher fertility levels in Anglo-Saxon countries at around 1.5 to 1.7 children, will be very important for global population trajectories in the 21st century.

There is much less certainty and more scientific debate on the consequences of population growth. The majority of researchers, though not all, foresee negative consequences of very large population sizes, while there is more debate about the positive and negative consequences of population growth in the nearer term.

Some researchers worry about potentially negative impacts of population decline at a national level, though these worries are usually linked to effects on the age structure (the ratio of older individuals to younger individuals) rather than the absolute population size. Insofar as the elderly are an increasing share of the population, that could place a variety of burdens on younger generations.

Most population growth will take place in low-income countries (with incomes per capita below about US$1000/year). But for the next several decades, most externalities of unsustainable consumption are linked to the current (and future) population size in high-income and upper-middle income countries. Thus, a focus on current individuals (contemporary population size and consumption, and their children) puts the focus on high-income countries, while a focus only on changes in population size (e.g. a focus on countries that will see large-scale population growth) puts more of a focus on low-income countries.

In the very long term, it is reasonable to assume that it is the eventual total population size of the entire world that will determine what a desirable or sustainable population is, and it makes little sense to distinguish between low and high income countries. However, for this century, most negative externalities of population growth will be caused by high-income and upper middle-income countries.

The consequences of global population growth will be context dependent and depend on current and future policy choices. Where societies make sustainable choices, the environmental consequences of population growth will be relatively smaller. Nevertheless, and especially given humanity's failure to make sufficiently sustainable choices, it is likely that a large global population will mean that future generations will continue to have to make trade-offs between, for example, material welfare, a sustainable eco-sphere, and the well-being of future generations. Such trade-offs will be harder if we greatly value aspects such as untouched wildness and global biodiversity, where a large human population will likely imply negative externalities for the foreseeable future, and a too large population may be associated with irreversible harm. The level of a sustainable global population will eventually be determined by what we as a society value, and what trade-offs we think are reasonable.

> "How many people the Earth can support depends in part on how many will wear cotton and how many polyester; on how many will eat beef and how many bean sprouts; on how many will want parks and how many will want parking lots; on how many will want Jaguars with a capital J and how many will want jaguars with a small j." (Cohen 2017)

Key factors

- Global population trends are primarily shaped by childbearing. Fertility levels are highest in low-income countries, but fertility levels in some middle-income countries (such as India and China) will be at least as influential for Earth's future population.

- Most population growth in the 21st century will take place in low-income countries, but each (living and soon to be born) person in high-income countries contributes more to current negative externalities of a large population size.
- A growing population may make it harder to balance different needs of future human populations, such as affluence, equity and the maintenance of the biosphere. Sustainable policy choice may reduce the need to make such trade-offs.

Governance of global population size

Population size is seen as a strictly national concern, and there exists no super-national organization or global treaty with a mandate to regulate either national or global population size. There exists no global consensus on, or governance of, what a desirable level of childbearing is; instead, there is considerable diversity in the policies and goals of different countries.

At the national level, different countries pursue very different population trajectories, where some countries spend considerable resources on reducing childbearing levels, while other countries implement polices to increase it. Since the 1970s, member countries of the UN have reported their population policies to the UN population division. They are asked if they have policies to support higher or lower fertility.

In 2016, of the 192 countries in the world 28% reported to the UN population division that they wanted to increase fertility, 15% that they wanted to maintain it, 42% that they wanted to lower it, and 15% reported that they had no official policy. In Europe, 66% reported that they wanted to increase fertility, while no countries reported that they wanted to lower it. In Africa 83% of countries wanted to reduce fertility, while 4% wanted to increase it. All countries that wanted to reduce fertility had childbearing above 2 children per women, and nearly all countries that wanted to increase it had fertility below 2. However, some Asian countries had fertility above 2, and still reported they wanted to increase it. Nearly all countries report policies both to support family planning, for example by making contraceptives available (which has the potential to lower population growth), and most countries—including nearly all high-income countries—report having child and/or family allowances (which has the potential to support growth).

During the 20th century, many developing countries sought to reduce population growth, and this was in many contexts encouraged and supported by western NGOs and aid agencies. Programs to reduce population growth took place in countries with weaker human rights and checks, such programs were associated with substantial human-rights abuses, for example in India and China. Such abuses were not limited to poor and non-democratic countries, as the history of forced sterilizations of ethnic minorities in western countries was sometimes motivated by populations concerns.[1]

Racist ideology was also prevalent in several NGOs involved in "family planning" projects in poor countries, that sometimes resulted in the non-voluntary use of contraceptives, forced abortions and sterilizations.[2] Today, several international organizations

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[1] https://daily.jstor.org/the-little-known-history-of-the-forced-sterilization-of-native-american-women/

[2] https://www.unaids.org/sites/default/files/media_asset/201405_sterilization_en.pdf

and some parts of the UN system continue to promote family planning programs in low-income countries, though there is a strong focus on female empowerment and meeting unmet needs/desires for contraceptives. Conversely, some states and inter-governmental organizations in rich countries—such as the European Union—instead fund programs with the aim of increasing population growth. In conclusion, there exists no unified governance for either population growth or a sustainable global population size.

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2. Demography and Climate Change

Gustaf Arrhenius, Dean Spears

In the demography literature there is empirical evidence and theoretical support for environmental impacts being roughly proportional to population size (see section 6), and for individuals in high affluence societies typically contributing more to environmental problems than individuals in low affluence societies. This has led many voices to call for fertility-reduction policies as a form of carbon mitigation policy. And more broadly, at least since Ehrlich's 1968 bestseller *The Population Bomb,* some environmental activists have welcomed, or even sought, the prospect of human depopulation as a solution to environmental challenges of various types.

One fact that is under-appreciated in this environmental discussion is that human depopulation is no mere hypothetical, as it may have been when Ehrlich's book was published, and when the size of the world population was growing at a rate of more than 2% per year. On the contrary, the global population science community unanimously projects the size of the human population to peak within the lifetime of an average child born today, and then to decline. Depopulation is the most likely scenario, as Spears (2023a, 2023b) argues with various coauthors.

Why is depopulation likely? Because birth rates are falling around the world. Two-thirds of people now live in a country where the birth rate would be too low to prevent depopulation. Because humans reproduce sexually, the dividing line—so called "replacement fertility"—is about two children per woman, on average.

In Sweden, the birth rate has been below two since 1993. For Europe as a whole, it is now about 1.5. The US is at 1.6. Latin America is at 1.8. East Asia is at 1.2. Even India, where Ehrlich famously worried about overpopulation, is now below replacement fertility. Sub-Saharan Africa is the only large world region where birth rates are currently above 2 (in fact they are above 4, on average), but even there they are falling.

Could birth rates reverse? Certainly, in principle. But that is not what leading population projections expect, at least for the next few centuries. The UN World Population Prospects project the size of the world population to peak around 10.4 billion in the 2080s. Other demography research groups, such as IIASA in Vienna and IHME at the University of Washington, place the peak even sooner. And a recently published statistical model estimates that there is a 90% chance that the global birth rate will still be below replacement levels in 2300 (Raftery and Ševčíková 2023). If this happens, depo-

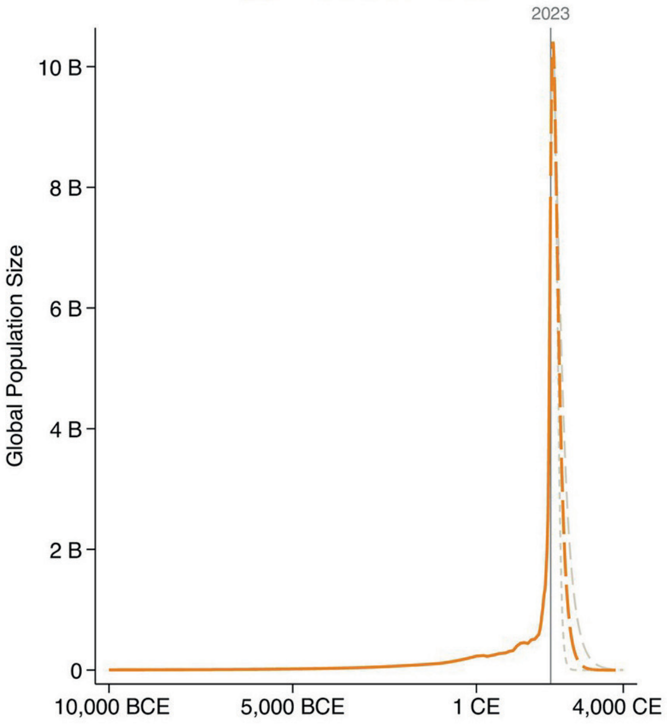

Figure 2. Global population as a spike in world history.
According to this graph the world population will peak in 2085 with 10 billion people. Spears, D., Vyas, S., Weston, G., G. & M. Geruso (2024).

pulation could be rapid: The size of the human population quadrupled over the past century and in the 2100s or 2200s the same exponential growth could be exponential decay.

So, depopulation is not merely an environmentalist *proposal,* depopulation is humanity's *likely future.* But should depopulation be welcomed, or even intentionally accelerated, to reduce carbon emissions?

The fundamental problem with this proposal is that the pressure of humanity on the environment is a *stock* but birth rates are a *flow.* Even large changes in demographic rates will not cause the size of the human population to deviate much from its most likely trend, over the coming few decades. Depopulation will happen at the pace of generations, and over the coming decades, the expected variation in the size of the human population is small, as Spears et al. (2023) argue.

Here is an overly simplified example. About 140 million babies will probably be born next year and about 60 million people will probably die. There are about 8.1 billion people. Imagine something very extreme happened and *nobody were born at all* next year. Though that is highly unlikely to happen, if it did we can ask: What would be the change in humanity's environmental impact? Instead of next year's population being about 8.2 billion people, it would be about 8.0 billion people. Having 8.0 billion people instead of 8.2 billion would be a 2.5 percent reduction in the size of the world population, as a result of the largest possible decline in birth rates (i.e., to zero births).

But that would be much too small of a change to be an adequate solution to humanity's urgent environmental challenges. One leading estimate in the literature is that a 1% change in population size causes a 1% change in carbon emissions (O'Neill et al. 2012).

Assuming that this is true, preventing all births next year would result in a 2.5% change in *that year's* carbon emissions. But the atmospheric concentration of carbon dioxide is itself a stock, into which any one year's emissions are merely a flow. So that 2.5% reduction in one year's emissions would be a tiny change in the long-term trajectory of global atmospheric carbon concentrations, and therefore only a tiny change in temperature changes—all from an enormous change in births.

More plausible changes in birth rates would have even smaller changes on the trajectory of the population and therefore make an even smaller difference to climate outcomes.

As Spears and Budolfson (2022) argue, population is likely to continue to grow even in the face of moderate population policy. The reason is *population momentum*: changes in the size of the population that would continue due to the age distribution of the population, even if fertility and mortality rates changed to replacement levels. Spears and Budolfson (2022), as well as Greaves (2022), point out that because there are currently more young girls than adult women in high fertility countries, the global population would continue to increase even if the global fertility rate fell to replacement level. Therefore, aggressively forcing the fertility rate to replacement levels would not make a significant difference to the emissions reductions goals set in the Paris Accords.

One implication of the slowness of population change, relative to climate policy, is that fast-moving changes in human carbon intensity are changing the environmental cost of an extra person. As decarbonization becomes more advanced, the carbon price of having a baby will get smaller and smaller: Your unborn descendants, if any, will probably add less carbon to the environment than you do. One implication of this is that if humanity achieves a more optimistic climate outcome—decarbonizing fast enough to limit warming to, say, 2.5 degrees—then the climate cost of an extra baby will soon be very small.

In short, human depopulation is no substitute for adequate climate mitigation policy. And the same logic works for other ways in which humans put pressure on the environment: The size of the population is too slow-moving of a stock, relative to the urgency of today's environmental challenges.

On the other hand, in the longer run, population size *will have* a proportional impact on nearly all environmental challenges, in particular those such as land use where humanity will continue to face important trade-offs a century from now—see section 5. In a longer time perspective, any population policy will have an impact on population concerns proportional to the achieved population reduction. If population policy affects the population growth rate itself over the long-term, the impact will continue to have an exponential impact on human population size, and the contribution of population size to environmental impacts (Kolk, 2022). How government policy can be used to affect birth rates, and what is likely to be effective as well as ethical, is discussed in Kolk (2021).

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3. Fair Population Reduction

Gustaf Arrhenius, Göran Duus-Otterström

It is often suggested that the world's human population ought to be reduced as a way of dealing with climate change and other environmental problems. Sometimes the claim is that, while the current number of humans is not too big, it will become too big unless humankind shifts to a lower population growth trajectory. Other times the claim is, more strongly, that there are far too many humans already, and that drastic reductions in the size of the population are needed. An idea one encounters in parts of the academic literature is that a human population of roughly three billion would be desirable:

> "According to our estimates, the optimum size that corresponds to a situation that would allow sustainable welfare at the level of the average European citizen of today is approximately 3.1". (Lianos et al. 2016, p. 1695)
>
> "… a *sustainable* global population run between two to three billion people…" (Cafaro 2022, p. 2274)
>
> "We recommend conservative goals regarding the survival of humanity... The most conservative baseline is to return to the stable global population at the start of the industrial revolution (1740, roughly 800 million) … A less conservative, more aspirational baseline would be roughly three billion." (Tucker 2022, p. 53).

How should we achieve this supposedly desirable reduction? According to these authors, there is no need for coercive policies. Instead, the idea is to use economic incentives and norm change. Cafaro (2022, p. 2273) suggests that "[t]o facilitate significant population decrease … governments should work to make one-child families the norm."

It is important to immediately dispel one misapprehension about why such a reduction in population would be desirable. It is sometimes claimed that mitigating climate change requires a significant population reduction. However, while the size of the population explains a substantial part of the current volume of greenhouse gas emissions (IPCC 2014), the population variable is much too slow-moving to play a major role in the climate solution. Even in the unlikely event that the world would move quickly to one-child families, this would not help much in respect to climate change since we need to solve this problem over the coming decades and, as was discussed above, the population will continue to grow even with a one-child policy because of population momentum. Let us explain.

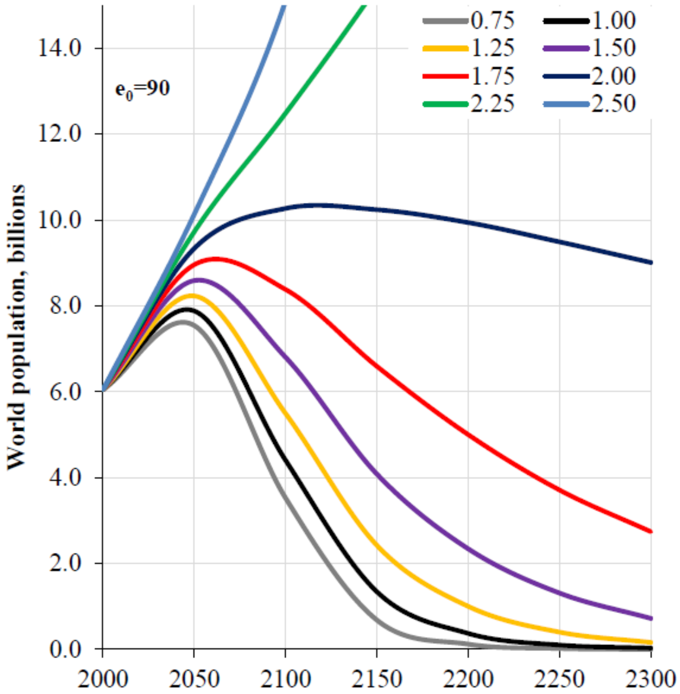

Figure 3. Global population given different total fertility rates, 2000–2300.
From Basten, Lutz & Scherbov (2013, p. 1153).

Figure 3 shows the global population size 2000–2300 resulting from alternative global fertility levels (TFR to be reached by 2030–2050 and then kept constant) combined with a maximum life expectancy of 90 (Basten, Lutz & Scherbov 2013). The Total Fertility Rate (TFR) is a standard demographic indicator used to estimate the average number of children that a woman would have over her childbearing years (i.e., age 15–49), based on current birth trends. As the black line in the diagram illustrates, even if we would get a situation in which each woman on average has one child (TFR = 1.00), the world population would continue to grow for another few decades. It would remain above 6 billion until around 2075. At that point it would be falling fast (population momentum would be over) and would reach 3 billion roughly around 2130. Hence, a one-child policy would be of very little importance, if any, as a climate mitigation method since the effect will set in much too late.

Yet, one might argue that in the long run, we need to stabilize the population at some lower level than today's level for other environmental reasons. For example, one might argue that protecting biodiversity requires that we settle on a much smaller human population in the coming centuries. Suppose this argument is correct and that we should settle on something like a three-billion world. This raises an intriguing question: how should the reduction be achieved? Since the reduction can be assumed to be a burden – it will, for example, come with economic costs and frustrate people's desire for having children – we need to ask how this burden should be shared.[3] What would be a fair way of distributing the burden of reaching the population target?

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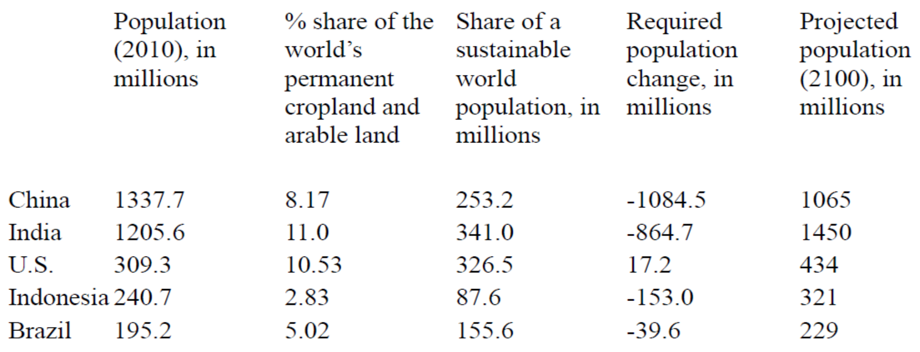
[3] There are of course also ethical problems regarding the implementation of population policies, but we set those problems to the side here.

Lianos et al (2016) (Cf. Cafaro 2022, p. 2271) have suggested what we may refer to as the *Arable Land Principle*:

> “The reduction in population should take place in every country according to some criterion. A simple, reasonable, and objective criterion is the proportion of cultivated land of each country.” (Lianos et al 2016, p. 1688)

The idea behind the principle is that the population reduction burden should be allocated among countries based on their ability to grow food. The arable land principle begins by formulating the target population (in Table 1, this is 3.1bn humans). It then takes each country’s share of the world’s permanent cropland and arable land and uses this to indicate the reduction the countries would need to put up to reach the target population. For example, as shown by table 1, China, with 8.17 percent of arable land, would be entitled to 253.2 million inhabitants, meaning that it would be required to shrink by more than a billion. Meanwhile, countries with a more favorable land-to-population ratio, such as the US, would be entitled to grow somewhat.



	Population (2010), in millions	% share of the world’s permanent cropland and arable land	Share of a sustainable world population, in millions	Required population change, in millions	Projected population (2100), in millions
China	1337.7	8.17	253.2	-1084.5	1065
India	1205.6	11.0	341.0	-864.7	1450
U.S.	309.3	10.53	326.5	17.2	434
Indonesia	240.7	2.83	87.6	-153.0	321
Brazil	195.2	5.02	155.6	-39.6	229

Figure 4. Required population changes according to the Arable Land Principle.
Cafaro 2022, p. 2272; Cafaro 2021, p. 60.

For obvious reasons, the arable land principle is extremely infeasible politically. Given that population reductions of this magnitude are a burden, it is difficult to imagine that countries like China and India would agree to massively shrink their population, especially when other major countries such as the US can grow its population. But the principle also lacks merit even if we set feasibility aside. For one thing, the principle implausibly elevates what is a morally arbitrary factor – the ability of one’s geography to support human life – to an ethical criterion. One can argue that countries should not be held responsible for the land they happen to inhabit in this way. Even if one were to disregard this point, however, the underlying norm of national self-sufficiency is very odd. The arable land principle essentially assumes that each country should be able to grow its own food[4], but this overlooks division of labor and trade between countries. Just like we do not expect all countries to, say, mine its own iron ore, we should not

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[4] Lianos et al. (2016, p. 1688) note that while the arable principle is not a “perfect criterion because it leaves out other resources (oceans, wind, solar energy, human capital, etc.)” it is “as a first approximation … a good way to measure the ability of each country to feed its people.”

expect them to grow their own coffee or bananas. By engaging in trade and division of labor, countries can support larger populations than if each were to rely only on what they can produce themselves.

One could formulate other principles based on a target population, but as Arrhenius and Duus-Otterström (2024) show, this will not help much since it is the assumption that there is a national target population that must be achieved which is problematic. The only sensible reason to assert that the human population must be capped is at least broadly environmental in nature. But since the motivation is environmental in nature, anyone who endorses it simply cannot focus only on the number of people. The number of humans that the earth can "carry" depends on how much they consume, extract, and pollute. Thus, we would need rather definite assumptions about these factors before we could even formulate a target population, let alone distribute it.

The proponents of a target population are aware, of course, that the human population as such is not all that matters. They derive their population target using assumptions about the standard of living and ecological footprint of the future, stable population. But Arrhenius and Duus-Otterström argue that they fail to take seriously enough the implications of focusing on environmental impact as opposed to population size as such. Focusing on impact not only suggests that population must be considered alongside other determinants of impact but also that there is no such thing as a target population unless one assumes, unjustifiably, that the other variables are fixed. The only way a 'target population' can be formulated is if one prejudges how, for example, what people's standard of living will be. But a country ought to be free to sacrifice some of its living standard if it would rather have a larger population.

There is also a second problem: even if we assume that the target population could be defined, from the perspective of distributive justice our focus should be on the costs actors face in reaching this population rather than human numbers in themselves. As Arrhenius and Duus-Otterström discuss, it should be possible for a country to refrain from doing their share of population-reducing if it fully compensates for this, for example by paying someone else to reduce more than their share. The strong focus on human numbers only makes sense if we reject the fungibility of the duty to reduce one's population. But the duty to reduce one's population does seem fungible in the sense that one can compensate others for not discharging this duty.

Arrhenius and Duus-Otterström's analysis suggests that the question in focus in this literature – how to allocate a required population reduction in a fair way – is not quite coherent. The basic problem is, to use a term Simon Caney has introduced in the climate justice debate, that the question is excessively "isolationist" (Caney 2012). By isolationism, Caney means (roughly) the tendency to treat an issue in separation from other issues. An example of this from the climate justice debate is the tendency to assume that the morally correct distribution of rights to emit GHGs is its own question, guided by domain-specific principles such as emissions egalitarianism. Caney argues that emissions egalitarianism is implausible because it focuses on one good – the right to use the atmosphere's absorptive capacity – rather than on the basket of goods each person enjoys. Unequal emissions are not unjust if those who emit less enjoy more of other goods in compensation.

The population reduction debate is strongly isolationist because it assumes that we should formulate principles specifically for reaching a target population. But even if we assume that countries should converge on some equal and sustainable level of environmental impact in the future, it should be possible for them to choose between different routes to reaching this level. And once we relax the assumption that each country must meet its quota directly, we must also consider that what is to be allocated are costs as opposed to population reductions per se. The conclusion, Arrhenius and Duus-Otterström argue, is that it is difficult to see why population reduction should be regulated by its own principles as opposed to by a general theory of justice.

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4. Public Attitudes

Malcolm Fairbrother, Martin Kolk, Kirsti Jylhä

Any policy actions that governments decide to take to shift population trajectories could be either impeded or facilitated by public opinion. Some research has been done, including previously by us, on public attitudes towards population issues. In the course of this project, we have further explored public opinion and attitudes about population and the environment, including how environmental concerns may influence people's own fertility decisions and their opinions about childbearing.

This work was also motivated by prior recent studies suggesting that many members of the general public link environmental problems to population—for example, that many think residents of high-income countries especially should take steps to limit their fertility (e.g., Davis et al., 2019). If correct, this suggests that environmental concerns may be important factors in people's decisions about childbearing in contemporary societies. And people may be connecting childbearing decision to environmental concerns in two different ways (Fu et al., 2022; Rackin et al. 2022). They may believe that each additional human being will impose a significant burden, contributing to the world's deteriorating environmental quality. They may alternately, or additionally, believe that children brought into the world today are likely to suffer, as the world's environmental quality is and will continue deteriorating rapidly.

Previous studies have, however, typically been conducted using small samples focused on specific populations (e.g., young people, people with high levels of concern about climate change). We therefore sought to provide a more systematic examination of the relationships between environmental considerations and both personal childbearing decisions and general views about reproduction. Furthermore, we investigated how such attitudes differ among individuals with varying demographic and psychological characteristics (e.g., age, actual and ideal number of children, climate worry, climate change beliefs, political trust).

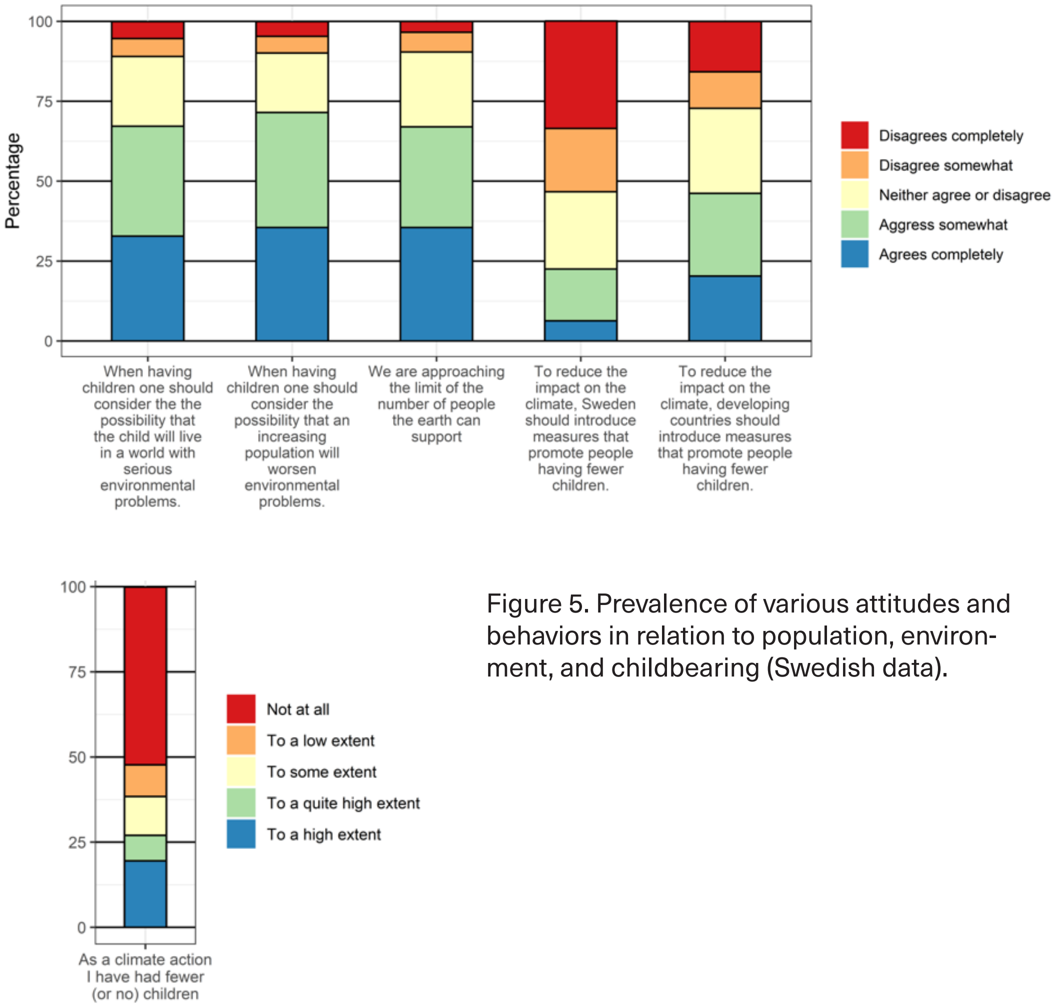

Figure 5. Prevalence of various attitudes and behaviors in relation to population, environment, and childbearing (Swedish data).

In two studies based on large Swedish datasets, we did not find that climate change worry has a notable connection with fertility outcomes. But we did find many people link environmental protection to childbearing decisions. Most people in Sweden think environmental considerations should influence decisions to have children, and that global population growth is a problem (see Figure 5). Significant minorities support governmental efforts to limit population growth. Parents are more worried about future generations but less worried about overpopulation than non-parents, which suggests people's outlooks change when they have children. Judging by these results, it seems that environmental concerns may influence future fertility trends indirectly, and/or induce various psychological reactions among individuals who choose to have children. Our work involved data collection of unique survey data of a kind not collected in any other context, and we describe our data and findings in detail in Jylhä, Kolk, & Fairbrother (2024) in our anthology.

In a separate study, we conducted an online survey experiment, in which we investigated how laypeople assess the relative desirability of different potential future scenarios—with different populations. In this study, we found most people would prefer a future world with a smaller number of people leading very high-quality lives, over a future with a larger population and greater total but lower average well-being. This supports previous work we have done, which also found that people value quality over quantity of human life. In principle that fact would suggest that policy measures for limiting future population growth should be acceptable to the public. However, we have also previously found that policy measures may not be popular, if they impose some burden (such as an economic cost or a limit on freedom), among people who distrust political institutions.

We also found evidence that laypeople have a strong aversion to social inequality. This suggests that any measures to limit population growth are likely to be unpopular if they are perceived to be unfair, or unbalanced in the burdens they impose on poorer relative to wealthier individuals and families.

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5. IPAT Analysis

Emma Engström, Martin Kolk

This sub-project had two goals, derived from the research questions set by GCF:

1.a. We will estimate a sustainable global population size, drawing both on previous research and novel calculations based on environmental economic models. The latter is based on values of adequate standards of living and a sustainable rate of resource extraction. Our estimates suggest that a population larger than the current one will be associated with important negative trade-offs with respect to several dimensions of well-being.

1.b. We will advance our theoretical and empirical understanding of the complex interactions between economic and technological growth, population change, and ecological sustainability. We will focus how and to what extent population policy, environmental policy, and technological change interact over different time horizons.

Our approach to address these questions has been to develop a novel IPAT-focused framework to integrate different assessment methods that concern the link between the key variables in this theory: Impact, Population, Affluence and Technology. These results have been published in the *Vienna Yearbook of Population Research* by Emma Engström and Martin Kolk in 2024 (Engström & Kolk, 2024).

We chose to focus on two key environmental outcomes, climate change (where impact is operationalized as greenhouse gas emissions) and human land use (operationalized in different ways). These environmental dimensions represent two of the most critical challenges facing humanity in the 21st century. They both point to the ways in which human actions risk destabilising the earth system according to the planetary boundaries framework (Rockström et al., 2009; Steffen et al., 2015). Land use, reflecting land-system change, is also closely linked to another critical planetary boundary, biosphere integrity, because a large share of biodiversity loss is attributable to habitat destruction through the conversion of forests into farmland (Dasgupta, 2021).

Climate change is an illustrative environmental challenge, because it is an environmental problem for which humanity has puts great emphasis on mitigation in the form of green technology, and such efforts are built into standard predictions such as forecasts by the *Intergovernmental Panel on Climate Change* (IPCC). In contrast, policy makers have not made similar efforts to reduce land-system change. Thus, climate change and land use represent two distinct environmental challenges which may concern a sustainable global population size in different ways.

Instead of using IPAT to explain why any *one* part of the identity can be seen as a *universal* tool for understanding all kinds of environmental challenges (which is how IPAT-related arguments have often been used in the past), we show that IPAT is perhaps equally or more useful for understanding how *different* environmental dimensions relate to various parts of the identity. Furthermore, we point out the usefulness of converting various environmental impact models – such as forecasts by the IPCC – into the IPAT framework to illustrate their different implications. We look at a variety of aspects, such as time scales and possibilities for technological solutions, as well as the elasticity of impacts with respect to population and consumption. Using this approach, we show why the relevance of population and affluence may vary for different types of challenges.

Our forecasting approach is quite complicated and use different scenarios. It is described in further detail in Engström and Kolk (2024). We give a summary of the three different approaches we use in Table 1. We use the three different approaches separately for land use, and climate change, thus creating 6 separate sets of model families. Within these scenarios we also explore if the forecasts for environmental impacts we do (I) are sensitive to changes in Population (P), Affluence (A), and Technology (T, that is the dependent variable that differs in our forecasts). More details are given in Engström and Kolk (2024). In this final report, we give particular emphasis on the relationship between population size P, and environmental impacts.

Table 1. Three different approaches to answer the interrelations between IPAT variables for land use and climate change.

Approach	Explanation
1) Extrapolation of historical trends	Seeing IPAT as an identity (York et al., 2003), we extrapolate historical trends in which values of *T* at different points in time are calculated based on observations of *I, A* and *P*. Annual historical changes in *T* are then calculated by assuming constant temporal developments, and these values are then assumed in predictions. Thus, projections of *T* do not depend on *P* and *A*.
2) STIRPAT-derived projections	We apply STIRPAT (Dietz and Rosa, 1997), with elasticities inferred from the literature Here, projections of *T* depend explicitly on *P* and *A*.
3) Forecasts in previous research	We infer *T* from projections for *P* and *A* and trajectories of *I* from published forecasts that directly model environmental impacts until 2100 (Fricko et al., 2017; IPCC, 2022; Popp et al., 2017; Riahi et al., 2017).

Forecasting future environmental impact

In our modelling (Engström, E. & M. Kolk, 2024), we used 2020 as our starting point in a study of developments until 2100. Our main approach was to use GDP forecasts from

OECD and population forecasts from the United Nations Population Prospects. We then explored different scenarios based on historical trends that reflected interrelationships between the IPAT variables from the 1960s to 2020. We subsequently evaluated the consequences of changing future population and affluence trajectories.

Our key results are shown in Figure 6, where we show the main IPAT model for the three different approaches and the two environmental outcomes. All values are relative to impact in 2020. For example, a value of P of 1.2 implies a population size that is 1.2 times greater than the population in 2020 (1.2* 7.8 bn = 9.36 bn people), and an I for climate change of 0.5 means annual emissions of Kyoto gases in units of gigatonnes (billion tonnes) of carbon dioxide equivalents (Gt CO2-equiv/yr) relative to levels in 2020, that is, 0.5 * 55 Gt = 27.5 Gt CO2-equiv/yr. A constant I of 1 would thus mean that humanity would emit the same constant level of climate gases into the atmosphere throughout the 21st century.

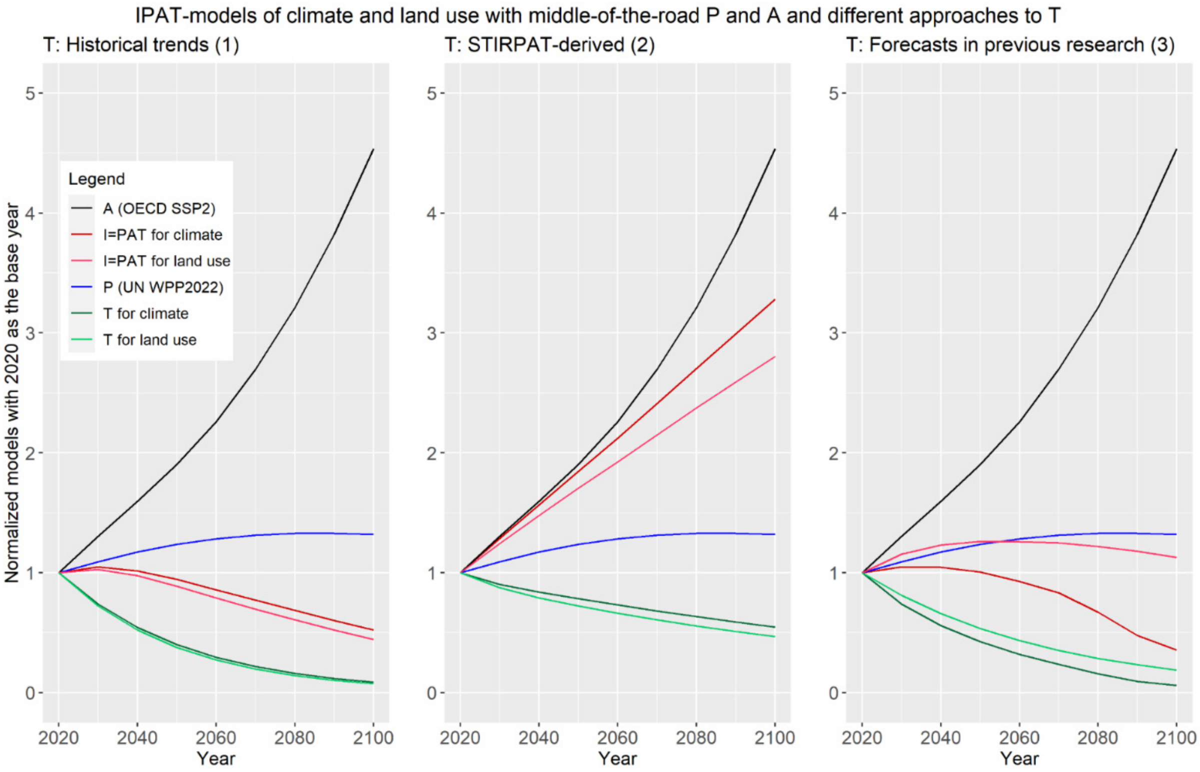

Figure 6. IPAT projections of impact, I, for climate impact (red) and land use impact (light red).

In all three panels, the same assumptions apply for population (P, blue) and affluence (A, black), while T varies. The left panel shows projections in which T for climate impact (green) and land use impact (light green) are based on the extrapolation of historical trends (Approach 1). The central panel is based on STIRPAT estimates of impact elasticities of P and A (Approach 2). The right panel shows forecasts in the literature in which T for climate impact is inferred from the IPCC's SSP2 (RCP 4.5) (Fricko et al., 2017; Riahi et al., 2017) and land use impact is derived from the SSP2 (Popp et al., 2017) (Approach 3).

Climate change targets that have been designed to decrease the risk that global climate change does not exceed 1.5 degrees Celsius imply zero carbon emissions around the year 2040, as reported in the IPCC report "Global Warming of 1.5 degrees Celsius". This means that the red line has a value of 0 in 2040 (Figure 6). It is clear that none of the forecasts are consistent with that. It is also evident that our forecasts show great variation in the environmental impact, based on both the type of impact (land use vs. climate change), and modeling approach.

For land use, target scenarios that are based on the assumption of the continuation of intense agricultural intensification imply I<1 in the future, while the STIRPAT-based elasticities calculated imply I>1. The scenarios with vastly increased human land use would be catastrophic from a human biodiversity perspective, given the share of land use that humanity already consumes. We discuss the results in much greater length in Engström and Kolk (2024).

We further explored how changing trajectories of the population would shift environmental impacts as seen through an IPAT lens. Our models can be used to highlight the relevance of addressing environmental concerns through policies aimed at reducing population or affluence, for example. In Table 2 we show the projected impacts on climate and land use based on a 10% variation in population. The values in the table are relative to the environmental impact in 2020. Broadly, we can see that population works as a scalar to environmental impacts, implying that a 10% smaller population means that environmental impacts are reduced by 10%. In some of the approaches below this is an outcome of a complex model; in others, it follows deductively from the assumptions of the modelling approach. Largely, the findings give support to the common-sense, but sometimes disputed idea, which sees population as a linear scalar factor to environmental challenges. We provide both empirical and theoretical support for this view.

Table 2. Impact I in 2100 compared to in 2020, showing ranges (and middle-of-the-road values) for ± 10% changes in population and affluence compared to the middle-of-the-road outcomes depicted in Figure 6.

Policy	Dimension	Impact I		
		Approach 1: Extrapolation of historical trends	Approach 2: STIRPAT-derived projections	Approach 3: Forecasts in previous research
P ± 10%	Climate	[0.47-0.58] (0.52)	[2.91-3.65] (3.28)	[0.32-0.39] (0.35)
	Land use	[0.40-0.49] (0.44)	[2.53-3.08] (2.80)	[1.02-1.24] (1.13)

We also related environmental impact to different scenarios for the future global population produced by the UN. We have chosen three UN WPP's (2022) three population prospects scenarios illustrating different population scenarios over the 21st century. The high rates of growth implied by the (maybe not so realistic) constant fertility scenario have very large impacts in all cases, whereas low fertility rates are associated with much smaller I (Table 3). Here we find that the quite dramatic differences in different UN scenarios are associated with very different environmental outcomes. This suggests that population does matter for environmental outcomes.

Table 3. Impact I in 2100 compared to in 2020, assuming the UN WPP's (2022) three population projections: low, medium and constant fertility; all other models in this paper are based on the WPP's (2022) medium scenario.

Dimension	Impact *I* in 2100 relative to 2020 for different population prospects		
	Approach 1: Extrapolation of historical trends	Approach 2: STIRPAT-derived projections	Approach 3: Forecasts in previous research
Climate	0.35 (low) 0.52 (medium) 0.97 (constant fertility)	2.12 (low) 3.28 (medium) 6.56 (constant fertility)	0.24 (low) 0.35 (medium) 0.66 (constant fertility)
Land use	0.30 (low) 0.44 (medium) 0.82 (constant fertility)	1.91 (low) 2.80 (medium) 5.17 (constant fertility)	0.76 (low) 1.13 (medium) 2.09 (constant fertility)

Calculating a maximum viable population size, given that we do not want to exceed current environmental emissions

For this final report, we have developed a new set of modeling forecasts, which were developed on the basis of the models developed in Engström and Kolk (2024). We use the same six different forecasting approaches as described in that study. Here our goal is different: we consider the models shown in Figure 6, and explore the implications if we would hold I constant over time at I = 1. In other words, we accept that environmental impact levels in 2020 are reasonable, and calculate that population size in 2100 that is consistent with this scenario. The results on maximum population size are shown in Table 4, and the values are derived from Engström and Kolk (2024).

It is important to note that we find this an unacceptable outcome for climate change. Such a trend for greenhouse gas emissions is consistent with some of the worst future scenarios in the Shared Socioeconomic Pathways framework that is associated with global warming of roughly four degrees Celsius. Still, it represents a good thought exercise as it illustrates the implications of continuing business-as-usual. For human land use, assessing whether a constant I = 1 is an acceptable or a harmful outcome is more complicated. In this case, it can be argued that a constant human land use is a reasonable benchmark that we should not surpass in the future. Thus, the values of the maximum population sizes that we calculate in this case are in a sense easier to appraise.

For climate impact (where it is important to note it is related to scenarios with very dramatic warming), the maximum possible population in 2100 varies from 3.6 billion (Approach 2) to 28.6 billion (Approach 3), given that we accept to keep impact constant, with the same GHG emissions in 2100 as in 2020. They show a great variation across the different modelling approaches. We note that with the STIRPAT method (approach 2) is perhaps the model with the most acceptability in the scientific literature. Given this approach, we find that even with constant emissions, the maximum global population size is substantially lower than the current one.

Table 4. Find maximum possible population P in 2100, given the assumption that we keep environmental impact, I, constant (2020-values in 2100), while A and T vary.

CLIMATE

Approach 1: Historical	**Approach 2: STIRPAT***	**Approach 3: Forecasts**
T = 0.09		T = 0.06
A = 4.54	A = 4.54	A = 4.54
Max possible P = 1/(T*A) = **2.45**	$P = (1/A^{c})^{(1/b)} = (1/4.54^{0.58})^{(1/1.12)} = \mathbf{0.46}$	P = 1/(T*A) = **3.67**
Max population in 2100	Max population in 2100	Max population in 2100
19.1 billion	3.6 billion	28.6 billion

LAND USE

Approach 1: Historical	**Approach 2: STIRPAT**	**Approach 3: Forecasts**
T = 0.07		T = 0.19
A = 4.54	A = 4.54	A = 4.54
Max possible P = 1/(T*A) **= 3.15**	$P = (1/A^{c})^{(1/b)} = (1/4.54^{0.5})^{(1/0.99)} = \mathbf{0.47}$	P = 1/(T*A) = **P = 1.16**
Max population in 2100	Max population in 2100	Max population in 2100
24.6 billion	3.7 billion	9.0 billion

When assessing land use, where the assumption is arguably of higher relevance, we also find a great variation in the maximum possible population size. In this case, the maximum possible population in 2100 varies from 3.7 billion (Approach 2) to 3.15 24.6 billion (Approach 1), given that we accept to keep impacts constant, with the same human land use in 2100 as in 2020. This shows that different reasonable forecasts of future land use give very different predications of what is a maximally acceptable population over time.

Generally, our results are consistent with previous research aiming to calculating a maximum viable population size such as those of Cohen (1996). He gave a multifaceted answer to the question, "How many people can the earth support?", which depended on the tradeoffs that we accept to make, and the assumptions of what an acceptable life is. In the final section, we summarize the results from the results in Engström and Kolk (2024), and our new calculations.

Conclusion

Below, we give a summary and conclusion of the part of the project that used IPAT models to answer the primary research question.

We find that:

1. Consumption and wealth are the largest drivers of many environmental challenges historically.
2. As the impact of population on environmental challenges is often close to one-to-one, population reductions will likely affect many environmental problems pro-

portionally, rather than substantially less or more. There are both empirical and theoretical reasons to see population as a scalar to environmental impacts.

3. Green growth – the idea that we can become richer without damaging the environment more – is possible and likely in the sense of *relative* decoupling, in which declining T is combined with increasing A; in contrast, it is much more challenging to achieve *absolute* decoupling, involving decreasing I over time, which implies very small values for T in long-term scenarios in which P×A is expected to increase considerably.
4. Some environmental challenges, such as achieving zero-emissions energy production, or radical decreases in the climate impact per unit of consumption, seem more feasible than others, such as radically changing land use and halting conversions of forests to farmland. Land use is driven by agricultural practices and forestry.
5. Even though large-scale technological transformation is viewed as plausible by the scientific community (e.g., the IPCC), such scenarios assume dramatic reductions in environmental impacts per unit of consumption (T).
6. When we calculate maximum viable population size, consistent with maintaining the same kind of adverse human environmental impact constant from 2020 to 2100, we find great variation in what is maximum population size 2100. The range goes from less than 4 billion to over 20 billion based on different way of forecasting technological change, and environmental challenge.
7. Models based on STIRPAT models, the dominant model in the field of industrial ecology and ecological economics, suggests a maximum human population size of less than 4 billion people.

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6. Paths to Sustainable Food in 2100: How Far Can Technology Take Us?

Karim Jebari, Emma Engström

Food production and the planetary boundaries

The Earth system is severely stressed, humanity having overstepped a safe operating space in several of the environmental boundaries stipulated by the *Planetary Boundaries* framework (Rockström et al., 2009; Steffen et al., 2015). This has increased the risk for abrupt and irreversible changes and a destabilization of the Earth system.

Population growth is a key factor in this trend, given that the demand for agricultural products is relatively uniform across the global population. This is pertinent in comparison to green house gas (GHG) emissions, where the difference in demand between the lowest and highest income deciles of the global population is much larger, which indicates that a given increase in the global population is likely to generate a larger increase in the demand for agricultural products than for fossil fuels. Fields (2005) reported that an American generates about 16 times more GHG emissions than an African. In contrast, the average per capita supply of food per day in 2019 was relatively similar in North America and Africa, with 3,8 kcal in the former vs. 2,6 kcal in the latter (FAO 2020). Moreover, the rise in per capita consumption of calories in low-income regions is higher than in high-income regions, which suggests a converging trend globally (FAO 2020). It is anticipated that these trends will go on in the future. In 2100, more food will have to be produced on a smaller total area than is currently used.

Several critical boundaries are linked to agriculture in general and the production of food in particular. This sector is the main driver of the growing imbalance in biogeochemical flows, as the application of nitrogen, industrial potassium and phosphate fertilizers are key drivers of the increased agricultural yields that have taken place in the last century (Fischer-Kowalski et al., 2014). Vitousek et al. (1997) found that annual total nitrogen fixation has been doubled by human activity. Smil et al. (2004) argued that, by fixating atmospheric nitrogen, the Haber-Bosch process enabled the global population growth, from less than two billion in 1900 to six billion in 2000 and eight billion today. This process has fundamentally altered numerous natural habitats, as nitrogen, prior to the industrial fixation, was a crucial element governing the operation of many ecosystems. Moreover, large concentrations of domestic animals in industrial farms produces large amounts of manure that has become a serious contributor to eutrophication, as nearby agricultural land becomes overloaded with manure, causing runoff into streams (Won et al., 2017).

Nitrogen and phosphate runoff causes hypoxia in lakes, rivers, estuaries, and coastal waters and reduces biodiversity in aquatic ecosystems and low-nitrogen soils. In a comprehensive meta-analysis, Poore & Nemecek (2018) estimated that food production is responsible for approximately 78% of global eutrophication.

Food production is also contributing to climate change. Poore & Nemecek (2018) reported that the food supply chain is responsible for about 26% of anthropogenic GHG emissions globally. Most of the climate impact from food production (6.8 t CO2e/household-year) is from non-CO2 GHG (56%) (Weber & Matthews, 2008). The most important types of emissions are methane (CH4) and nitrous oxide (N2O) from livestock and crop production that derive from ruminant digestion and the application of manure on pastures (Food and Agriculture Organization (FAO) (2020)). The Haber-Bosch process requires the use of methane gas and high inputs of energy to produce fertilizers. Fossil fuels are used for industrial machinery for irrigation, application of fertilizers and pesticides (Fischer-Kowalski et al., 2014; Smil et al., 2004). Bardi & Alvarez Pereira (2022) described agriculture as "a system that transforms fossil energy into food" (p. 35).

Moreover, food production is the most important sector driving land use change, which, in turn, is the main driver behind biodiversity loss (Kok et al., 2018). Biotopes are transformed into agricultural land, which accounts for about 43% of the Earth's ice- and desert-free land. Of this, a vast majority (roughly 87%) is used for food production (Poore & Nemecek, 2018). A recent Chatham House report concluded that food production is the primary factor causing habitat loss, as natural ecosystems are converted to areas for crop production or pasture (Benton et al., 2021). Agriculture is a threat to a vast majority of the species at the risk of extinction (86%) (Benton et al., 2021). Preventing the conversion of forests and wetlands to farmland is thus of fundamental importance for both land-system change and biosphere integrity (Garnett, 2014).

Food security is another reason for concern (Garnett, 2014; Godfray et al., 2010; van Vuuren et al., 2015), considering that more than two billion people experience micronutrient deficiencies, and 795 million suffer from hunger (FAO, 2017). This challenge is anticipated to increase in urgency considering that the World's population is predicted to reach 9.7 billion by 2050 and 10.4 billion by 2100, according to the most recent estimates by the UN Department of Economic and Social Affairs (DESA) (2022). FAO (2017) has estimated that 653 million people will remain undernourished without efforts to promote pro-poor development in 2030. The organization has calculated that around 50% more food will have to be produced by 2050 than in 2012 (FAO, 2017). Another study found that the demand for grains, including maize, wheat and rice, could increase by 70% by then (Donovan, 2020). Adding to this challenge, it has been estimated that one-fourth of current farmland is highly degraded (De Clercq et al., 2018).

Can technology solve these problems?

In Jebari and Engström (manuscript), the authors reviewed emerging technologies that could have the potential to address these challenges associated with population growth. The review resulted in a list of technologies with potential to contribute to sustainable food production in 2100. With a basis in this list, they identified three technologies with potential for transformative change, one within each food group that we focus on: vertical farming for vegetables and some fruits, C4 photosynthesis for grains, and realistic substitutes for meat and dairy products. These are examined more thoroughly in the following subsections.

Vertical farming

For vegetables and fruits, vertical farming was identified as a technology with large potential to contribute to our target in 2100. Its features and implications are detailed below.

Vertical farming is the practice of growing crops in vertically stacked layers in a controlled environment that has been optimized for plant growth using no-soil techniques such as hydroponics (Van Gerrewey et al., 2021). In hydroponic cultivation, a crop is planted in an inert medium (e.g., gravel) and nutrient-rich water. Since water and nutrients are circulated in the hydroponic system, rather than allowed to evaporate, water use is greatly reduced. It has been estimated that vertical farms can save up to 99% of the water as compared to surface irrigation (Benke & Tomkins, 2017). For example, 2–24 liters of water are needed to produce 1 kg tomatoes in vertical farms, as compared to 60–200 liters in open-field farming in southern Europe (The Economist Intelligence Unit, 2023). This corresponds to a reduction of freshwater use of 93% to 99%.

By stacking layers of crop plantations, vertical farms also substantially reduce the land used for cultivation, which is attractive from the perspective of biodiversity and land system change. Vertical farms could be placed in areas of low value from a biodiversity perspective, such as industrial parks in depopulated towns, unused parking lots or abandoned mines. For some crops, it has been estimated that the yield per acre can increase by 10 to 20 times as compared open-field farming (Jiang, 2023). An especially promising example is lettuce, for which it has been estimated that yields per square meter could be more than 80 times the yield of a traditional farm (Van Gerrewey et al., 2021). The U.S. Agricultural Research Service is investigating the potential of vertical farms for small fruits such as strawberries and tomatoes, and it is also evaluating its potential for larger fruit tree crops, including apple and citrus (Jiang, 2023). It has been argued that basically any crop can be cultivated in this way (Benke & Tomkins, 2017; Despommier, 2010).

In addition, the recirculation of nutrients in the hydroponic system means that eutrophication can be reduced by 70–90% per unit of yield compared to traditional agriculture (Wildeman, 2020). Moreover, since the growing environment is controlled, this type of farming does not require pesticides and herbicides to the same extent as traditional agriculture. The controlled environment also facilitates the prevention of pesticide and herbicide contamination in the natural environment and reduces harm to non-pest insects and aquatic animals.

The reduced need for water compared to traditional agriculture implies that vertical farming is especially attractive in regions where water is scarce and expensive, yet electricity is affordable, for example, regions where desalinated water is used for irrigation (Allegaert, 2020). Additionally, vertical farming may be beneficial for countries with limited arable land to satisfy their population's needs, especially those striving for a level of food self-sufficiency. Vertical farming could also be attractive to regions that depend on costly imports for fresh food.

The main drawback of vertical farming is that it requires artificial light, since only the top layer in a stack of plants can be exposed to the sun. Moreover, vertical farms require a significant amount of electricity for ventilation and cooling per kg of produce (Asseng et al., 2020). The prospects for a reduction of these costs from a twenty-first century perspective is positive. LED lamps have in the last two decades followed a forecast articulated by Roland Haitz (2007) and have become increasingly energy efficient. However, while this trend is likely to continue, the theoretical limit for white LED lamps is 265–300 lumen/watt, so artificial light will never be as cheap as natural sunlight. Increased energy efficiency in cooling is also a necessary condition for vertical farms to be practical. Nonetheless, since there is also a limit for how energy effective cooling can be, this is the only part of the innovation set that is necessary to make this technology viable.

Vertical farming is relatively labor intensive and requires a highly skilled and thus expensive workforce. Vertical farming will not be able to compete with traditional farming for most crops as long as this is the case. Technologies to make the harvesting and tending of crops more efficient are needed to reach price parity for medium-value crops such as legumes and fruits. Here, future developments in robotics could make a significant difference. Improvements in machine vision and robotic manual dexterity would be particularly important. This is an area of research and development that has the potential to make substantial progress over the next few decades. Moreover, improvements in algorithmic evaluation of humidity, temperature, chemical composition of the nutrient solution are also important. Today, many of these systems are monitored and fine-tuned by humans.

In sum, the most important variable to make vertical farming viable and sustainable is cheap and abundant fossil-free electricity and innovation in robotics. The cheaper the electricity, the more crop types would be relevant for vertical farming. This technology essentially trades many negative environmental impacts of traditional agriculture (water use, land use, eutrophication, chemical contamination) for substantively increased electricity needs, mainly for artificial lighting, ventilation, and cooling systems. This means that the total environmental impact of vertical farming will be determined by the energy mix that is being used to generate electricity. In other words, if electricity is supplied by coal, the environmental impact of vertical farming would be largely negative, relative to traditional agriculture.

Moreover, if vertical farms use the energy from diffused renewable energy sources, such as solar photovoltaic (PV) panels or wind turbines, some of the land-use benefits of vertical farms would be negated, depending on where the renewable energy is placed. Since solar PV has about 20% conversion efficiency, using land to produce electricity that is then used to illuminate crops implies a considerable efficiency loss in terms of land use. To produce a certain quantity of crops with artificial light powered by solar PV would require about four to five times more land than growing the same quantity in a traditional field. This can still be worthwhile if mostly marginal or low value land (from a biodiversity and or ecosystem services perspective) is used for renewable installations, such as rooftops, parking lots etc. It should nonetheless be noted that vertical farms powered by solar PV might still be superior to traditional farms with regards to water use, eutrophication, and pesticide/herbicide contamination.

Another potential advantage is that vertical farms could be used to balance energy demands, which will be increasingly important as variable renewable energy becomes a larger fraction of the energy mix, as most crops require light for about 16 hours per day. For example, vertical farms could be used when electricity demand is low or when energy production is high, thus balancing the demand curve in the electricity system. Lastly, vertical farms produce significant amounts of waste heat, which could synergize well with residential areas, if connected to district heating networks. They could also be used in combination with ordinary greenhouses, since these often require heating.

Vertical farming is already used for certain high-value crops, such as lettuce, chili fruits and herbs. However, vertical farming is at the moment not a viable alternative to traditional farming for most crops, as the current wave of bankruptcies in the vertical farming sector suggests (Benke & Tomkins, 2017).

Currently, many of the negative externalities associated with traditional farming are not included in the price of agricultural products. For example, farmers rarely pay market prices for scarce water, or pay any cost for the eutrophication caused by fertilizer or the environmental harm to wild animals and plants caused by pest control agents. Neither is the impact on local biodiversity and land use change included in the price of food. If such costs were internalized (i.e., with an environmental tax), solutions such as vertical farming might become much more attractive, especially in water and land scarce regions with access to cheap energy.

We assess that there is significant potential to develop the right technology mix that would allow more crop types to be used in vertical farming over the next decades. As the main bottleneck for this technology is related to the amount of light that can be used for photosynthesis, the potential for vertical farming is related to the dry weight of crops. As a general rule, the larger the fraction of a crop that is non-water, the more light is needed to produce a certain amount of that crop. Thus, it is, in our view, very unlikely that vertical farming could replace all crops before 2100, as it is simply not likely to be an economically viable alternative for cereals. However, we believe that it could replace most non-tree and non-cereal crops such as pulses, fruits, vegetables, herbs, root and tubers, etc. If vertical farming could be used for this wide array of crops, it would be a highly disruptive innovation. These crops comprise about 16% of the currently cultivated land area and replacing them would be a major step in bringing back humanity to a "safe operating space".[5] Moreover, as the world's population becomes more affluent, the demand for these crops is likely to increase, since these crops are more expensive per calorie than most cereals.

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[5] http://www.fao.org/faostat/en/#data/

C4 photosynthesis for cereals

Cereal crops, such as wheat, rice, barley, and maize are the backbone of global food production, and cover currently about 740 million hectares for rice and wheat, as well as 353 million hectares for coarse grains such as barley, corn, and oats (Hannah Ritchie & Rosado, 2023). Any technology that improves the yield per hectare of these crops could thus have a significant impact on global land use (Leegood, 2013). In the food group that includes grains, we identified C4 photosynthesis as a technology with large potential to contribute to meet environmental targets.

Genetically modified crops have rapidly proliferated in the last two decades, and have, despite political opposition in some countries, been a considerable commercial, environmental and public health success, mostly in low and middle-income countries (Smyth, 2020). However, the full potential of agricultural biotechnology remains unfulfilled, and it could radically transform productivity and yields for cereal crops. One of the techniques with this potential involves improving the photosynthesis of plants.

Photosynthesis is the process by which crops convert light energy into chemical energy. This process involves converting carbon dioxide (CO2) to sugars through the process of carbon fixation. There are two main types of carbon fixation in common agricultural crops, C3 and C4. C4 carbon fixation plants are superior at capturing energy from the sun, especially in sunnier climates. C4 plants have also generally higher efficiency in water and nitrogen use (Osborne & Sack, 2012). Carbon fixation relies on an enzyme known as RuBisCO, which "catches" CO2 molecules, which are needed for photosynthesis, from the air. However, RuBisCO is not very good at this task in a low CO2 environment such as ours, and consequently it sometimes catches O2 (oxygen) molecules by mistake. O2 is a very reactive molecule and is harmful for the plant, which means that C3 plants need to spend much energy on containing and expelling oxygen. By contrast, C4 plants create an intermediary mechanism that provides the RuBisCO enzyme with a CO2 rich environment, where it is less likely to catch O2 by mistake.

While most cereal grains, including rice, wheat, barley, and oats use C3 carbon fixation, some of the most productive crops, such as maize, sugar, and sorghum, are C4 plants. There is ongoing research to produce rice that can use C4 photosynthesis, which is an innovation that could increase yields, reduce nitrogen runoff, and reduce water needs. It has been estimated that the radiation use efficiency is 50% higher for C4 crops than C3 crops (Kajala et al., 2011; Wang et al., 2012). C4 rice could double the yield per hectare as compared to C3 rice, according to Ermakova et al. (2020, 2021).

Moreover, genes that could be used for creating C4 wheat have recently been identified, opening up the possibility of creating a strain of wheat and other cereal plants with much higher yield (Rangan et al., 2016). This area of research is still in the laboratory stage but has a significant potential to radically increase the amount of wheat per hectare.

Since the C4 mechanism is metabolically expensive for the plant to sustain, it has the greatest potential to increase yields in regions with abundant sunlight, for example the lands in the Ganges, Indus, and Mekong River valleys. As a rule, C4 plants can be deployed in regions where their C3 counterparts are. Moreover, since C4 plants are better at retaining water, they are more resistant to conditions of drought and high temperatures. The largest potential for C4 crops is in tropical and subtropical regions. Today these include some of the most productive agricultural regions in the world. Even if C4 variants were limited to these regions, and even if it would be limited to rice, it could make a very large contribution to increased yields per hectare. However, we find it likely that C4 carbon fixation can be expanded to cover most of the cereals over the coming decades, making a major contribution to increasing yields.

Realistic substitutes for animal products

In the third food group, protein foods from animals, we see that alternatives from non-animal sources are needed to meet global demand and environmental targets. However, this will only be feasible if the alternative products achieve a sufficient degree of similarity with regards to taste and consistency as animal products.

Domestic animals play an important role in food production (e.g., meat, dairy products, eggs, etc.). However, producing food through animal rearing is in many cases inefficient in terms of environmental impact per unit of calories. This is especially true for beef cattle, as every calorie of meat from cattle requires on average 326 m^2 of land to produce (Poore & Nemecek, 2018). As a rule, the larger the animal, the more energy is required as an input for a given amount of food calories from its meat. While some domestic animals eat food that cannot be consumed by humans (grass, for example), and *some* of that food grows on land that could not be used to grow food for human consumption. However, in modern agriculture, most livestock that are reared for human consumption are fed significant quantities of human-type foods such as soybeans, corn, or wheat.

Consequently, producing agricultural goods in this way is a major contributor to human land-use change and destruction of wild habitats, both for grazing and for the cultivation of crops to feed animals. Domesticated animals in agriculture also have a significant negative contribution to other concerns discussed in the planetary boundaries' framework, such as eutrophication, water use, and GHG emissions (Henry et al., 2019; Xu et al., 2021). The eutrophication problem is very difficult to avoid, as it is a consequence of concentrating a large number of animals in a limited space and feeding them a nutrient-rich diet. The resulting manure is heavy and costly to transport over long distances, often leading to overuse in nearby fields, leading to significant leakage. Thus, reducing the number of domestic animals in food production is a necessary requirement for reaching a safe operating space for humanity with respect to the boundaries of land use change, ecosystem integrity, biogeochemical flows, and climate change. This implies reducing the amount of animal products in our diets, especially from ruminants (mostly cattle and sheep), since these contribute disproportionally to these problems. Unfortunately, current trends are not favorable (Parlasca & Qaim, 2022). While the share of vegetarians has increased in high income countries, meat consumption has also increased in almost every country in the last 20 years (Parlasca & Qaim, 2022). The consumption of animal protein is often part of complex cultural, economic, and political systems, as well as social identity. Thus, dietary shifts to reduce overconsumption are unlikely to happen quickly (Rust et al., 2020; Valli et al., 2019). While a tax on the negative externalities of animal products could reduce demand, such pricing would also be rather unpopular. Carbon taxes are an instructive example of the political costs of taxing products that are in high demand. As many people feel that eating meat is a morally acceptable, and even culturally valuable, activity, taxes that penalize meat-eating are often seen as assaults on certain lifestyles and cultural traditions. This makes the political economy of taxes on animal products even more vexed than that of some other goods with negative externalities.

This positions broadly acceptable substitutes for animal products as potentially disruptive technologies. For example, while each liter of dairy milk requires about 9 m^2 of land, a liter of oat milk requires about 0.8 m^2 of land. Dairy milk consumes 630 liters of fresh water and produces 10 grams of runoff for each liter, while the equivalent number for oat milk is 48 liters and 1.6 grams respectively (Poore & Nemecek, 2018). In the dairy-substitute market, several wheat, soy and almond based products are already available at prices that are somewhat more expensive than traditional milk. More importantly, over the last decade, these products have also seen improvements in taste and texture; for example, milk substitute products designed for coffee drinkers no longer curdle at high temperatures (Brown et al., 2019).

An even more disruptive possibility involves creating protein rich food not from plants or fungi, but from hydrogen-metabolizing bacteria. While using bacteria to produce or alter food is as old as the agricultural revolution, (e.g., yoghurt) novel experimental developments offer the prospect of creating food without the use of plants. Rather than using plant-based sugar as the energy source (such as in the production of Quorn), some companies have adopted a type of bacteria with an unusual metabolic process: oxidizing hydrogen. Since hydrogen can extracted be from water with electricity, (and/or heat) these bacteria enable the production of food without the otherwise inefficient process of photosynthesis (the most effective plants convert about 4% of light energy to biomass energy). By not requiring plant-based products to produce food, this method could not only outmatch animal-based protein, but also plant based protein in terms of land use efficiency. Even when using solar PV (one of the least effective methods of producing electricity in Finland in terms of land use) the Finnish company Solar Foods maintains that their method, that uses the bacterium *Xanthobacter* VTT-E-193585, can produce proteins with only 10% of the land required to produce an equivalent amount with soybeans. This technology is still experimental, and it has yet to prove that it can be scaled up.[6] However, even if it was an order of magnitude less efficient than claimed, it would constitute a significant achievement.

Prima facie, using bacteria to create proteins is far more viable than using animal cell cultures to produce meat for human consumption, as some companies hope to do. An animal muscle cell divides every 24 hours, while a bacterium typically divides every 20 minutes. A typical bacterium, such as E. coli, can under optimal conditions produce about 10^72 bacteria in 24 hours, while the number of muscle cells will only be 2–4. The stark differences in reproductive rate between bacteria and muscle cells mean that the requirements for keeping cell cultures free from contaminants are daunting, as a single microbe can quickly destroy an entire batch of cells. Moreover, animal muscle cells are adapted for growing inside bodies, protected by skin and the immune system, and fed by blood vessels, adding to the relative complexity and cost of cultured meat relative to bacteria-based alternatives for producing protein.

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[6] https://solarfoods.com/news/

Substitutes for animal foods based on plants, fungi or bacteria face some obstacles to gain widespread use. First, financial incentives in high-income countries favor traditional means of producing animal-based foods. For example, the EU subsidizes cattle rearing with about 30 billion €, an estimate that amounts to up to 20% of the EU budget (Greenpeace European Unit, 2019). Second, to reduce prices, the manufacturing of plant-based products needs to attain much larger scales, something which has yet to be. Third, there is still need for significant investment in research and development for this technology to better mimic the taste and texture of animal food.

These products could, if producers of animal food were forced to internalize the cost of their negative environmental externalities, displace some animal products, most notably dairy milk, in the next decade. Plant-based substitutes for other dairy products (e.g., cheese, yoghurt) have also entered the market and could also win a significant market share if provided with a favorable legal environment and financial incentives.

Thus, this is a technology sector that is able to benefit from market-based incentives and regulatory support. For example, the EU should facilitate the approval of novel food technologies that use genetically modified organisms.

Plant-based products are in some respects superior to their animal-based alternatives but are often perceived to be inferior in terms of taste and quality. These trade-offs can over time be addressed by further research and development in this sector but may not ultimately be eliminated. A more widespread adoption of plant-based alternatives could also be a concern for organic farming, that often depends on manure for fertilizer.

Plant-based products are also more resilient to conditions of drought and natural disasters, as for example oat grains are easy to transport and store in comparison to milk and other dairy products. Plant-based products would be even more affordable if prices of staple crops were reduced, as the bioengineering techniques described above could bring about.

While previous generations of plant-based substitutes for animal food products were acceptable to some consumers, they did not taste like “the real thing” and did little to attract people who enjoyed the taste of animal-based food. In the last decade, there has been significant innovation in this space, and novel plant-based substitutes for animal products have entered the market. These novel products aim, to a greater extent than previous generations, to mimic the flavor and texture of the original, and thus have the potential to disrupt the traditional animal food market. Products include Beyond burger and Impossible food (minced beef), and products that mimic tuna (BettaF!sh), caviar (CaviArt), chicken (Tindle) etc. The common denominator of these products is that they are not primarily aimed at the vegetarian/vegan consumer segment, but at the animal-consuming mainstream market. These products are already (to some extent) commercially viable and could, on a level playing field, become truly disruptive. This is an area where both venture funds and philanthropic capital have made major investments, and we are likely to see major improvements over the next decades. Plant (or fungi) based animal products could conceivably replace a significant fraction of animal-based products well before 2050.

If everyone adopted a vegan diet, the amount of land used for producing the curren- number of calories could be reduced by 75%.[7] This reduction is almost entirely due to

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[7] https://www.economist.com/graphic-detail/2022/01/28/if-everyone-were-vegan-only-a-quarter-of-current-farmland-would-be-needed

beef, dairy and mutton. A global diet that would only remove these food categories, but retain all other animal food products, would lead to a comparable reduction in the needed land. A hypothetical scenario where humanity would forgo these sources of food would imply that global goals for land use and likely biodiversity could be reached.

Consequently, in our estimate, no pathway to achieving the desired outcomes with regards to land use change, biodiversity and eutrophication is possible without making drastic reductions in the world's consumption of beef, mutton, and dairy. However, the necessity of the degree of this transformation depends in part on other technologies. For example, major improvements in the productivity of rice cultivation would allow for a less drastic reduction of consumption of these foods.

It's also important to note that, on current projections, the world's population will increase by at least 25% (from 8 to 10–11 billion), and that the expected economic growth this century will lead to an increase in the caloric intake per capita, mostly among low-income populations (Parlasca & Qaim, 2022). Meanwhile, some of the best land for agricultural use has been or is likely to be degraded by climate change, either by desertification, flooding, salinization or by making daytime temperatures too hot to work in (UNCCD, 2022). According to the UNCCD's Global Land Outlook 2 Report, 40% of the world's land is classed as degraded (UNCCD, 2022). So, while forgoing animal products from ruminant livestock would make a significant and necessary contribution to land use change, it is not evident that it would be *sufficient* to reach the desired outcome in this back-casting exercise, given the expected increase in population, consumption of calories per capita and the ongoing and future degradation of productive agricultural land. Nevertheless, no single intervention is likely to be as effective as replacing animals in reducing the problems of eutrophication, land-use change and biodiversity as reducing the amount of food produced by sheep and cattle.

However, there are considerable adoption challenges for non-animal alternatives to meat and dairy products. Meat and dairy are integral parts of many human cultures, and people seem to be more unwilling to change food consumption habits relative to other human habits. Moreover, meat is in many contexts a symbol of wealth and affluence, and therefore highly desired. This is why we believe that only when non-animal alternatives are sufficiently similar will there be a significant shift in behavior. But similarity in the experience does not guarantee universal adoption. Consider the resistance of EU consumers against genetically modified and irradiated food, even when this food does not differ in taste or appearance (Castell-Perez & Moreira, 2021). As such, non-animal alternatives will likely need to be promoted in various ways, even when competitive in terms of price and indistinguishable in taste. Such political promotion could in some countries become a controversial political issue, especially as farmers sometimes have disproportional political influence.

Quantitative assessment of the potential of technology adoption

We have quantified the potential of the three identified technologies to reduce environmental impacts in 2100 as compared to current levels. The analysis is based on the assumption of ubiquitous adoption of the three proposed technologies. The projected impacts in 2100 should not be interpreted as precise predictions, but rather as rough global estimates of the capabilities of the three technologies across environmental domains. We consider the current global daily consumption of different food products (2009-2011 average), and the corresponding environmental impacts as per Poore & Nemecek (2018). The three food groups (fruits and vegetables, grains, and animal products), make up 83% of the total retail weight in an average global diet as listed in Poore & Nemecek (2018): Table S14. For comparison, we also calculate the environmental impact of all other foods (denoted "other"), which we assume will be produced similarly as currently.

A premise for all our 2100 projections is that fossil-free energy will be readily available by then. This is grounded in The Paris Agreement, which calls for keeping global warning to no more than 1.5°C, and this legally binding agreement has been signed by 196 parties who have pledged to take actions involving financing, technology, and capacity. To reach this climate goal, the energy sector is central, because the consumption and production of energy measure up to 86% of global carbon emissions (UNEP, 2023). Stabilizing the concentration of GHG in the atmosphere is thus premised upon a drastic increase in carbon-free power (Jean-Baptiste & Ducroux, 2003). As reported by UNEP (2023), 97 parties representing 81% of global GHG emissions have adopted net-zero promises, and 37% of global emissions are covered by 2050 net-zero targets. In view of these global pledges, it is reasonable to assume that abundant access to clean energy in 2100 is plausible. Nevertheless, we recognize that this is a considerable assumption and that huge global efforts are needed to reach this climate goal.

If these three proposed technologies are widely adopted, and carbon-free energy is available, we project that food production will be climate neutral by 2100 (Figure 7). Most importantly, this would obliterate climate impact from animal products, which account for more than half of the current GHG emissions from food.

Moreover, we estimate that total annual land use impacts from food would decrease by 62% until 2100, from 5.61 m^2 multiplied by years occupied (current level) to 2.16 m^{2*}years in 2100 (Figure 8). Most of this reduction can be attributed to substitutes for animal products, which would imply that impact would decrease by three-fourths, from current levels of 3.58 m^{2*}years to 0.86 m^{2*}years in 2100.

Further, we find that total annual eutrophying emissions could decrease by 61%, from 17.53 g phosphate equivalents (PO_4^{3-}eq, current level) to 6.86 g PO_4^{3-}eq in 2100 (Figure 9). Again, substitutes for animal products account for the largest share of this reduction, since the adoption of this technology would imply a decrease in eutrophying emissions by 90%, from current levels of 9.82 g PO_4^{3-}eq per person per year to 1.0 PO_4^{3-}eq in 2100.

Lastly, we calculate that freshwater use could decline by 50%, from 488.9 l (current level) to 229.1 l in 2100 (Figure 10). Following the other investigated environmental dimensions, the largest share of the reduction relates to substitutes for animal products. The decrease is also massive for vertical farming, as freshwater use is reduced by 95% in this projection. Note that an unusually large share of current impacts can be attributed to grains, mainly rice production, which demands 1,575 liters per person per day (Poore & Nemecek 2018).

Recall that the presented projections (Figure 7–10) are per capita, and that our pre-defined end-goal was a 50% increase in food production to eliminate hunger and allow

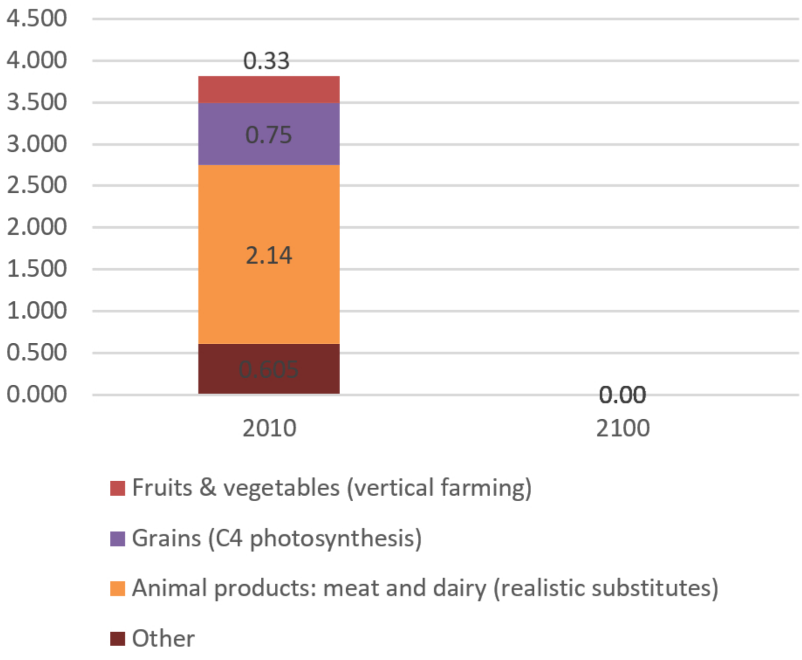

Figure 7. Estimated climate impacts from global average daily food consumption in 2010 and projections for 2100.

The 2010 assessment is based on Poore & Nemecek (2018).

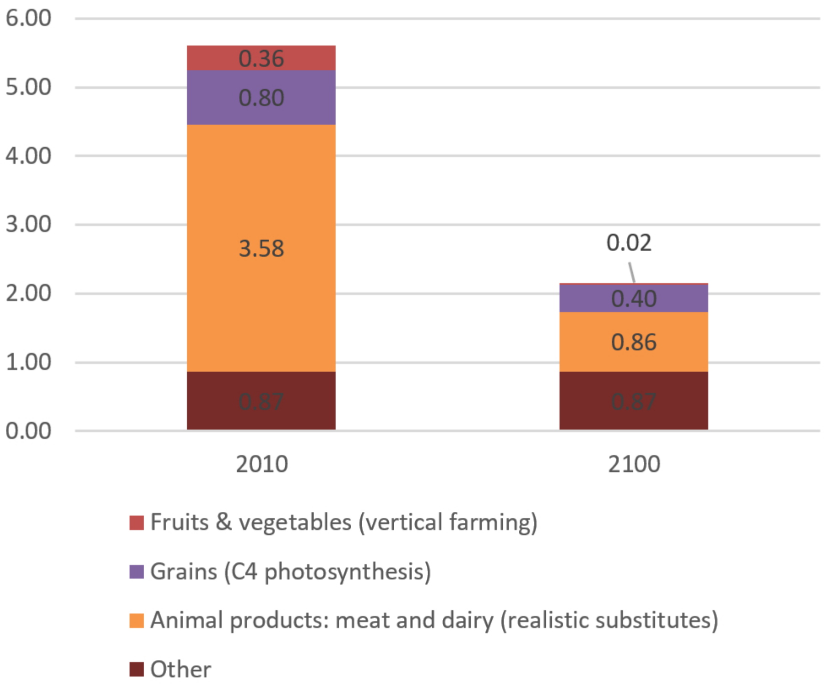

Figure 8. Estimated land use impacts (m^2 multiplied by years occupied) from global average daily food consumption in 2010 and projections for 2100.

The 2010 assessment is based on Poore & Nemecek (2018).

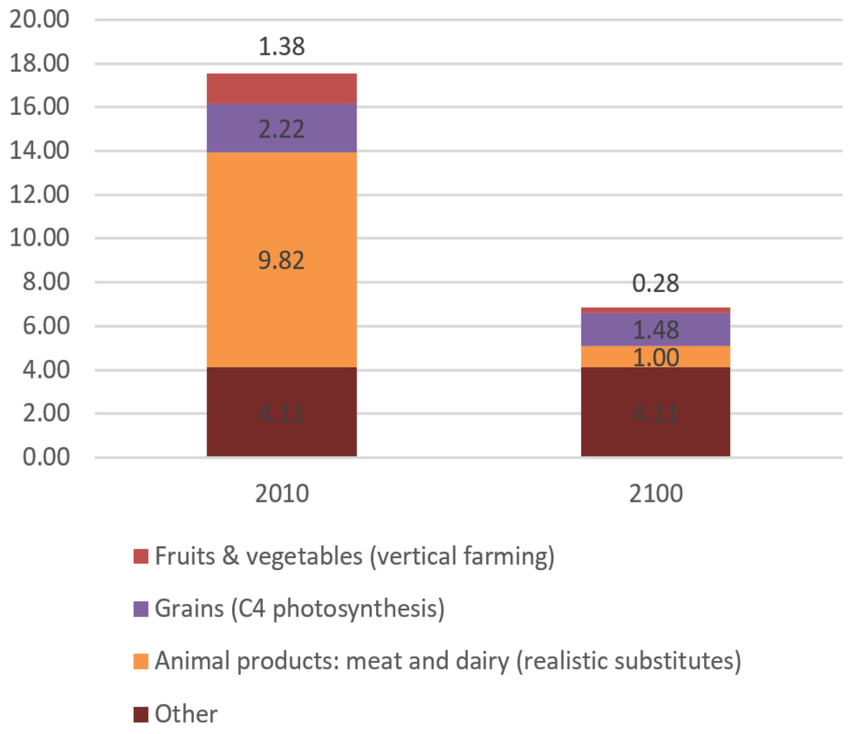

Figure 9. Eutrophying emissions (g PO_4^{3-}eq/g) from global average daily food consumption in 2010 and projections for 2100.
The 2010 data are based on Poore & Nemecek (2018).

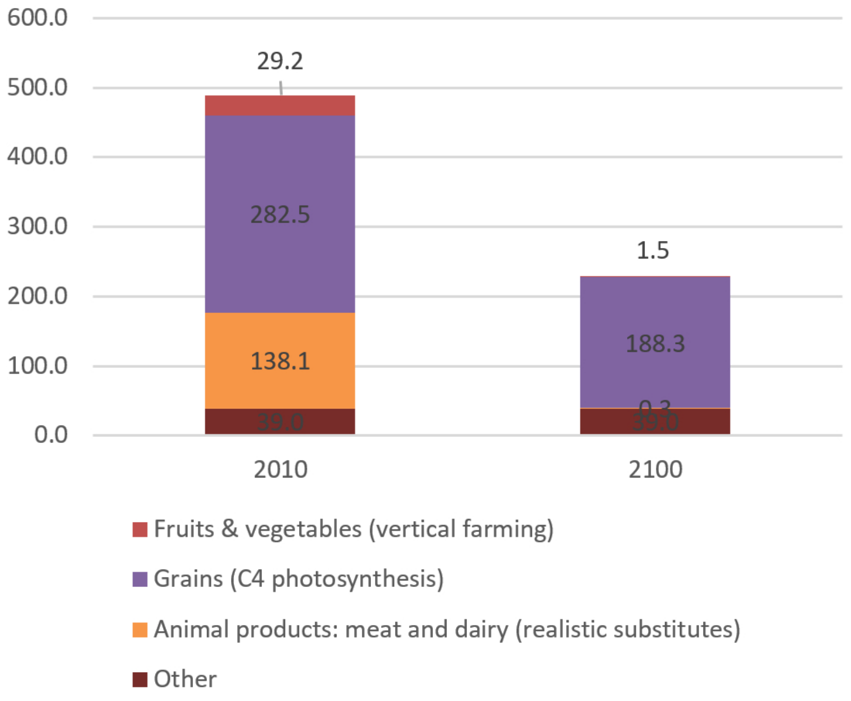

Figure 10. Freshwater use (liters) from global average daily food consumption in 2010 and projections for 2100.
The 2010 data are based on Poore & Nemecek (2018), and the 2100 projections are grounded the assumptions listed in Appendix C of the full working paper.

for a larger global population in 2100; thus, we also need to consider the environmental impacts if 50% more food would be produced. Multiplying all the estimated impacts in 2100 with 1.5 would generate estimates of land use impacts of 3.23 m^{2}*year (58% of current levels), eutrophying emissions of 10.30 (g PO_4^{3-}eq) (59% of current levels), and freshwater use of 344 l (70% of current levels). This shows that impacts across these three domains would decrease – even under substantially increased food production – if the three proposed technologies were massively adopted.

Discussion

We have focused on technologies that involve a change in how food is produced and that require only limited changes in consumer behavior. By concretely discussing the performance of specific technologies in relation to sustainability goals, we can conceptually assess the feasibility of the supply-focused solution to food security, in comparison to the other two conceptually different pathways discussed by the global community, which focuses on changes in demand and the food system as a whole, respectively (Garnett, 2014; van Vuuren et al., 2015). An in-depth assessment of the technology-focused pathway is an instructive exercise because it allows us to articulate the challenges and trade-offs that this approach entails.

By forcing the analysis towards technological solutions rather than reducing demand or systems change, we have aimed to identify and concretize the implications of this pathway. In a way, this allows us to find the minimum required behavioral change and systems change required to achieve sustainable food production. We have looked to find only technological solutions, with minimal behavioral impacts, but even those that we find demand *some* behavioral changes and systems changes.

However, considering the severe environmental challenges facing the agricultural sector ahead, we do not see that adoption of such technologies can take place without *some* element of social change and systems change. In particular, one of our proposed technologies, realistic alternatives to animal-based food products, involves some change in consumer behavior. The assumption here is that these alternatives will taste *almost* like meat from animals. This is supported by current trends, as the taste of plant-based dairy and meat have converged towards conventional animal products. Note also that almost all disruptive technological innovation requires *some* change in consumer behavior, so this is not unique for the solutions we have suggested here.

We have explored a technology-oriented pathway towards food security in 2100, given the assumption that the global population, on average, will not fundamentally change its food habits until then. We consider an end goal in which food supply has increased by 50% as compared to levels in 2020. The technologies that may enable sustainable agriculture in terms of the critical planetary boundaries, i.e., biogeochemical flows, land systems change, and biosphere integrity are feasible. While non-technological solutions may be part of the solution ahead, this study has focused on how much of the transition burden can be placed on adoption of technological innovations. The most important technology in terms of impact are alternatives to animal-based food products that could be accepted by many people.

The main political challenges involve changes in taxation and regulation to make GM crops and non-animal-based food alternatives commercially viable. Two potentially disruptive technologies, bacteria-based proteins, and vertical farms, imply the electrification of agriculture. These technologies require abundant cheap fossil free electricity.

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Befolkningskontroll som ett sätt att hantera klimatkrisen kan vi glömma.

Gustaf Arrhenius

Hur många kan vi vara på jorden?

Henric Karlsson

I projektet Hållbar folkmängd – möjlig levnadsstandard, har forskare på IFFS försökt svara på en av de mest grundläggande frågorna i klimatsammanhang – hur många kan vi vara på jorden? Forskarnas modeller visar vidden av de utmaningar vi står inför, samt vilken betydelse antalet människor egentligen har för frågor om hållbarhet, klimat och planetens gränser. (Denna text publicerades först i Institutet för framtidsstudiers *Verksamhetsrapport 2023*.)

År 1798 publicerade den brittiske ekonomen Thomas Malthus An Essay On the Principle Of Population med den berömda tesen att befolkningsökningen alltid skulle springa ifrån våra möjligheter att producera förnödenheter. Befolkningskontroll var nödvändig för att inte hamna i svält, nöd och misär.

Teknologisk utveckling, inte minst genom ”den gröna revolutionen” och dess innovationer, har sedan 1950-talet fört med sig en enorm expansion av gränserna för jordbruk och markanvändning. Men hur länge till? Nya gränser har under denna tid också blottlagts. Klimatets till exempel. För att hålla uppvärmningen under två grader över förindustriella nivåer får inte mer än ytterligare cirka 1 000 gigaton koldioxid släppas ut. Det är vår återstående så kallade koldioxidbudget som med nuvarande takt är förbrukad om två årtionden. För 1,5 grader är den slut om sex år. I projektet Hållbar folkmängd – möjlig levnadsstandard, har forskare tittat både på klimat och markanvändning. För Malthus var befolkningens storlek nyckeln till att inte överskrida jordens gränser. Hur ser det ut i dag? Befolkning och klimatpåverkan Martin Kolk, docent i demografi och forskare vid Institutet för framtidsstudier (IFFS), förklarar att relationen mellan klimatpåverkan och befolkning är ett till ett.

– Blir befolkningen tio procent större, blir klimatpåverkan också tio procent större. Sambandet är linjärt. I den bemärkelsen betyder befolkningens storlek mycket. Men, den påverkar samtidigt mindre än vår konsumtionsnivå, säger Martin Kolk. På åttio år fram till år 2100 väntas den globala befolkningen växa med ungefär 20 procent, från dagens åtta till ungefär tio miljarder människor. Samtidigt beräknas BNP globalt öka med faktorn 4,5, eller 350 procent, enligt OECD. Relationen mellan klimatpåverkan och BNP är förvisso inte ett till ett som för befolkning, vilket betyder att konsumtionsnivån kan öka utan att klimatpåverkan ökar lika mycket. Detta spelar dock inte så stor roll eftersom den förväntade ökningen av BNP är så mycket större än den förväntade befolkningsökningen.

– Säg att BNP ökar med 350 procent och att det ökar klimatpåverkan med 150 eller 200 procent. Samtidigt har du en befolkningsökning på runt 20 procent, vilket ger 20 procent ökad klimatpåverkan. Den mycket högre takten av den ekonomiska tillväxten gör att den blir relativt mycket viktigare, säger Martin Kolk. Detta understryks också av tidsaspekten i klimatfrågan. Utsläppen av växthusgaser måste ned snabbt, medan befolkningsmängd styrs av tröga processer.

– Tvärtemot vad många tror finns det ingen befolkningspolicy som kan hjälpa oss att hantera klimatkrisen. Detta då det tar mycket lång tid innan sådan får en nämnvärd effekt på populationsstorleken, 50 år och mer, och vi behöver lösa klimatkrisen de närmaste 20–30 åren. Detta beror på vad som kallas ”population momentum”, att befolkningen fortsätter att växa även om fertilitetsnivån föll direkt till ersättningsnivån 2,1 barn per kvinna. Även om man i dag införde en policy där fertilitetsnivån direkt gick över till ersättningsnivån, vilket förstås är omöjligt, skulle befolkningen ändå fortsätta öka till nio miljarder 2060. Att ändra den globala befolkningen är som att vända en oljetanker, det tar mycket lång tid, och befolkningskontroll som ett sätt att hantera klimatkrisen kan vi glömma, säger Gustaf Arrhenius, professor i praktisk filosofi och projektledare för forskningsprojektet.

Vilka är då de andra lösningarna? I många sammanhang är antagandet att de består av ny och mer effektiv teknologi. En uppgift i projektet har varit att bena ut just teknologins roll i de olika vedertagna modellerna som beskriver möjliga framtida scenarion för klimatpåverkan. Forskarna har använt ett ramverk som kallas IPAT som beskriver relationen mellan klimatpåverkan (I=impact), befolkningsstorlek (P=population), välfärd (A=affluence) och teknologi (T=klimatpåverkan per producerad enhet i ekonomin). Genom att tillämpa IPAT-ramverket på till exempel medelscenariot RCP 4.5 som tagits fram av International Panel on Climate Change, IPCC, kan man visa vilka antaganden om teknologisk utveckling som görs.

– Om vi vet klimatpåverkan, befolkningsstorlek och hur mycket ekonomin kommer att växa, kan vi räkna ut teknologins roll. Man kan säga att vi benar ut T, säger Emma Engström, teknologie doktor i miljöteknik. I IPCCs medelscenario växer ekonomin i samma takt som den gjort historiskt med ungefär tre procent per år, vilket ger en 4,5 gånger större ekonomi år 2100. I detta scenario landar den globala temperaturökningen på 2,7 grader över förindustriella nivåer. Långt över två grader och bortom vad IPCC kallar ”farlig” temperaturökning. Men även detta scenario, som alltså missar målet, innehåller ett antagande om en mycket optimistisk teknikutveckling. När man lägger IPAT-ramverket över IPCCs scenario blir resultatet att teknologi måste effektivisera ekonomin till den punkt att klimatpåverkan per producerad enhet år 2100 i det närmaste måste vara noll.

> ” Våra studier gör det tydligt att även IPCCs medelscenario inbegriper en drastisk förbättring av teknologi till 2100. Och det är ändå inte tillräckligt för att nå klimatmålen.
>
> *Emma Engström*

– Våra studier gör det tydligt att även IPCCs ”middle of the road-scenario” inbegriper en drastisk förbättring av teknologi till 2100. Och det är ändå inte tillräckligt för att nå klimatmålen. Vår modell understryker vilken stor tilltro IPCC har till teknologi, säger Emma Engström.

Vilket fog har då IPCC att vara så optimistiska? Blickar man bakåt är det ganska gott. Effektiviteten i ekonomin avseende utsläpp av växthusgaser har ökat med cirka tre procent per år. Och i forskningslitteraturen finns gott om exempel på redan framtagen tek-

”Den mycket högre takten av den ekonomiska tillväxten gör att den blir relativt mycket viktigare än befolkningsökningen.

Martin Kolk

nik som kan öka effektiviteten mycket även framöver. Tekniken finns redan, det är tillämpningen och den politiska viljan som saknas, som IPCC uttrycker det. Definitionen av teknik är också sådan att även politiska innovationer som till exempel koldioxidskatt räknas in. Befolkning och markanvändning För markanvändning, den andra gränsen som forskarna undersökt, verkar däremot teknik inte kunna spela samma stora roll. Två av tre metoder som forskarna analyserat genom IPAT-ramverket visar att mänskligheten behöver öka andelen av jordens mark den brukar fram till 2100. Teknologi kan enligt dessa modeller inte kompensera för ökad befolkning och ökat välstånd. Den tredje metoden visar däremot minskad markanvändning fram till 2100. Den bygger på antagandet att den historiska takten i ökad effektivitet i markanvändningen, kommer att fortsätta i samma takt fram till 2100. Det finns dock starkare skäl att tvivla på en sådan optimistisk hållning i det här fallet.

– Den gröna revolutionen med förädlade grödor, konstbevattning, bekämpningsmedel och gödsel ökade effektiviteten drastisk. Men i forskningslitteraturen finns det betydligt färre exempel på teknik som kan öka effektiviteten framöver så drastiskt som skulle krävas. Jordbruket är också en mer komplicerad sektor med miljontals, kanske miljarder aktörer – bönder – runt om i världen. I klimatfrågan är det ett fåtal stora aktörer i fossilindustrin som driver problemet. Då blir det lättare att se vad lösningen skulle kunna vara, säger Emma Engström. Om hoppet inte kan sättas till teknologin med samma optimism i fallet med markanvändning, återstår modellens P och A: Befolkning och välstånd.

– Dessa dimensioner blir relativt sett viktigare när det kommer till markanvändning. Perspektiv som argumenterar för minskad ekonomisk tillväxt, och åtgärder för att begränsa befolkningsökningen blir mer relevanta här, säger Martin Kolk.

Men på kort sikt är befolkningspolicyer inte heller ett alternativ för markanvändningsdimensionen – av samma anledning som för klimatet: Trögheten. Och om man på lång sikt vill minska befolkningen globalt för att minska markanvändning, finns stora utmaningar med det också.

– I den mån man vill minska befolkningen måste man tänka på både effektiva och etiska sätt att göra det. Något som vi har kommit fram till i projektet är hur viktiga välfärdssystemen är för att förstå barnafödandet. Det handlar om hur stora barnbidragen är, hur föräldraförsäkringen ser ut, barnomsorg och liknande. Vill man ha lägre barnafödande är det sannolikt åtgärder likt lägre barnbidrag som är etiskt försvarbara, särskilt om folket tillsammans fattar beslut om det genom demokratiska processer, inte förbud eller andra mer radikala åtgärder, säger Martin Kolk.

Sambandet familjestorlek och välfärdssystem gäller i hög- och medelinkomstländer, vilket också är de länder där de allra flesta kommer att leva i framöver. Avgörande för befolkningsutvecklingen i världen kommer därför att vara vilken familjepolitik som man inför i till exempel Indien och Indonesien. Vissa resultat i projektet stödjer också antagandet att människor faktiskt är villiga att gå med på detta. Martin Kolk tillsammans med kollegorna Malcolm Fairbrother och Kirsti Jylhä genomförde en enkät där människor bland annat tillfrågades om hur mycket klimat och miljö spelade in i deras egna beslut att skaffa barn, samt om de ansåg att en ökad befolkning var ett problem för klimatet. Överraskande många ansåg detta.

– För det egna personliga beslutet att skaffa barn eller inte spelade inte klimat och miljö så stor roll. Vilket ungefär vad det vi förväntade oss. Men något som förvånade oss var att väldigt många på en generell politisk nivå är oroade över en stor och växande befolkning, och anser att det är rimligt att tänka i termer av begränsad befolkning och barnafödande i frågor om klimat och miljö, säger Martin Kolk. Åtgärder för att minska befolkning har alltså stöd, kanske mer stöd bland allmänheten än vad många politiker inser, tror Martin Kolk. Kanske behövs det dock, i det långa loppet, varken åtgärder eller folkets stöd för att åstadkomma en minskad befolkning. På grund av bland annat ökat ekonomiskt välstånd, högre utbildningsnivå, ökad jämställdhet och reproduktiv frihet, faller barnafödandet redan över hela världen. De flesta prognoser pekar på en framtid där befolkningen kommer att nå en topp någonstans mellan 2060 och 2090, för att sedan stabiliseras, och kanske minska. Många lever redan i länder med barnafödande under två barn per kvinna i snitt, vilket innebär färre människor totalt i det långa loppet. Men återigen, det är på lång sikt. Inget att hoppas på för den som oroar sig för uppvärmning, biologisk mångfald eller utarmade jordar. Befolkningsminskningen kommer i detta hänseende att komma för sent. Och medföra sina egna problem. Något som Dean Spears, ekonom vid Austins universitet i Texas och forskare i projektet, tog upp i en artikel i New York Times i september 2023:

> ”Under de senaste 200 åren har mänsklighetens befolkningsökning gått hand i hand med djupgående framsteg inom levnadsstandard och hälsa: längre liv, friskare barn, bättre utbildning, kortare arbetsveckor och många andra förbättringar. [...] Ekonomer som studerar tillväxt och framsteg anser inte att detta är en tillfällighet. Innovationer och upptäckter görs av människor. I en värld med färre människor kan förlusten av så mycket mänsklig potential hota mänsklighetens fortsatta väg mot bättre liv”.

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