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The return of Malthus? Resource constraints in an era of declining population growth

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ABSTRACT

Will natural resources comprise an important constraint on economic development in the 21st century? We use a macroeconomic model (MAVA) to demonstrate the precise nature of this problem. First, we employ the model to demonstrate that resource constraints do not substantially limit future economic growth under parametric conditions prevailing in the period 1960–2010. Second, we examine the sorts of changed conditions that are unavoidable in the coming century and demonstrate that declining population growth (and the increased dependency rates this implies) is likely to result in increasingly important resource constraints. Ironically, it is the decline in population growth rates—and not the opposite—that may occasion the return of Malthusian constraints.¹

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1. Introduction

Over most of human history, societies lived under the *Malthusian economic system* (Maddison, 2007).² In this regime, technology advanced so slowly that population dynamics determined such a society's real income level through birth and

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² For research on the fundamentals of the Malthusian economy, see Clark (2008) and Sharp et al. (2012).

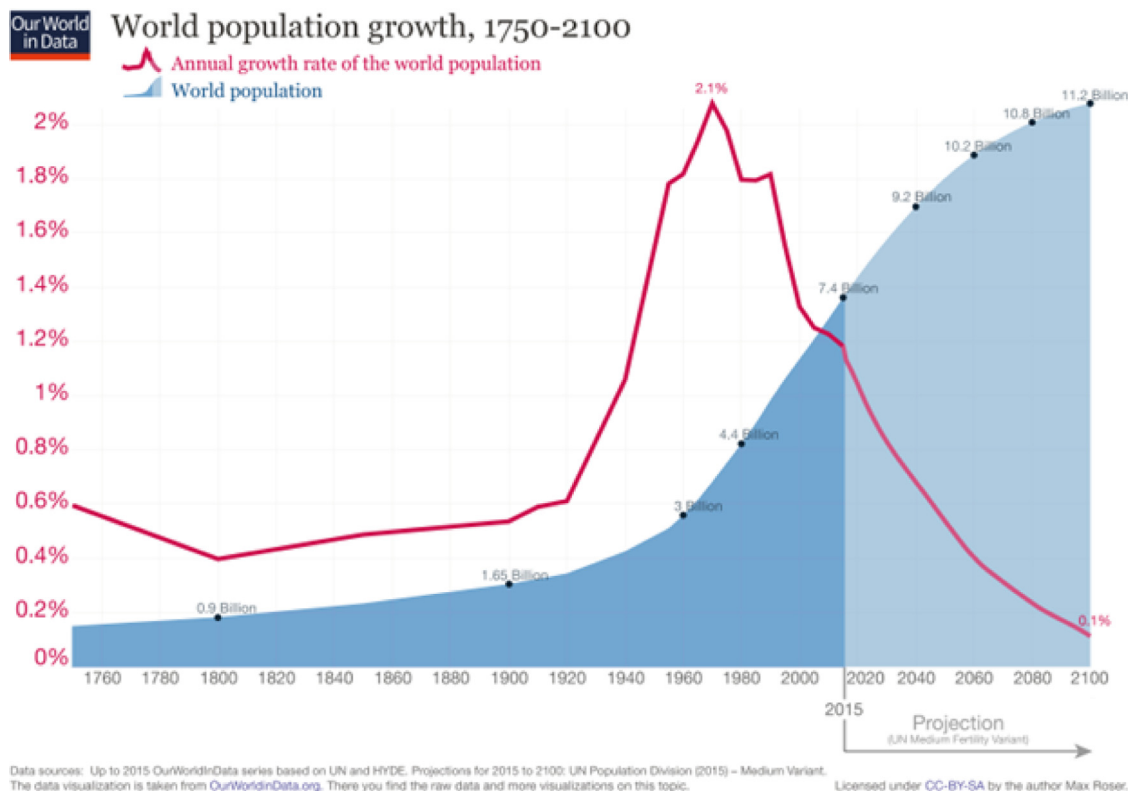


Fig. 1. World Population Growth Source: UN Population Division (2015), HYDE, University of Oxford (OurWorldinData) and our own Projections (from 2015 to 2100).

death rates. Increased population growth would put pressure on natural resources (e.g. land), depressing living standards and raising mortality rates, which would in turn decrease fertility rates. Societies would be constantly constrained by the amount of natural resources available to them.

The industrial revolution liberated human societies from these dynamics (Clark, 2008) and (Clark and Cummins, 2009).³ Beginning about two hundred years ago, technological advancement increased at such a rapid rate that increasing productivity became the real driver of material living conditions. During this period, neither population dynamics nor natural resources were an impediment to economic development—if anything, population growth increased the pace at which human societies developed.

We now appear to be entering a third phase in human history, a period of reduced population growth and increased life expectancy. For the first time, humanity has to provide for a substantial proportion of *dependents*, that is, individuals who do not now, and will not in the future, contribute any labour to the economy. How does this very different demographic structure impact upon the role of resource constraints in the functioning of the future economy?

In this paper, we investigate how the demographic pattern we have observed emerging over the last fifty years or so might impact upon society's capacity to provide for the food supplies required by a population of 12 billion. In what follows we show that the resulting dependency rate might shift society toward a more resource-reliant pathway. Thus the peculiar population dynamics of the present might result in the return of the sort of Malthusian concerns that typified pre-technological societies.

Most analysts agree on the nature of the coming demographic problem. It is one of high levels of population in combination with precipitously declining population growth rates. As Fig. 1 shows, this decline in the overall growth rate in global population is already occurring, with the rate peaking in about 1966 and declining ever since. This process is expected to continue in the face of escalating population levels for the remainder of this century.

Evidence from the historical record does not reveal any clear, deterministic relationship between drastic population changes and consequent resource constraints. There are records of civilisations that have incurred environmental collapse on account of perceived population problems (Brander and Taylor, 1998) and (Taylor, 2009). And there are also apparent success stories from population growth resulting in technological change that enables societies to address problems arising from apparent resource constraints (Boserup, 2017).

³ For research on the break with the Malthusian era, see e.g. Strulik and Weisdorf (2008).

The current demographic problem is that the combination of higher population growth rates before 1960, together with the drastically lower rates that have existed since, imply *dependency rates* that are rapidly increasing from this point onward.⁴ While the level of the population continues to move toward a crest at about 12 billion individuals, the United Nations forecasts that the dependency rate, which has been relatively constant over the past fifty years, will increase from 6% to about 30% over the coming century. These fundamental demographic changes imply that there is a need to provide for an ever-increasing number of dependents from an ever-reducing labour force: the demographic pyramid of the previous century is being inverted.

The empirical issue this raises concerns whether it is feasible for the extant labour force to solve resource problems under these much-altered circumstances. This is an empirical question in the sense that the outcome is likely determined by comparing the changing costs of innovation (by means of investments in fertility, education and R&D) with the changing costs of resource constraints. It is the estimation of how costly human capital is to produce, or how elastic is the response of innovation to such investments, that will determine whether the resource problems of the future are soluble (Bretschger, 2013).

To address this question, we formulate a model in which it is possible to compare the costs of satisfying the needs of an increasing population, via increased reliance upon either technology or resources. Although we are examining the problem of resource constraints, our focus here is on labour allocation as the fundamental means for solving economic problems. To pursue societal objectives, the available labour force is allocated to six distinct sectors (including fertility, research, manufactures, resource extraction and agricultural production) in order to sustain the population and produce consumption (Lanz et al., 2017).

To address the empirical question raised above, our model is then fit to historical parameters deriving from the period 1960–2010. We then run this fit forward to forecast the manner in which the economy might respond to resource constraints over the coming century: do these changing demographic conditions imply a pathway for the economy that is more resource-reliant or more technology-reliant?

Our quantitative findings are that (under prevailing conditions) the global economy has demonstrated remarkable resilience in its capacity to deal with increasingly severe resource constraints. Minor changes in labour allocation, from 4% to 6% in agricultural R&D, are sufficient to meet increasingly stringent resource constraints.⁵ This resilience in the response of the economy is achieved through labour re-allocation and technological change, as predicted by various analysts (Bretschger, 2013).

The problem for our future economy arises when the same model is fit to the very different dependency rates that are forecast for the coming century. Then the optimal path for the economy shifts away from innovation and toward enhanced resource-reliance. This is because the inverted demographic structure that results (with ever larger dependency groups sustained by ever smaller groups of labourers) is incapable of performing all of the labour-allocations that are required in a technology-based economy. The economy shifts back toward increased resource dependence, as labour resources become relatively more costly. We conclude that this outcome is avoidable through intervention, but that otherwise it is likely that Malthusian constraints might recur on account of the dramatically changing demographic conditions.

In the remainder of the paper, we proceed as follows: In [Section 2](#) we review the literature that discusses the problem of population, technology and resources. In [Section 3](#) we describe our modelling of the problem, and the manner in which we employ our empirical fit. In [Section 4](#) we give the projections for the path of the future economy, and demonstrate its resilience in response to imposed resource constraints. In [Section 5](#) we employ the changed dependency rates expected over coming years, and demonstrate the impact of reduced population growth and increased dependency. In [Section 6](#) we conclude.

2. Literature review

This paper sits at the interface between a number of literatures concerned with growth, resources, technological change and population dynamics. The particular question we wish to consider is whether population growth contributes positively or negatively to the resolution of resource constraints, and how this impacts economic development. In particular, we wish to understand better how the pattern of population growth occurring over the current century is likely to impact upon these constraints.

This raises all the basic issues of how population dynamics (fertility and mortality rates) and technology interact. Economic historians have investigated this interaction extensively for pre-industrial societies, the so called Malthusian economies. In a Malthusian economy, population dynamics determine living standards via natural resource use (see e.g. Clark, 2008 and Sharp et al., 2012). As Sharp et al. (2012) show, in the Malthusian equilibrium economic development is then wholly constrained by natural resource availability.⁶

⁴ Dependency rates are the proportion of the population over a given age who depend on the working population for consumption without contributing to production. In the UN definition, the “dependent population” is that group of people over 70 years of age (UN Population Division (2015)).

⁵ By prevailing conditions, we are referring to the parametric fit of the model to conditions prevailing in the global economy in the period 1960–2010. It is these conditions that are imposed upon the model, and then run forward through the year 2100 in order to forecast future economic pathways.

⁶ Changes in technology in a Malthusian economy do not alter real income levels, but change birth and death rates, which again exert pressure on resources.

The possibility that population growth might violate resource constraints has been the subject of papers considering the collapse of civilisations (Brander and Taylor, 1998) and (Taylor, 2009). Alternatively, population growth might also induce technological change, thus impacting upon the economy both directly (by expanding scale to approach resource constraints) and indirectly (by advancing innovation to address these resource constraints). Boserup (2017)

To explore these two possibilities, we use a model that emerges from the unified growth theory literature (Galor and Weil, 2000) and (Galor, 2011). The unified growth theory has incorporated how population might interact with resource constraints via induced technological change.⁷

This literature endogenises fertility choice through the recognition that fertility and human capital decisions are often joint ones (so-called quantity versus quality considerations). It is then possible to generate explanations for how population transitions might accompany industrial/technological ones. For example, the shift to an industry-based society (and away from a resource-based one) can increase the cost of food (and so fertility) resulting in a change in the future fertility/technology pathway (Strulik and Weisdorf, 2008).

This literature has also focused on how the costs of fertility are associated with technological change. In general, fertility choice is seen to change first through the substitution of quality for quantity in children at early levels of growth. Quality in fertility refers to the need to generate human capital commensurate with the technological scale of the economy, thus resulting in the increasing costliness of fertility as technology progresses (Galor and Weil, 2000) and (Tamura, 2002). For this reason, further technological advances become increasingly costly, as each step up the technological ladder results in greater costliness for the further accumulation of human capital.⁸

More recently, a literature in growth/resource economics has investigated in much more detail whether population levels and population growth contribute positively or negatively to the resolution of resource constraints. The paper closest to our own is probably (Bretschger, 2013), and the author there focuses on the capacity for labour markets and population growth to substitute for resources in the macro-economy. In that paper the rate at which technological change occurs depends upon labour allocation and specifically the product of two particular parameters: a) the elasticity of labour in child-rearing; and b) the elasticity of labour in research and development. If these parameters are sufficiently large, then it is possible for technological change to continue against a backdrop of population growth as a means of addressing resource constraints.

It is this capacity for investments in the generation of human capital and technological change that is also at the core of our modelling of this problem, as our approach hinges on the capacity for investment in human capital to address resource constraints. And, it is our estimation of these parameters (the impact of labour in creating human capital and in generating R&D) that determines our primary results.⁹

Similarly, in work by Peretto (2020), Peretto and Valente (2015) and Peretto (2015), the authors describe a potential three-stage path to economic sustainability which exists under given initial parameters. In the case of the sustainable pathway, agents initially build up population levels through resource exploitation, then pursue innovation from population growth, and finally converge upon growth without the necessity of any increased use of physical inputs (only knowledge accumulation). The result hinges upon adequate initial resource endowments, population levels and input substitutability. Again this result indicates that it is primarily the parameterisation of the model that determines sustainability. Whether resource constraints may be met at various stages of population transition depends on the parameters determining the economy's capacity to produce its own resilience.

In sum, the literature observing the interaction of population, technology and resource constraints indicates that there is a double-edged sword at work in the inter-play between population and resources. On the one hand, increasing population levels necessarily place increased pressure on the resource constraint, as the scale of the human population reaches the natural limits imposed by land, food or other natural systems (such as climate). On the other hand, population can also contribute to the resolution of such resource constraints, through the application of labour to research and development. The question of whether population contributes more to increased problems or to potential solutions is likely an empirical one, determined by the respective contributions of population growth at the current stage of the economy.

In order to address the empirical aspects of the problem, we develop a model that looks at resource constraints by considering how global food supply and population interact in a quantitative way. This may constitute a contribution to an already-existing and much more developed literature on the questions of sustainable land use and global food supplies. There are many existing models examining land use at the global level (Schmitz et al., 2014), (Steinbuks and Hertel, 2013) and (Steinbuks and Hertel, 2014). These land use models are typically partial equilibrium models integrating the agricultural, bioenergy and forestry sectors with the aim of providing policy analysis on global issues concerning land use allocation between the major land-based production sectors (Ramankutty et al., 2006) and (Steinbuks and Hertel, 2013). These models can be global in scale (like ours) but usually have much finer resolution in terms of land use sectors and regional dif-

⁷ Often times the focus has been on how population growth and knowledge accumulation are able to substitute for resource-based inputs in economic production, by means of some shock that shifts society from a resource-based sector to a more technology-based one (Hansen and Prescott, 2002) and (Lucas et al., 2002).

⁸ In the literature, technology is conceived of as being similar to an Aghion/Howitt technological ladder, in that each step up the ladder subsumes all of the knowledge going before it. Aghion and Howitt (1990)

⁹ In a more recent paper, the author reaches the same conclusion in the context of climate change problems, with the addition of a third parameter of interest—the elasticity of substitution between natural resources and other inputs (Bretschger, 2019). We have also explored elsewhere the manner in which the elasticity of substitution between natural resources and other inputs impacts upon these outcomes in our model. Lanz et al. (2017)

ferences.¹⁰ Our contribution to this literature is relatively minor, consisting of a very general analysis of how technology interacts with population in determining the future pathway of the global economy.¹¹

In general, however, our enquiry is specifically concerned with the direction that the economy will take, now that population growth is slowing. We are interested in the problem of global food security primarily as a case study in the question of whether resource constraints can become real problems once again for a global society experiencing dramatically declining population growth, i.e. will Malthusian problems return?

3. Modelling of population, technology and resources

As indicated above, the distinguishing feature of our approach to the problem of global resource constraints is its basis in macroeconomics, and especially in the unified growth theory (Galor, 2011). This theory has been built up in order to combine economic systems, as distinct as population, technology and production. Our approach is to combine these sectors together with those involving land use and agricultural production.¹²

We develop this macro-economic model of population and production, to model the joint movement of a system comprised of several co-determined processes: fertility, technological change, agricultural and manufacturing production, resource extraction and exploitation, and food requirements. We specify the equations within the system by making reference to the economic history and development literature, in order to attempt to develop a single internally consistent modelling framework. We then undertake a fit of the model to historical data (1960–2010), and demonstrate that the model is able to replicate these outcomes relatively straightforwardly.

In the first part of this section, we provide a short description of the components of the model and the estimation procedure. In the second part of the section we describe the method and approach to fitting this model to the period 1960–2010. A complete description of the model, together with detailed motivation of its structure, as well as sensitivity analysis, is reported in Lanz et al. (2017).¹³

3.1. The MAVA model of population, technology and resources

The model we use here is an exercise in optimal labour-allocation, with two types of technologies (manufacture and agriculture) and one natural resource (land). At every period, the working population is allocated across six different sectors (agriculture, agricultural R&D, manufacture, manufacture R&D, land clearing and child rearing), depending on the relative productivity of each sector.

As we see in Fig. 2, individuals maximise a classic utilitarian social welfare function, subject to the labour available to be allocated to this objective. Welfare is the product of per capita consumption and total population. Consumption consists only of manufactures from allocation of labour to that sector. Population increases with investments in fertility, and agricultural output is required to sustain the existing population. Thus, within this basic formulation of the manufacturing and agricultural sectors, the economy would only grow to the extent that population and capital stocks experienced any growth, and resources remained to sustain growth.

Increases in population (fertility investments) require labour time (for education etc) but, in addition, there is a food requirement constraint that has to be met each period for the entire population (labour and dependents). For this reason, sustaining the population requires both labour allocations and also other resources (food derives from technology, labour, capital and land).

The other approach to generating growth in this economy is via investments in advancing technology. The economy moves forward in this way, first, by reason of allocations of labour to the tasks of child-rearing/education. Then, secondly, these new labour units (i.e. educated offspring) are then allocated to the R&D sectors in order to effect technological change, and thus move productivity forward in the relevant sector.

These different pathways are available to enable the growth of the economy, so long as either resource exploitation and/or technological advances remain feasible. The optimal choice of pathway for growth will depend on the relative cost of the two paths: resource-reliance or technology-reliance. The reason that the optimal choice of population/technology

¹⁰ The models are then used for a wide variety of research purposes that range from climate change impact assessment (Tomassini et al., 2010) to the land use implications of biofuel (Frank et al., 2013). Examples of such large-scale models are GLOBIOM (mainly developed at IIASA, see for example Schneider et al., 2011) and IMAGE (mainly developed at PBL, see for example Smith et al., 2010 and Alcamo et al., 2005).

¹¹ We are asking only whether the solution to the global food security problem is to find some way to continue down technological pathways that are compatible with food requirements. For this reason, our paper also makes only a minor contribution to the literature in environmental sciences and economics that studies how to meet the world's food requirements as population increases (see e.g. Foley et al., 2011). These authors look at a wide range of possible resource problems in global agriculture, and a comparably long list of potential policy approaches to them. Our research is circumscribed to the issue of whether population growth under current constraints is compatible with technology-based solutions.

¹² The paper refers to resource constraints but only incorporates one resource within the modeling of resource constraints, i.e. land. It is true that we use land as the resource variable of interest, but it is not the case that this elides the impacts of general resource availability. In the MAVA model that follows, we develop an agricultural production function that relies upon inputs of land, labour, capital and technology. Because this function is then fit to observed global food production figures, this means that all output must be attributed to this set of factors. For this reason, the land may be conceived of as the variable capturing the effect of all resources in agricultural production. So long as other resources (such as water, seeds, fertilisers, chemicals) are used in approximate fixed proportions to land, their impacts on output would also be captured by the impact of land in agricultural production.

¹³ The way in which the model is fit and operated is discussed in a practical manner in the online appendix to this article.

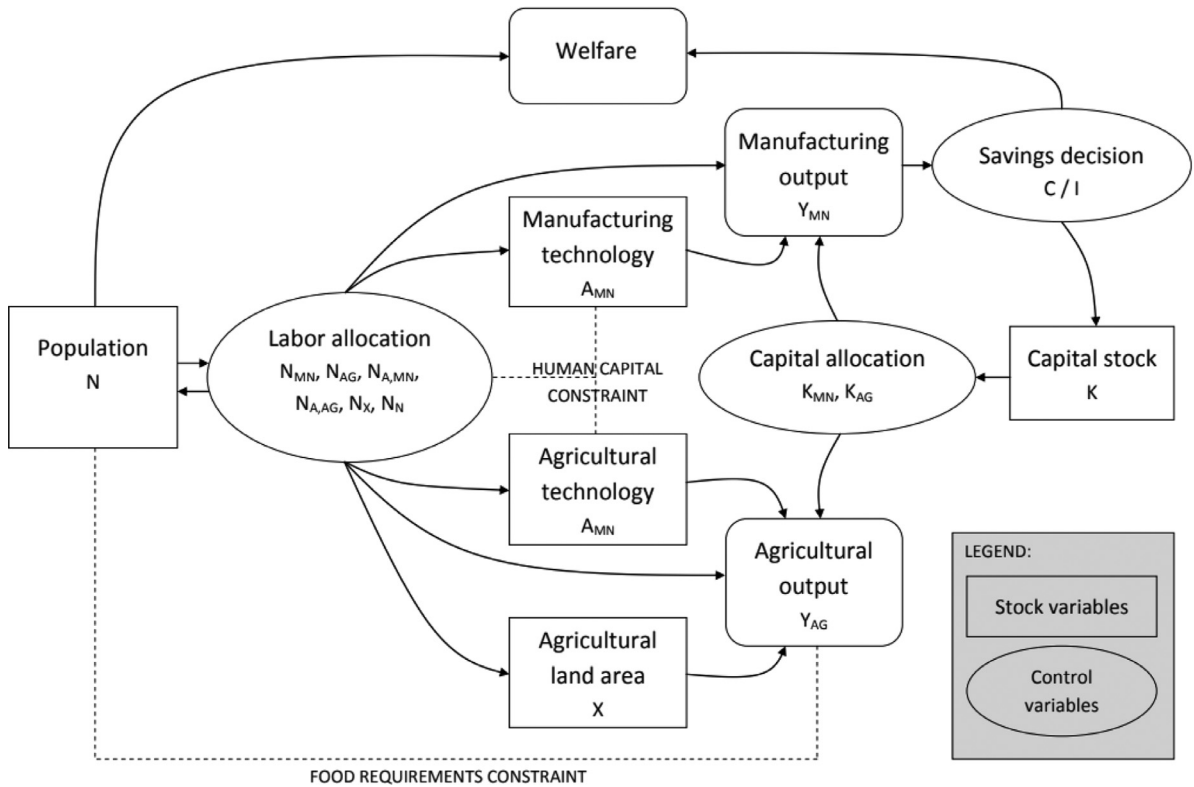


Fig. 2. Schematic representation of the model.

pathway changes over time is that the costs of investments in R&D are rising over time. As the cost of moving down the R&D pathway increases, resource-reliant strategies can, once again, become more likely to be chosen.

Thus, in our model (as in all of the unified growth theory) fertility choice is determined by the costs of child-rearing/education, and these are increasing. As technology advances, more education is required to train a new individual to be ready for employment. This increasing cost of education reduces fertility, slows population growth and, ultimately, results in the slowing of the economy down this pathway. The question we consider here is: will this slowing of the technology-reliant economy (i.e. the economy based on technology and population advancement) result in a return to resource-reliance and Malthusian constraints?

In the remainder of this section we describe the basics of the model we will use throughout the remainder of the paper. It is a fairly standard unified growth theory macro-model, with the addition of the agricultural sector and food constraint. Here we describe the model, the approach to its solution, and the fitting of its initial parameters.

3.1.1. The economy

The model comprises two sectors: a manufacturing sector that produces a consumption good and an agricultural sector that produces food to sustain contemporaneous population.

The manufacturing output is given by,

$$Y_{t,mn} = A_{t,mn} K_{t,mn}^{\vartheta} N_{t,mn}^{1-\vartheta}, \tag{1}$$

where $Y_{t,mn}$ is real manufacturing output at time t , $A_{t,mn}$ is an index of productivity in manufacturing, $K_{t,mn}$ is capital allocated to manufacturing, $N_{t,mn}$ is the workforce allocated to manufacturing, and $\vartheta \in (0, 1)$ is a share parameter.

Agricultural output is given by,

$$Y_{t,ag} = A_{t,ag} \left[(1 - \theta_X) (K_{t,ag}^{\theta_K} N_{t,ag}^{1-\theta_K})^{\frac{\sigma-1}{\sigma}} + \theta_X X_t^{\frac{\sigma-1}{\sigma}} \right]^{\frac{\sigma}{\sigma-1}}, \tag{2}$$

where $\theta_{X,K} \in (0, 1)$, σ is the elasticity of substitution between a capital-labour composite factor and agricultural land, X_t .¹⁴

¹⁴ We set $\sigma = 0.6$ based on long-run empirical evidence (Wilde, 2012). In Appendix C, we change this parameter to study the impact of reduced substitutability on long-term land use.

3.1.2. Innovations and technological progress

As in the Schumpeterian model of [Aghion and Howitt \(1992\)](#), sectoral TFP evolves as:

$$A_{t+1,j} = A_{t,j} \cdot (1 + \rho_{t,j}S), \quad j \in \{mn, ag\}. \quad (3)$$

where S is the maximum growth rate of TFP each period and $\rho_{t,j} \in [0, 1]$ is the arrival rate of innovations each period.¹⁵

The rate at which innovations arrive in each sector is a function of labour allocated to sectoral R&D:

$$\rho_{t,j} = \lambda_j \left(\frac{N_{t,A_j}}{N_t} \right)^{\mu_j}, \quad j \in \{mn, ag\},$$

where N_{t,A_j} is labour employed in R&D for sector j , $\lambda_j > 0$ is a productivity parameter, $\mu_j \in (0, 1)$ is an elasticity, and N_t is the total workforce in the economy.¹⁶ Note that our representation of R&D implies decreasing returns to labour in R&D through the parameter μ_j . The parameter λ_j is normalised to 1 to ensure that TFP growth is bounded between 0 and S .¹⁷

3.1.3. Population dynamics

The change in population derives from the contemporaneous rate of fertility n_t and mortality δ_N :

$$N_{t+1} = N_t(1 - \delta_N + n_t), \quad N_0 \text{ given}. \quad (4)$$

where δ_N is the inverse of the expected working life time.

Addition to the stock of effective labour units is a function of labour allocated to child rearing activities as well as the prevailing level of technology:

$$N_t n_t = \chi \frac{N_{t,N}^\zeta}{A_t^\omega}, \quad (5)$$

where $N_{t,N}$ is labour allocated to child rearing activities, $\chi > 0$ is a productivity parameter, $\zeta \in (0, 1)$ is an elasticity representing scarce factors required in child rearing, A_t is an index of technology, and $\omega > 0$ measures how the cost of children increases with the level of technology. Note that, as the technological level increases, the cost of child rearing also increases, characterising the quality-quantity trade-off.¹⁸

Population dynamics are further affected by food availability, as measured by agricultural output. Specifically, in each period, agricultural production is consumed entirely to sustain contemporaneous population:

$$Y_t^{ag} = N_t \bar{f}_t \quad (6)$$

where \bar{f}_t is per capita demand for food, i.e. the quantity of food required to maintain an individual in a given society.

We further specify per capita demand for food as a concave function of per capita income:

$$\bar{f} = \xi \cdot \left(\frac{Y_{t,mn}}{N_t} \right)^\kappa \quad (7)$$

where ξ is a scale parameter and $\kappa > 0$ is the income elasticity of food consumption.

3.1.4. Land dynamics

Land input to agriculture has to be converted from a total stock of available land \bar{X} . Over time, the stock of land used in agriculture develops as:

$$X_{t+1} = X_t(1 - \delta_X) + \psi \cdot N_{t,X}^\varepsilon, \quad X_0 \text{ given}, \quad X_t \leq \bar{X}, \quad (8)$$

where $N_{t,X}$ is labour allocated to land clearing activities, $\psi > 0$ measures labour productivity in land clearing activities, $\varepsilon \in (0, 1)$ is an elasticity, and the depreciation rate δ_X measures how fast converted land reverts back to natural land.¹⁹

¹⁵ In the original work of [Aghion and Howitt \(1992\)](#) time is continuous and the arrival of innovations is modelled as a Poisson process. Our representation is qualitatively equivalent, but somewhat simpler, as $\rho_{t,j}$ implicitly uses the law of large number to smooth out the random nature of innovations over discrete time periods.

¹⁶ This formulation implies that TFP growth increases with the share allocated to the R&D sector, rather than the absolute amount. It avoids the so-called 'population scale effect', which is not supported by data (see [Jones, 1995](#)).

¹⁷ Unlike recent work on the impact of R&D on technological progress (see e.g. [Cai et al., 2017](#)), we do not explicitly model the time dynamics between investment in R&D and productivity. Because we have an economy-wide model, the lag between investment and increased productivity is implicitly taken into account by the welfare costs of reallocating labour from one sector to the other.

¹⁸ By inverting the right hand side of [Eq. \(5\)](#) and dividing it by the labour share in child rearing, we can calculate the amount of years that are necessary to prepare a new individual to work.

¹⁹ We assume that the period of regeneration of natural land is 50 years, so that $\delta_X = 0.02$. The overall constraint on land, \bar{X} , is set to 2 billion hectares.

3.1.5. Preferences and savings

The utility function of a representative household is defined over own consumption of manufactured good c_t , fertility n_t and the utility its children will experience in the future $U_{i,t+1}$:

$$U_t = \frac{c_t^{1-\gamma} - 1}{1-\gamma} + \beta n_t^{1-\eta} U_{i,t+1}, \quad (9)$$

where γ is the elasticity of marginal utility of consumption of the manufactured good, β is the discount factor and η is an elasticity determining how the utility of parents changes with n_t . The objective function is given by the utility function of the dynastic head and obtained by successive substitution of the recursive utility function:

$$U_0 = \sum_{t=0}^{\infty} \beta^t N_t^{1-\eta} \frac{(C_t/N_t)^{1-\gamma} - 1}{1-\gamma}, \quad (10)$$

where $C_t = c_t N_t$ is aggregate consumption at t .

Aggregate consumption derives from manufacturing output, which can alternatively be invested into a stock of capital:

$$Y_{t,mm} = C_t + I_t, \quad (11)$$

where I_t is aggregate investment. The accumulation of capital is then given by:

$$K_{t+1} = K_t(1 - \delta_k) + I_t, \quad K_0 \text{ given} \quad (12)$$

where δ_k is the per-period depreciation rate.

3.1.6. Solution

We consider the planner's problem of selecting the allocation of labour and capital as well as saving rate to maximise the utility of a representative dynastic household. Specifically, a representative household chooses paths for $N_{t,j}$, $K_{t,j}$ and $C_{t,j}$ by maximising Eq. (9) subject to constraints (1), (2), (3), (4), (8), (11), (12) and resource allocation constraints for capital and labour:

$$K_t = K_{t,mm} + K_{t,ag} \quad N_t = N_{t,mm} + N_{t,ag} + N_{t,Amm} + N_{t,Aag} + N_{t,N} + N_{t,X}$$

The numerical model is solved as a constrained non-linear optimisation problem.²⁰

3.2. Fitting the model

With our model in place, we would now like to apply it to the question of the choice of pathway under future resource constraints and demographic conditions. This we believe to be an empirical question, concerning the capacity of the technology sector to respond to increasing constraints.

A distinguishing feature of our model is its basis in empirically and historically observed relationships, by means of fitting the model to parameters derived either from the historical literature or from the fitting of the relationships described in the model to observed aggregates (global population, production, technological change and land use).²¹ Lanz et al. (2017)

In order to create a reasonable baseline forecast for the coming century, we first utilised observed relationships within the historical literature that are seen to evince some regularity across time.²² Where it is not possible to derive estimates of parameters from the historical literature, we then fit this linked system to historical data (1960–2010) for estimates of the missing parameters.²³ The period we use is important because it demonstrates a relatively smooth trajectory of growth and production for all of the processes being observed together.²⁴

Given the parameter settings set out in Appendices Appendix A and Appendix B, we then derive a fit of the model to all six of our observed aggregate variables. The model demonstrates that all of these processes are moving together, and relatively smoothly, for the period described by these parameters. Population, production, technology, and resources demonstrate a fairly regular relationship over the period 1960–2010 (see Fig. 3).²⁵

²⁰ First-order conditions for a static version of this model, with intuition, is presented in Lanz et al. (2017).

²¹ The manner in which the model is fit and solved is discussed in a practical manner in the online appendix to this article.

²² See, for example, Clark (2008) for a discussion of many of these relationships in agriculture.

²³ See Appendix A for parameters utilised in the fit of the model and Appendix B for the historical data used.

²⁴ Fitting the model to earlier data—dating back to 1910—was feasible but involved the incorporation of major shocks from events largely unrelated to population and agricultural growth, e.g. economic depression and military conflict. The period chosen is remarkable for the relatively smooth movement of these processes together, and the final section of the paper will investigate how basic changes in the process will impact upon the manner in which it operates.

²⁵ In our approach to this problem, our estimated and fitted parameters (set out in Appendices Appendix A and Appendix B) constitute the only truly exogenous pieces within our approach. These arise from historical literature and the fitting of observations in the fifty years prior to 2010. The question this raises concerns whether the conditions extant in that period - in terms of this combined production system - will continue into this century. In Section 6 of the paper we explore one important way in which we know that this certainly will not be the case, i.e. the dependency rate applicable in future.

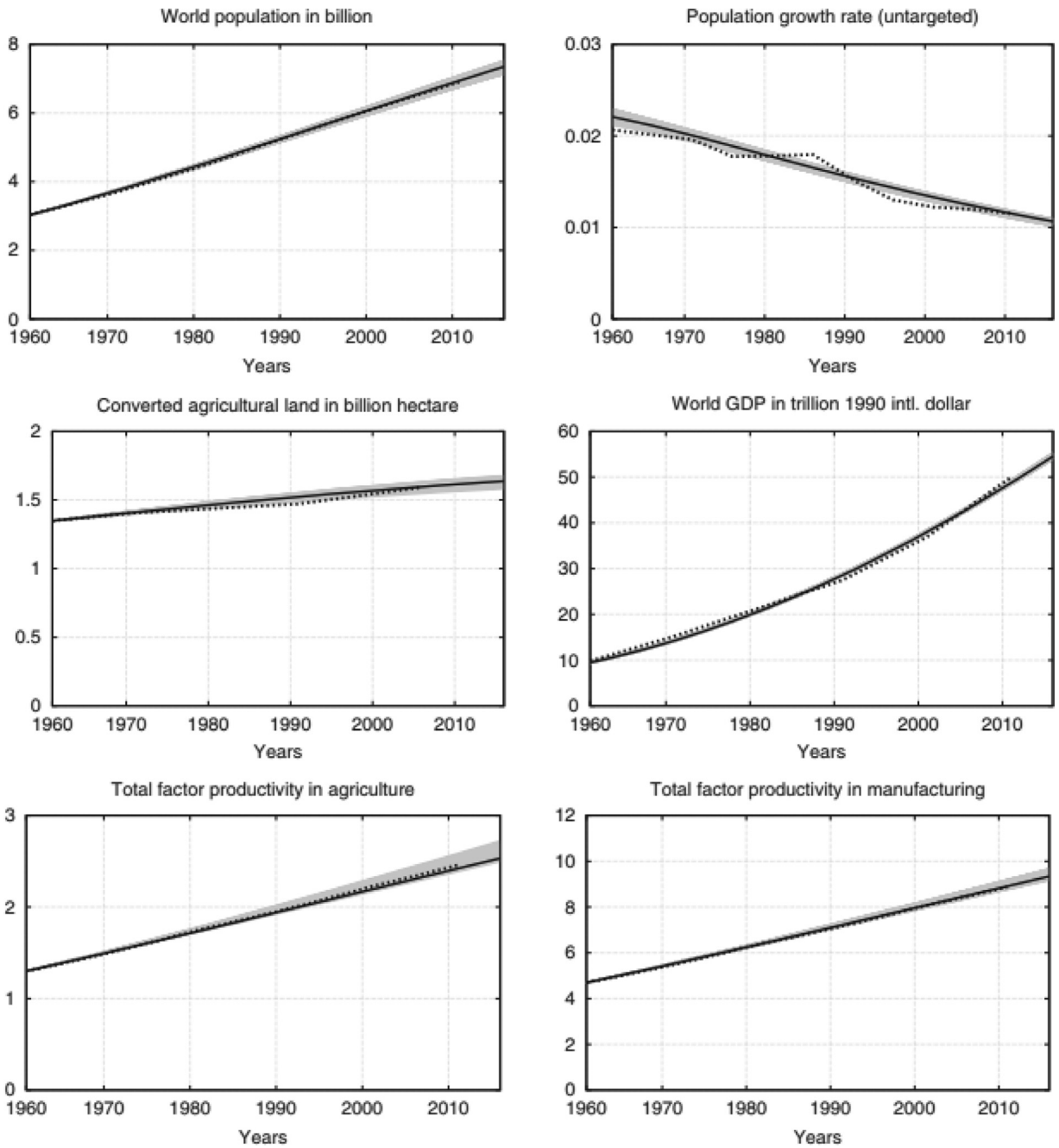


Fig. 3. Historical Fit: 1960–2010.

In the next section, we will use the estimated MAVA model to run projections for this joint system, running through the 21st century, and then observe how the model responds when significant resource constraints are imposed upon it.

4. Economic response to resource constraints - Projections

4.1. Projections for 21st century

Using the parameter estimates and model described in the previous section, we now run the MAVA model forward, from 2010 to 2100. These projections are shown in Fig. 4. They show that in 2100 we forecast an expected population of 12.4 billion, expected land use of 1.77 billion hectares, and a 300 per cent increase in expected global GDP. These represent

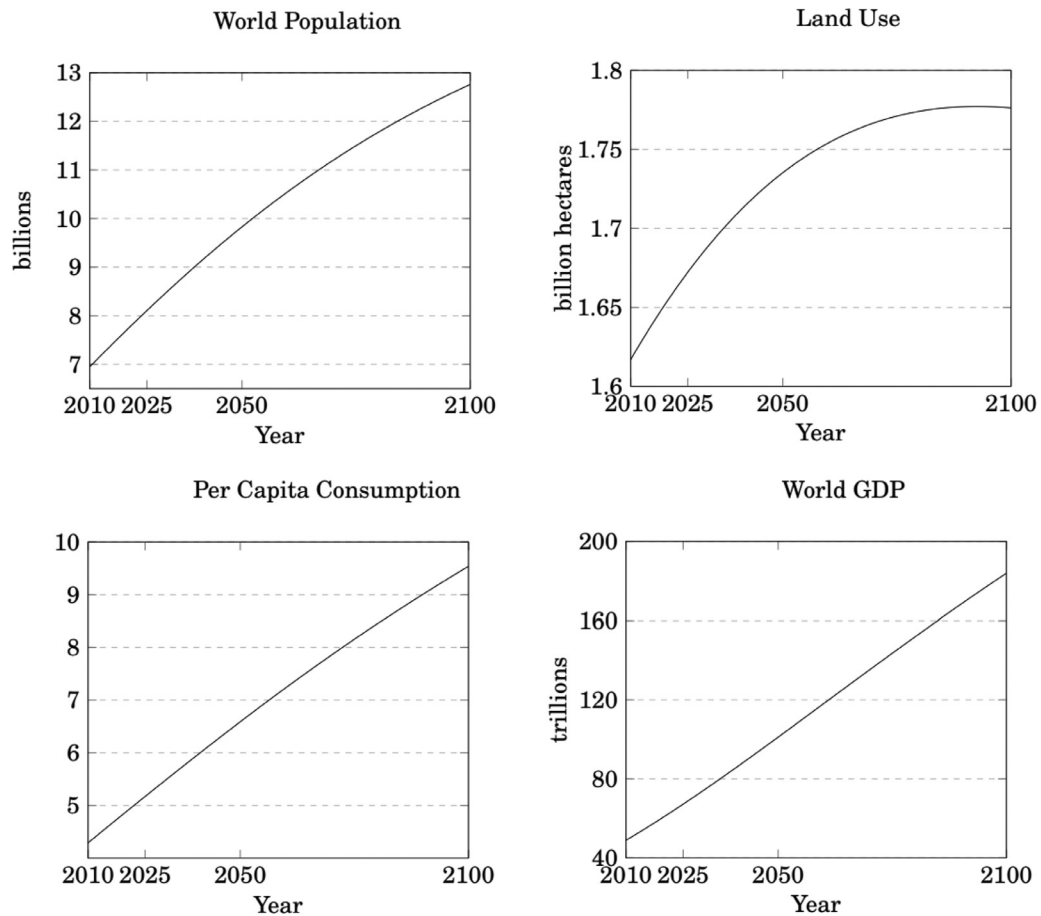


Fig. 4. Projections: 2010–2100.

substantial increases over the current levels: 7.2 billion people, 1.5 billion hectares of agricultural land, and 125 trillion USD in production.²⁶

Despite these significant increases in the absolute scale of the economy, the growth rate of the global economy appears to be slowing, and on a course for a soft landing around the end of the century. This is generally consistent with findings by the OECD Forecasting Group, which foresees OECD group economic growth of approximately 2% over the coming half-century and non-OECD growth falling off from 7% toward 2.5% over the same period. These changes being driven by productivity growth declining toward 1.5% and general demographic decline (Johansson et al., 2012).²⁷

As a result, all of the measures of economic change and development - population, land use, manufacturing output, productivity - appear on a path of long term secular decline (Fig. 5).²⁸ Most notably, the use of resources within the model is the first to approach the steady state. Its growth rate approaches zero by the middle of the century.

²⁶ Our projections are in line with those forecasted by UN bodies, e.g. aggregate world population slightly below 10 billion by 2050 and converted agricultural lands around 1.7 billion hectares by 2050 (United Nations, 2013) and (Alexandratos et al., 2012). Our long term population projection for 2100, 12.4 billion, lies in between the medium and high projections (10.9 billion and 16.6 billion respectively) of the United Nations (2013). Our projections also lie on the upper limit of the 95 percent confidence interval implied by the probabilistic projections reported in Lutz and Samir (2010). Probabilistic projections use the same cohort-component method but weight different fertility scenarios at the country level by some probability distributions. Being based on the assumption that all countries converge to replacement fertility, at the median population stops growing by 2050 and remains around 9 billion. Importantly, agricultural land area stabilises at around 1.77 billion hectares before 2100 (an increase of approximately 150 million hectares over current levels), so that the total amount of land that can be used for agriculture is never exhausted, even though our model emphasises economic growth as the objective of social welfare.

²⁷ This finding is consistent with the view that the global economy has entered into a new phase of reduced growth in terms of population and other economic variables (Gordon, 2015).

²⁸ In our modelling, these paths decline along a balanced growth trajectory toward the point where population, land and capital reach a steady state.

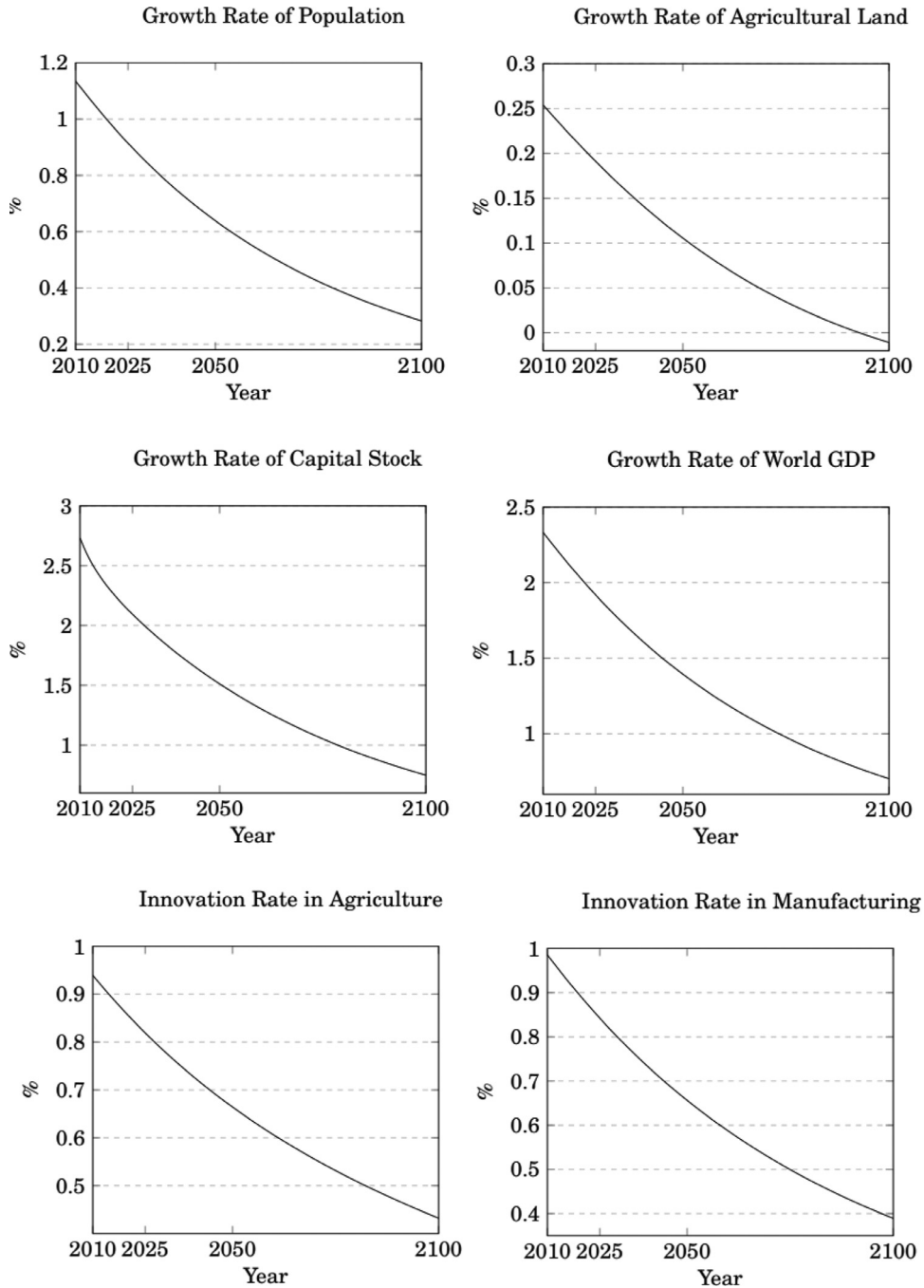


Fig. 5. Projected Growth Rates: 2010–2100.

The economy continues to grow despite the absence of any continued expansion in land use. Agricultural output increases by 67 percent between 2010 and 2050, when land use increases a mere 6 per cent.²⁹ Then agricultural output increases by 31 percent in the final fifty years of the century, despite little or no expansion in the use of resources. This growth in agricultural production is associated with a 22 percent growth in population, which is itself associated with a 32 percent growth in per capita income. Thus, the other important economic variables continue to exhibit positive growth after increases in land use become irrelevant to the economy.

²⁹ These figures are consistent with an observed two percent annual growth rate in global agricultural output forecasted by Alexandratos et al. (2012) for the period 1960 to 2010, and very close to the 72 percent projected by the same authors between 2010 and 2050.

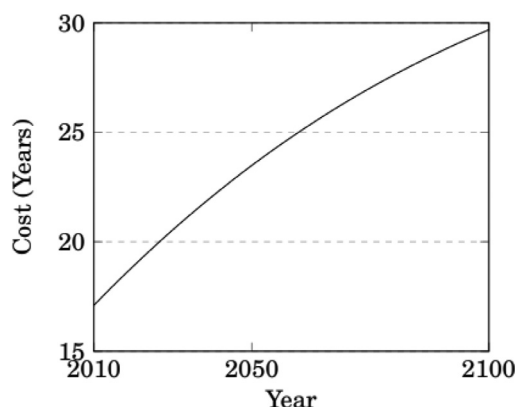


Fig. 6. Cost of Child Rearing (in Years).

What is driving the slowing growth in the economy? This is attributable at base to the increasing costs of child rearing/education, the consequent decline in population growth, and the resulting loss of labour to be allocated across all the sectors of the economy. As mentioned previously, the costs of fertility along a technology-reliant pathway will be increasing with the advance of technology. Although productivity gains remain achievable with investment in fertility (and resulting educated offspring), these additional investments become increasingly costly.³⁰

As we see in Fig. 6, the cost of raising a child over the period of our forecast goes from approximately 18 years in 2010 to 29 years in 2100. That is, in 2010 the estimated amount of labour required (by the current generation) to produce one useful member of the labour force (in the next generation) is 18 years, and that is continually increasing over the course of the century until the same useful member requires 29 years of education.³¹

Thus, the cost of fertility is increasing throughout the century, until the cost of the production of one useful unit of labour in 2100 has become 50% greater than in 2010. On account of these increasing costs, fertility declines precipitously, and consequentially so do population growth rates, rates of innovation, and technological advance. Thus, at base, it is the increasing cost of preparing individuals for the labour force that is driving this economy toward the steady state.

In sum, our projections demonstrate that the economy is on a pathway of slowly declining growth over the coming century. Most notably, while growth continues, it does so in the absence of reliance upon the use of much, if any, natural resources. The reason for this outcome is that the economy continues on a path of increasing reliance upon investments in human capital and technological advance, and the increasing costliness of this pathway continues to restrain the growth of the economy. At the same time it increasingly frees the economy from reliance upon resources. In the next sections we investigate the robustness of the economy's commitment to this pathway.

4.2. The impacts of imposed resource constraints

Now that we are able to see the projected pathway of the economy, and its relative lack of reliance on resources, we would like to investigate how the economy adapts to increasing resource constraints. In the remainder of this section, we investigate the impact of increasing resource constraints on the availability of land for agriculture.³² We impose a constraint on agricultural land use of 1.40, 1.20 and 1.00 billion hectares (relative to current baseline use of approximately 1.6 billion hectares), in order to observe how the model adjusts to lower levels of agricultural land availability. We find that the macro-economy is resilient with regard to these very substantial resource constraints.³³ Finally, we explore how the economy responds to the imposition of such constraints, and find that it does so via relatively minor re-allocations of labour toward agricultural R&D.³⁴

4.2.1. Impact of resource constraints on welfare

Table 1 shows the welfare losses for the constraints of 1.4 and 1.2 and 1.0 billion hectares result in aggregate welfare losses of only 0.19%, 0.45% or 0.88% if they are pursued over the medium run (i.e. achieved by 2050).

³⁰ This is attributable, in large part, to the specification in Eq. (5) above, in which the current scale of technology resides in the denominator of the cost of fertility function.

³¹ This is not necessarily requiring eighteen years of the new person's life, but eighteen years of the working population's labour allocation.

³² In the baseline scenario, we are assuming that the available agricultural land consists of approximately 2.1 billion hectares globally. Alexandratos et al. (2012) In what follows we will impose increasingly severe constraints on land use in agriculture, and test for the resilience of the existing pathway. Such land use constraints might be imposed for numerous policy reasons, such as biodiversity conservation or climate change mitigation.

³³ We also investigate the robustness of this conclusion in terms of the assumed agricultural production function, and find that it holds for a wide range of elasticities of substitution between land and labour (see Appendix C).

³⁴ The nearest example to our work here is Steinbuck and Hertel (2013), in which the authors examine the issue of long run global land use allocation. They also find that continued conversion to agriculture is probably unnecessary after mid-century.

Table 1
Change in Welfare under alternative land use constraints.

Land Constraint	2050	Welfare 2035	Loss 2025
1.4 billion hectare	-0.19%	-0.25%	-0.29%
1.2 billion hectare	-0.45%	-0.59%	-0.73%
1.0 billion hectare	-0.88%	-1.18%	-1.59%

Notes: Welfare losses are calculated using the non-constrained case as the baseline.³⁵

The welfare losses under the stricter constraint (1.0 billion hectare by 2025) results in maximum welfare losses of 1.59%. This result derives from the fact that the growth of the economy has become increasingly less reliant upon resources over the past half century, and so constraints on resource use have little significant impact along its current path.³⁶

4.2.2. Impact of resource constraints on labour allocation

We now turn to the manner in which the economy adjusts to the imposed constraints. As shown in Fig. 7, the main response is for society to shift labour resources toward the agricultural sector, principally agricultural R&D. The shift is very substantial in terms of the percentage increase in agricultural R&D (nearly a fifty percent increase in the share of labour in agricultural R&D at the outset of the program). However, in terms of the overall workforce, this change is relatively small. This is because agricultural R&D employs only about 4% of the total labour force at the outset of the program, and so a large increase in the allocation results in only a small number of workers being re-allocated. The model is able to achieve almost the same level of agricultural output, while using 10–20% less agricultural land, with the shift of only a few percent of the labour force into agricultural R&D.

Labour shifts toward R&D out of three sectors (child rearing, land clearing, and manufacturing). However none of these shifts is as significant as 1% of the labour force, demonstrating the ability of the economy to manage these constraints with minor adjustments. Overall, the imposition of substantial land use constraints barely nudges the economy off of its existing pathway. Minor shifts in labor between sectors—from land clearing and child rearing to agriculture—are sufficient to restore the economy to the optimal pathway.

4.3. Impact of intervention - Increased agricultural R&D sector

These findings are consistent with much recent work on the role of R&D in agriculture (Alston et al., 2009). Productivity increases in agriculture have derived principally from technological change at the frontier, and this has been true for several decades.³⁷ Given that technological change has been relatively straightforward to achieve through investments in R&D, small amounts of R&D are likely to be able to substitute for large amounts of land conversion.

We are able to demonstrate the general point that increased allocations toward R&D generate substantially increased productivity (and reduced resource reliance) by looking at how the model responds to small interventions regarding labour allocation. The simulations reported below result from forcing labour into the R&D sector, in excess of that along the baseline (optimal) path, in order to demonstrate the impact of this intervention in terms of productivity (TFP), resource use (Land), and social welfare (Welfare).

Table 2 demonstrates the benefit and the cost to society from shifting resources toward the R&D sector. The results in the table demonstrate that, at a fairly minor cost in terms of social welfare (0.2% - 0.6%), the society may shift resources significantly toward the R&D sector, causing TFP to increase by 20% to 30%.

As mentioned above, the reason that this significant increase in TFP may be achieved at relatively low cost is because of the relatively insignificant share of the labour force within the agricultural R&D sector at present. A change of 50% in the agricultural R&D sector represents a minor change in the overall re-deployment of the labour force. The simulation demonstrates that it is possible to shift resources toward agricultural R&D with substantial increases in agricultural productivity, reduced reliance on resources, and minimal impacts on aggregate welfare.

³⁵ Welfare losses are calculated using the social welfare objective function $\sum_{t=0}^{50} \beta^t N_t^{(1-n)} \frac{c_t^{1-\gamma} - 1}{1-\gamma}$ as a percentage difference between its value with and without the constraint.

³⁶ The importance of the timing of the constraint arises on account of the allowance of less time for the shifting of the economy. It occurs in our modelling by reason of the fact that the model assumes that “natural” land uses are only able to return at a rate of 2% per annum in the absence of a labour allocation. If higher rates of reforestation are desired, then a labour allocation would be required, at a cost to the economy. So, the size of the welfare losses from such constraints will vary with both their timing and restrictiveness.

³⁷ The more substantial issues concerning the productivity increases in agriculture at the global level concern the problems of lags in adoptions and in diffusion of technology within the frontier (Swanson and Goeschl, 2014). These are important problems that are necessarily subsumed into the global productivity averages of our very general approach to technological change, but nevertheless critical issues for policy analysis and consideration. (Cai et al., 2017) In our approach, such problems may be considered by shifting labour into the R&D sector, thereby increasing the general efficiency of that sector, but doing so comes at a societal cost, as discussed in the next section.

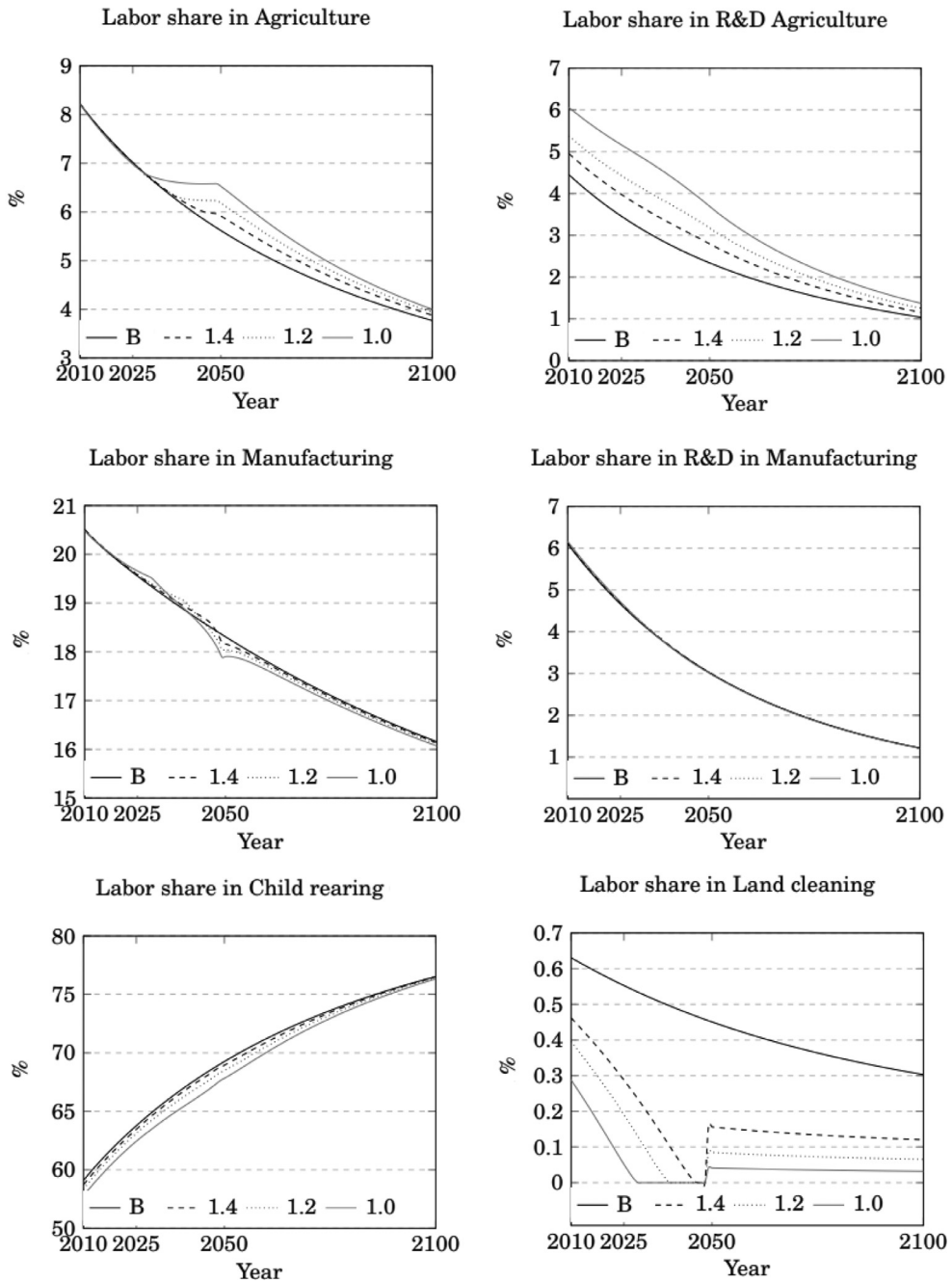


Fig. 7. Labour Share of Activities Notes: Forecasts calculated for land use constraints of 1.4, 1.2 and 1.0 billion hectare imposed as of 2050. B represents the baseline scenario, and the other scenarios correspond to the respective land constraints.

We also see that little further land conversion is required to meet future food requirements. As the R&D sector is expanded, the amount of land used in agriculture declines by 5–10%. Thus, the simulations demonstrate the flexibility of the economy which, with intervention, may be caused to move in the direction of increased technology-reliance rather than resource-reliance.³⁸

³⁸ This flexibility is investigated further in Appendix C, and in other papers, by means of robustness checks considering a range of elasticities of substitution between land and TFP in the agricultural production function.

Table 2
Change in Path with Exogenous Shift of Labour Resources into Agricultural R&D.

Variable	Baseline	50% Increase	100% Increase
Ag R&D	100%	150%	200%
Ag TFP	4.57	5.30	6.06 (+33%)
Land	1.77	1.67	1.58 (-10%)
Welfare	937	935	931 (-0.6%)

Notes: This table presents simulations with an increased share of labour allocated to agricultural R&D ("R&D"). The reported numbers indicate outcomes of the path at end of time horizon. R&D refers to the agricultural research sector, and is constrained to be 150 and 200 per cent of baseline in the two reported simulations. The R&D sector is 1.04% of the total labour force in the baseline simulation.

5. Changed demographic conditions

As mentioned in the introduction, the demographic changes of the current century represent substantially changed conditions from those experienced over the previous two centuries. How will these changed demographic conditions impact upon the capacity of the economy to respond to resource constraints?

A shift from the expanding populations of the past two centuries to the relatively stable populations of the future implies dramatic demographic changes. Throughout the past decades, increasing population growth implied that there were always larger labour forces coming into existence, than the groups that they were replacing. Those who had stopped working (at around 70 years) were always a relatively small part of the population on account of growth. This implied a demographic structure that remained stable and pyramid-shaped over many decades.

The current decline in population growth implies that the current labour force is smaller than the one it is replacing. Greater longevity implies that there is greater dependency as well, so long as the retirement age remains relatively stable (at about 70).³⁹ These two factors together generate estimated dependency rates that are rapidly changing over time—as per the United Nations Population Forecast set out in [Table 3](#).⁴⁰ This means that the demographic structure of society is almost literally inverting over the course of the coming century.

Table 3
UN dependency rate forecasts.

Year	Dependency Rate
2010	7%
2015	9%
2020	10%
2025	12%
2030	13%
2040	17%
2050	19%
2060	22%
2070	24%
2080	26%
2090	28%
2100	29%

Notes: Dependency rate refers to the proportion of the population that is neither in the labour force nor in training during the period concerned. Source: World Population Forecast, United Nations (2015).

We now consider how these changed demographic circumstances might impact upon the conclusions reached earlier.⁴¹ Increased dependency rates may be conceived of as an increased food production requirement per labourer, i.e. the requirement to produce the food for the extant labour force and for its dependants. In this case, the optimal path will then exhibit

³⁹ The problem with simply extending the retirement age in order to change the structure of the labour force is that the basic problem is one of human capital, and such is a function of investment in education. If such investments depreciate over time, as seems reasonable to assume, then it is likely that altering the age for exiting the labour force will do little to increase the human capital within it.

⁴⁰ The parameterisation of the model assumes that the estimated parameters that fit the period 1960–2010 continue to be pertinent throughout the current century, and the dependency rate remained approximately constant at 6–7% throughout that period. This section investigates the impact of changing this assumption on the optimal path, and the impact of possible interventions.

⁴¹ We take the UN Dependency Rate Forecast as a fixed constraint, implying that society does not respond to the problem by increasing either fertility or mortality rates. We discuss this approach in greater detail in our online appendix.

the same population as the baseline, and the same size of labour force. But each labourer then has an additional food requirement, ranging from 1 - 20%, relating to the additional non-active population that is carried in the model. In effect, thinking of enhanced dependency in this way implies that society must deal with a problem of increased food requirements per effective member of the labour force (as each member is required to feed itself and its dependents).⁴²

5.1. Impact of increased dependency on labour allocation

What is the impact of increased dependency on the economy? Fig. 8 describes how labour is reallocated within the model when the dependency rate increases over time.

We see that the economy shifts labour from child-rearing and manufacturing to agriculture, land clearing, as well as to agricultural R&D. It is important to note here that re-allocation of labour toward R&D alone is incapable of meeting the additional resource constraints generated by the increasing dependency rate. The system is also re-allocating more workers

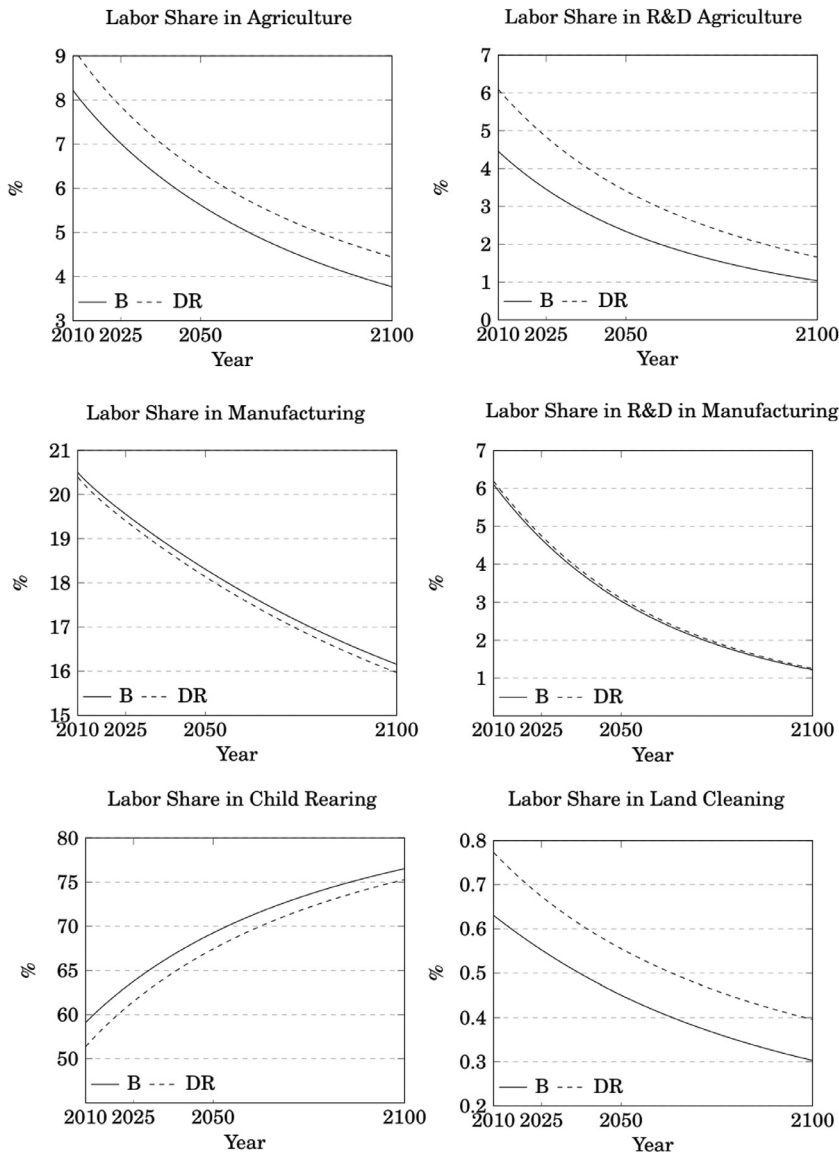


Fig. 8. Labour Shares in Activities with Increased Dependency Rates Notes: Forecasts calculated using the UN Dependency Rate Forecasts (see Table 3). B refers to baseline scenario and DR refer to scenario with increasing dependency rates.

⁴² This is accomplished in the modelling of the problem by replacing Eq. (6) with $Y_t^{ag} = h(N_t \bar{f}_t)$, where $h > 0$ is the factor of increased food requirements per labourer given the enhanced dependency rate.

toward the more basic agricultural tasks (land clearance, production). On account of the relatively increased cost of labour, the system is also shifting back toward more resource-reliant agriculture (in addition to technology-reliant agriculture) resulting in both agricultural pathways being pursued simultaneously.

5.2. Impact of increased dependency on resource requirements

On account of the way in which the economy responds, increased dependency implies an increase in the amount of land required in agriculture, as demonstrated in the Fig. 9.

In Fig. 9, the increased dependency rate implies increased resource requirements, as other factors (land, capital) are moved into agricultural production in response to the relatively increased scarcity of labour. The increase in resource allocation is approximately 0.5 to 1.0 billion hectares of land, resulting in land use requirements in agriculture increasing toward 1.8 - 1.85 billion hectares. Given that the overall constraint on potential agricultural land is approximately 2 billion hectares, it may be seen that the increased dependency rate is causing the economy to shift toward pathways of increased resource-reliance.

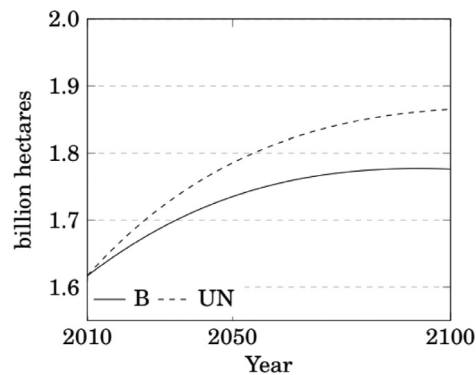


Fig. 9. Change in Dependency Ratio - Resource Requirements Notes: Simulations for dependency ratio following the UN projection (linear approximation). Here, increases in dependency ratio are equivalent to increases in per capita demand for food, \bar{f} .

5.3. Malthus returns? The impact of interventions

Under conditions prevailing over the previous 50 years, it was possible to envision the economy dealing relatively easily with resource constraints, even in the face of rising populations and increasing food requirements. The relatively easy substitution of technology for resources rendered the economy capable of moving away from very substantial resource constraints.

In the next century, however, it is difficult to see how the experience of the previous fifty years can be easily replicated. With the slowdown in population growth, in-built demographic changes mean that we will have a much larger group of dependents reliant upon a much lower proportion of the population in the work force. This inverted demographic structure renders technological approaches to production relatively more costly, and traditional approaches to production (using more capital, labour and land, and less technology) more likely. We have shown that these demographic changes may ultimately translate into higher rates of resource usage, and so move society back toward a more resource-constrained outcome.

This need not be the case, however, as it is possible to constrain the model away from such resource-reliant pathways. What is the societal cost to pushing the economy onto a more R&D reliant pathway? Given the results reported in Table 2 above, it should be clear that it is indeed feasible to move resources between sectors at relatively low social costs.

To demonstrate the responsiveness of the model to changed allocations of labour, we once again constrain the model to allocate increased shares of the labour force toward the R&D sector, this time in the context of the increased dependency rates reported in the UN figures. The outcomes are reported below in Table 4.

Table 4 demonstrates that the dependency problem may be addressed in a straightforward manner through increased allocations of resources to the R&D sector. The allocation of a 50% increase in labour resources to R&D generates an increase of over 20% in TFP, and reduces the amount of aggregate land used in agriculture by more than 10%. The costs of this intervention in terms of social welfare losses run from about 0.3% to 1.3% of aggregate welfare.

The reason that this is possible at reasonable cost is seen by comparing the baseline outcomes in Table 2 and Table 4. The baseline R&D labour force increases from 1.04% to 1.60% of all labour, prior to any intervention. This means that the

Table 4
Change in Path with Exogenous Shift of Labour Resources to Agricultural R&D with Increased Dependency Rates.

Variable	Baseline	50% Increase	100% Increase
R&D	100%	150%	200%
TFP	5.28	6.72	8.31
Land	1.87	1.70	1.54
Welfare	924	921	911

Notes: This table presents simulations with an increased share of labour into agricultural R&D and dependency rates. The aggregate land use is presented in billion hectares. Baseline R&D allocation is 1.60% of the labour force in this simulation.

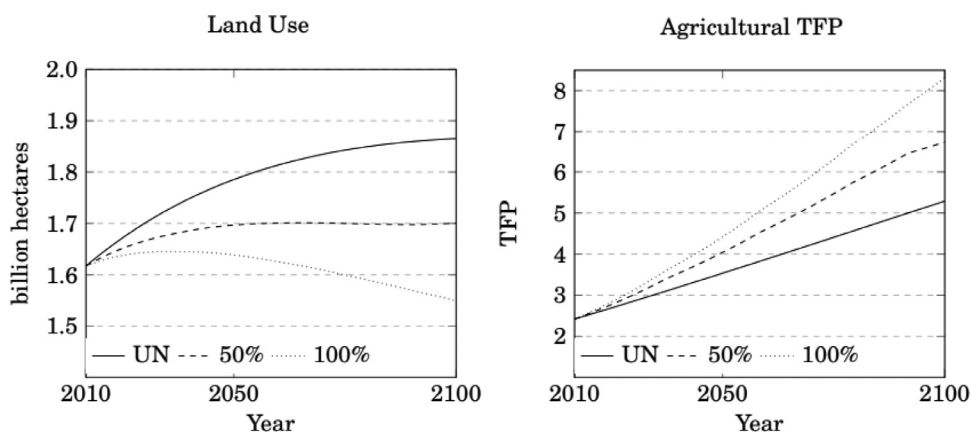


Fig. 10. Land Use and Agricultural TFP with increased labour share in agricultural R&D.

optimised pathway is already addressing the problem of increased dependency rates with increased allocations of labour to the R&D sector (increasing the size of the R&D sector by 50%). The optimal pathway is already pursuing a combination of both strategies simultaneously - a path of increasing resource and technology-reliance. The extent of emphasis on the two sectors is a matter of election, given the flexibility of the economy and the low cost of changing the degree of emphasis.

The manner in which society may move between the two pathways is illustrated in figure 10 below. Shifting labour toward the R&D sector causes the TFP in the economy to shift upward at relatively minor social costs (0.3% to 1.3%), and results in the shifting downward of the aggregate quantity of land used in agriculture (from 1.86 b. to 1.54 b. hectares, or about 15%) (Fig. 10).

The shifting between resource and technology-reliant pathways is a matter of the relative costliness of these resources. As labour becomes more costly and more scarce, the economy will tend to shift away from technology reliant pathways, relatively speaking. This may point to the re-emergence of the possibility of relevant resource-constraints, for the first time since Malthus. As population growth slows for the first time in centuries, the technological pathway becomes more costly and the reliance on resources (and the problem of resource scarcity) becomes important once again.

Nevertheless, and to a great extent, the choice of the optimal pathway remains an open question for society. The pathway that market forces would elect would not necessarily avoid increasing reliance on limited natural resources, but this is largely a matter of societal choice. As natural resources become more limited, and costly, the choice of forced investments in the technology sector remains an option.

6. Conclusion

The prospects for ongoing growth and development in the 21st century concerns the manner in which food security and population growth might interact, given the changes in the economy expected over the coming decades. Population growth has already collapsed, and the dependency rate (long stable at about 6%) is now in a rapid rate of escalation. By the end of the century, it is expected that the global dependency rate will be nearing 30% and the demographic structure of society will be nearly inverted.

Once these basic demographic trends are accepted, the reasons for the re-emergence of an important resource constraint is clear: At the same time that the labour force has an increasing number of mouths to feed, it also has a declining number of effective labour units to supply to the production process.

Researchers have noted that the problem of population and resource constraints is as much one of growth as it is one of scale. So long as there is adequate population to supply the human capital to pursue technological solutions, it can be possible to substitute these inputs for the natural ones.

Ironically, this implies that the problems outlined by Malthus (population-induced resource constraints) have been avoided during the period of maximum population growth rates, mostly on account of those increasing rates of population growth. It is the end of this stage of development—and the arrival of the period of demographic transition (i.e. declining population growth rates and the resultant increase in dependency rates)—that may occasion the re-emergence of an important resource constraint on global development.

Its re-emergence will depend upon the technological production function—and the ability of society to respond to this slowdown with increased rates of productivity from declining labour inputs—since there is no means of avoiding the fact of the increasing rate of dependency. Future research—and production—efforts should be targeted on those factors that might assist in the advancement of innovation in the face of population decline.

Appendix A. Parameters of the Model

The table below reports the value for the 27 parameters included in the model, distinguishing between parameters value that are imposed using external sources, those that are calibrated to match some observed quantities, and those that are estimated for the model to fit 1960 – 2010 trajectories on world GDP, population, crop land, and sectoral TFP. For the estimated we also report the range of values supported the shaded area, representing estimates achieving a slightly lower objective. For more details about the fitting procedure see [Lanz et al. \(2017\)](#).

Table 5
List of parameters of the model and associated numerical values.

Imposed parameters		
ϑ	Share of capital in manufacturing	0.3
θ_K	Share of capital in capital-labor composite for agriculture	0.3
θ_X	Share of land in agriculture	0.25
σ	Elasticity of substitution between land and the capital-labor composite	0.6
δ_K	Yearly rate of capital depreciation	0.1
S	Maximum increase in TFP each year	0.05
$\lambda_{mn,ag}$	Labor productivity parameter in R&D	1
γ	Inverse of the intertemporal elasticity of substitution	2
η	Elasticity of altruism towards future members of the dynasty	0.001
κ	Income elasticity of food demand	0.25
β	Discount factor	0.99
Initial values for the stock variables and calibrated parameters		
N_0	Initial value for population	3.03
X_0	Initial the stock of converted land	1.35
$A_{0,mn}$	Initial value for TFP in manufacturing	4.7
$A_{0,ag}$	Initial value for TFP in agriculture	1.3
K_0	Initial value for capital stock	20.5
δ_N	Exogenous mortality rate	0.022
δ_X	Rate of natural land reconversion	0.02
ξ	Food consumption for unitary income	0.4
Estimated parameters		
μ_{mn}	Elasticity of labor in manufacturing R&D	0.581
μ_{ag}	Elasticity of labor in agricultural R&D	0.537
χ	Labor productivity parameter in child rearing	0.153
ζ	Elasticity of labor in child rearing	0.427
ω	Elasticity of labor productivity in child rearing w.r.t. technology	0.089
ψ	Labor productivity in land conversion	0.079
ε	Elasticity of labor in land-conversion	0.251

Appendix B. Observed and Simulated Data

The table below reports both observed and simulated data from 1960 to 2100, by 10-year intervals. Note that agricultural area is not available for 2000.

Table 6

Data supporting the estimation and projections to 2100.

Year	Population (billion)		Population growth (%)		Crop land area (billion ha)		GDP (trillions 1990 intl. \$)	
	Observed	Simulated	Observed	Simulated	Observed	Simulated	Observed	Simulated
1960	3.03	3.03	0.021	0.022	1.37	1.35	9.8	9.5
1970	3.69	3.74	0.020	0.020	1.41	1.41	15.3	14.3
1980	4.45	4.51	0.018	0.018	1.43	1.47	21.3	20.6
1990	5.32	5.32	0.015	0.015	1.47	1.52	27.5	28.5
2000	6.13	6.14	0.012	0.013			36.9	38.0
2005					1.59	1.60		
2010	6.92	6.95	0.011	0.011		1.62	50.0	48.6
2020		7.74		0.010		1.65		60.5
2030		8.49		0.009		1.69		73.2
2040		9.19		0.007		1.71		86.6
2050		9.85		0.006		1.73		100.5
2060		10.46		0.006		1.75		114.5
2070		11.02		0.005		1.76		128.5
2080		11.53		0.004		1.77		142.4
2090		12.00		0.004		1.77		156.1
2100		12.42		0.003		1.77		169.3

Appendix C. The impact of land constraints with reduced substitutability

Our conclusions regarding the impact of a land constraint, as presented in Section 4, mainly relied on the substitution of labour in agricultural R&D for agricultural land. This shift towards other production factors for the production of food depends on the way in which we have specified the production function in agriculture, and its capacity to produce food from various inputs (land, capital, labour, technology). Therefore, it is important to test the robustness of our conclusion regarding the impact of a land constraint to our assumption about substitutability between inputs, as measured by the parameter σ . A lower level of σ will result in a higher level of required labour allocation—in compensation for the same constraint on land use.⁴³

In this section, land is constrained as before (to 1.4, 1.2 and 1.0 billion hectares) but now in a model with lower substitutability between land and other production factors in agriculture. More specifically, the model is re-estimated for trajectories to fit 1960 to 2010 data under the assumption that $\sigma = 0.2$. While the capability of the model to fit the data is not affected by changing the parameter σ , estimated parameter change significantly. Therefore, the model rationalises observed trajectories under the assumption of lower substitutability. The new set of estimates is reported in Table 7.

Table 7

Alternative estimates consistent with high and low substitutability in agriculture.

Parameter	Definition	Baseline	Reduced
σ	Elasticity of substitution in agriculture	0.6	0.2
χ	Productivity in child rearing	0.153	0.155
ζ	Elasticity of child rearing	0.427	0.417
ω	Elast. of child rearing w.r.t. tech.	0.089	0.085
μ_{mn}	Elast. of labor in R&D	0.581	0.575
μ_{ag}	Elast. of labor in R&D	0.537	0.549
ψ	Labor productivity in land conversion	0.080	0.063
ε	Elast. of labor in land conversion	0.251	0.174

Notes: Table reports structurally estimated parameters (see Lanz et al. (2017) for a detailed a discussion of the procedure). The two sets of estimates refer to different assumption about land substitutability in agricultural production, as measured by the parameter σ .

A reduction in substitution possibilities in agricultural production has the effect of making the constraint on land use much more costly to attain. Indeed, more labour and capital are now needed to compensate for the lower level of land on a account of a much lower substitutability. Hence, the impact of the land use constraints on the various variables of the economy should be much more severe now. This exercise allows us to examine how dependent the model is of assumptions on the substitutability between labour and land.

Welfare change ($\sigma = 0.2$)

Results derived under the assumption of a lower σ , reported in Table 8, demonstrate that the strictest constraint (1.0 billion hectares) is unattainable along this pathway on account of the restriction, i.e. the model would not converge over

⁴³ This might be the case, for example, if the agricultural economy found it difficult to function with less land in use than is already in place.

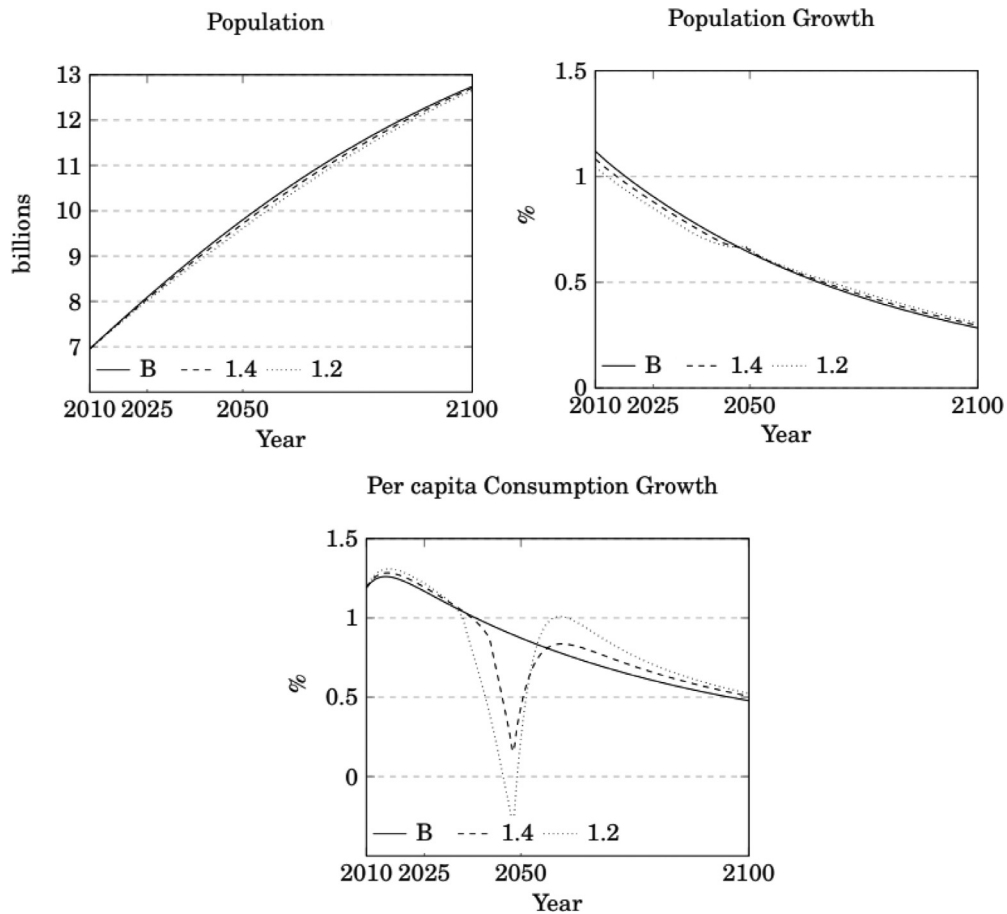


Fig. 11. Population and Per Capita Consumption ($\sigma = 0.2$) Notes: Forecasts calculated for land use constraints of 1.4, 1.2 and 1.0 billion hectares imposed as of 2050.

Table 8
Change in Welfare under alternative land use constraints ($\sigma = 0.2$).

Land Constraint	Welfare		
	2050	2035	2025
1.4 billion hectare	-0.79%	-0.97%	-1.10%
1.2 billion hectare	-1.71%	-2.18%	-2.71%

Notes: Welfare losses are calculated having the non-constrained case as the baseline.

any of the proposed restrictions. However, the other two constraints remain within the realm of feasibility, but at a slightly higher cost. The 1.2 constraint generates a social welfare loss running between 1.7% and 2.7% relative to the baseline (see Table 8). On the other hand, the 1.4 billion hectare constraint results in a welfare loss of only 0.8% to 1.1%.

Therefore, costs associated with the 1.4 billion hectare agricultural land constraint remain relatively small even under the much stronger assumptions regarding substitutability, while the 1.2 billion hectare constraint remains feasible but at significant cost. These findings are important because they demonstrate that the economy functions in the fundamental way in which was described previously, even under assumptions that render it much more difficult for it to do so. The basic finding—that the economy can be shifted away from an agricultural technology that is land-based and toward one that is R&D-based—is confirmed.

Supplementary material

Supplementary material associated with this article can be found, in the online version, at [10.1016/j.euroecorev.2020.103499](https://doi.org/10.1016/j.euroecorev.2020.103499)

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