



A macroeconomic approach to global land use policy[☆]

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ABSTRACT

It is important to dedicate substantial parts of the global land supply to public good uses in the 21st century, for purposes of climate change management and biodiversity provision. But will it also be possible to meet the food requirements of 12 billion people while doing so? Using a macroeconomic model (MAVA), we demonstrate that it may be possible to provide both for food requirements and environmental services in the long run. We first show that it may be possible to provide for food requirements with very substantial constraints on the amount of land used in agriculture with relatively minor welfare losses. We then show that global policies that re-allocate labour across sectors may have the capacity for directing the economy toward reduced reliance on land in agriculture. Focusing on land management, research and development, and fertility choices may be the best way to meet these combined goals.

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1. Introduction

There will be critical land use challenges arising in the coming century (Foley et al., 2011, Cai et al., 2017, Hertel, 2015 and Steinbuks and Hertel, 2016). As the world becomes richer and more populated, the world demands more food. The FAO has projected that food demand will rise by 60% by 2050, and some researchers predict a 100% increase in global crop demand from 2005 to 2050 (Tilman et al., 2011, Cirera and Masset, 2010 and Kearney, 2010). These increased food requirements are likely to call for a significant expansion in agricultural land use over the same time period.

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Increasing pressure on land resources will not come from rising food requirements alone. Global public good provision for climate change mitigation and biodiversity conservation will also become increasingly important over the coming century. Unconverted lands are the reservoirs of much of the world's biodiversity and the services it provides. And forests are also an important land use for capturing carbon from the atmosphere and storing it securely. The provision of these important goods and services will also require an increasing allocation of lands (Hertel, 2017).

So, as Steinbuks and Hertel (2014) demonstrate, both agriculture and environmental services will require substantial amounts of land in the medium and long run. Lasting solutions will recognise that the two problems—food production and environmental quality—must be addressed together (Foley et al., 2011).

In the first part of this paper, we examine the question of whether it will be possible for land resources to meet the combined objective of global public good provision and food requirements. Can we allocate lands to both these uses in a manner that satisfies both of these important objectives?

To address this issue, we employ a novel macroeconomic model to examine ways in which humanity might be able to reduce reliance on land use in the next one hundred years. We first show that it is possible to place the global economy on a path that meets population-based food requirements in the coming century, while simultaneously providing for a very substantial reduction in agricultural land use. Pursuing this pathway will make available the land required for the global public goods mentioned above, and simultaneously help to stabilise the production system.¹

An equally important issue concerns the policies that might be employed to address these two objectives together, when they seem so much in conflict. This conflict implies the need to examine potentially new approaches to economic growth and development, that can work in ways that combine the two objectives.

In the second part of the paper, we demonstrate that this important outcome may be attained via macroeconomic policies designed to move the economy down potentially preferred pathways. We demonstrate the impact of policies related to direct land-clearing activities (with minor impacts on the direction of the economy), but we also look at less direct forms of interventions working through human capital accumulation (such as compulsory education policies) and technology transfers (such as educational exchanges and extension services). These latter instruments have much broader impacts on the direction of the economies concerned, while also aiding with the pursuit of the land use objective. In this way we are able to see how the pursuit of these joint objectives are important parts of the over-arching problem of considering the general solution for the optimal pathway for global growth and development.

We proceed as follows: In section 2, we present a review of some of the literature on global land use, and use it to explain how our approach relates to others in the field. In section 3, we outline the MAVA model, the manner in which it has been fit to the past 50 years of observed data, and the derived forecast for the global economy over the next one hundred years. In section 4, we describe the food requirement and land use trade-off analytically, and estimate the welfare loss associated with several global land use constraints. In section 5, we examine various policy instruments available for re-directing the economy, and reducing land use in the long run. Section 6 provides a simple framework for considering and comparing these various instruments, and their impacts on the pathway of the general economy. Section 7 concludes our work.

2. Literature review

In this paper, we employ a macroeconomic model to study global land use in the long run. The model we use—the MAVA model—has its basis in the Unified Growth Theory (see e.g. Galor, 2011 and Galor and Weil, 2000). This theory has been developed to describe how transitions in the patterns of development occur in the very long run, and it allows us to simulate how the global economy will evolve in the next one hundred years.

The MAVA model has two features different from the canonical unified growth theory model. First, we fit the model with historical data of the last fifty years (1960–2010). This enables us to estimate several model parameters and to evaluate how well our model fit the past. Second, we add land to the agricultural production function. To produce food, society must use and clear land, which then is employed in agriculture to sustain the population. With these two changes, we are able to forecast how land might be allocated between differing uses over the coming century.²

We also build upon the economic and environmental science literature that researches land use and land availability. Our work is closely related to recent studies that have investigated the challenges humanity faces to meet food and environmental requirements in the long run.

Schmitz et al. (2014) study the relationship between agricultural production and environmental services by comparing several agronomic models. They find that most models analysed predict a cropland increase of 5–10% by 2050, which is similar to our predictions for land use in the coming century. Steinbuks and Hertel (2013) examine how uncertainties over three drivers affecting competition for land—energy and climate policies, agriculture and climate impacts, and technology—affect the global land profile in the long run. They find that uncertainty in energy prices dominates the other two drivers. Cai et al. (2017) study

¹ We are not the first to note that it should be possible for food security to be attained through reduced land use (Hertel, 2015). The distinctive element of our approach is its emphasis on the potential role of macroeconomic policies in achieving this outcome.

² For more details on the way we created the model and its feature, see Lanz et al. (2017). The MAVA model has also been employed to study other topics, such as the expansion of modern agriculture (Lanz et al. (2018a), land conversion under uncertainty (Lanz et al. (2018b)), and the role of resource constraints and dependency rates (Naso et al., 2020).

the right timing and required spending on agricultural R&D to meet food requirements in the future. They find that “society should accelerate R&D spending up to mid-century, thereafter moderating this growth rate”. Finally, [Steinbuks and Hertel \(2016\)](#) employ a dynamic, forward-looking, optimisation framework to understand how economic, agronomic, and biophysical drivers affect global land use. In line with our predictions, they find that continued conversion of land to agriculture is probably unnecessary after mid-century.

Our study benefits from the insights and results of these papers. The primary distinction between our work and theirs is that we are interested in additionally considering what we term ‘macroeconomic policies’—that is, policies that operate by effecting broader changes within the economy, not just direct changes in land use. For example, we are able to consider policies that drive a lower overall population (fertility policies) and also policies that induce increased technological change (technology policies), both types of policies being compatible with a reduced need for land use in agriculture. We also consider the effect of policies that operate more directly on land use for comparison purposes.

Our work is also related to recent research that analyses the long term challenges of meeting the world’s food requirements. [Foley et al. \(2011\)](#), for example, propose potential solutions for the environmental and food production challenges global agriculture is facing now. They show that increased efficiency, such as shifting diets and reducing waste, could double food production in the future. Their paper complements ours in the sense that they analyse different types of policies that our model does not allow us to consider.

[Hertel \(2015\)](#) overviews the main findings from the literature on global sustainability and the global food system. He attempts to make sense of the great global challenges of meeting global food requirements while ensuring environmental sustainability, a relationship that is also the focus of our paper: how can humanity increase food production given the necessary provision of global public goods?

We recognise all of these important preceding contributions, and believe that our results fit fully within them. The only piece of the puzzle we bring in addition is the examination of macropolicy impacts that achieve the outcomes being advocated throughout this literature.

3. The MAVA model

The MAVA model is based on the insight that four key economic variables—population, land use, technology and production—move together across time as an inter-linked socio-economic system. It is a standard endogenous growth model, but with an added agricultural sector.

The model functions by determining the optimal level of population at every period, and then by allocating shares of the associated labour force to all of the various economic sectors: (i) land clearing; (ii) food production; (iii) manufactures production; (iv) child rearing; (v) agricultural R&D; and (vi) manufactures R&D. It does this allocation in such a manner as to follow an optimal pathway over time for population, production, land use and technology.

By fitting the model to historical data, we are able to see how this system has moved together across the past 50 years, and to run the same fit forward in order to forecast how we would expect the system to move in the future. In this paper, we examine how various policy interventions might have an impact on the economy as a whole, in the next century, focusing on the management of global land use as the main policy objective here.

The literature that examines land use allocation in the long-run is vast. Our study benefits from recent work that has extensively examined global cropland expansion ([Schmitz et al., 2014](#)) and the optimal allocation of land use between public good uses (mainly climate) and private uses (mainly agriculture) ([Steinbuks and Hertel, 2013](#), [Golub et al., 2009](#) and [Hertel et al., 2013](#)).³ We incorporate elements of these models. The main distinction of our approach in terms of modelling is that we use unified growth theory to combine various economic phenomena into one system, rendering it feasible to examine how broader sets of policies might impact on land use in the longer run.

3.1. Description of the model

This section provides a succinct description of the main components of the model. We invite readers to look at [Appendix A](#) (equations), [B](#) (parameter values) and [C](#) (historical data), and at [Lanz et al. \(2017\)](#) for a comprehensive description of the MAVA model.

3.2. Preferences

As in [Barro and Becker \(1989\)](#), we use a dynastic utility function, where fertility and the utility of children are complements in parents’ utility. This implies that society seeks the path that provides the greatest utility for the greatest number of people.

³ There are other existing models examining land use at the global level. They 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](#)). The models are 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. \(2011\)](#), IMAGE (mainly developed at PBL, see for example [Smith et al., 2010](#) and [Alcamo et al., 2005](#)). A dynamic, forward-looking optimisation framework is used in looking at long term land use issues in FABLE ([Steinbuks and Hertel, 2013](#)).

Utility is obtained solely via consumption of a manufactured good; food production is implicit solely in the food requirement constraint necessary to sustain the current population.

3.3 Production

Our model has two sectors: the manufacturing sector, which produces the good that is consumed by individuals; and the agricultural sector, which produces food to sustain contemporaneous population. Production in both sectors requires physical capital and labour, and is also determined by the technology state of each sector. In addition, agricultural production requires arable land as an input.

3.4. Technological progress

As in the Schumpeterian model of [Aghion and Howitt \(1990\)](#), technology in both sectors evolves along a technology ladder at a rate determined by an innovation production function. This rate is determined by the labour shares employed in agriculture and manufacture R&D, and by their respective productivity.

3.5. Population dynamics

In each period, the change in world population is given by the difference between fertility and mortality—that is, the rate at which population exits the labour force. Fertility (labour units production) derives from the allocation of labour to child-rearing, which is a combination of sustenance and education. In line with the literature on the demographic transition, child-rearing incentives alter with the technological state of society. As technology advances, more education is required to train a new individual to be ready for employment. This technological effect increases costs of child-rearing, but, at the same time, makes newly produced individuals more productive as compared to the earlier generation. Finally, population dynamics are further affected by food availability—in every period, society must provide food to all its members.

3.6. Land in agriculture

The land input to agriculture has to be converted from a total stock of available land by applying land clearing labour.⁴ The rate at which natural land is cleared is determined by the land clearing labour share and its productivity.

3.7. Summary

[Fig. 1](#) illustrates how our model works, commencing from the left of the diagram. An optimal path for the economy will hinge on determining a pathway for population. Given population, society's welfare is maximised by the allocation of labour between six different tasks indicated: Manufacturing, Agriculture, R&D (Manufacture and Agriculture), Land Use and Fertility. The manufacture sector produces the consumption good, whereas the agricultural sector provides society's food requirements. These six sectors then operate to produce the current state of the economy in terms of population, production, land and technology. These generate a current level of social welfare, and return us to the left hand side of the diagram.

3.2. Baseline projections: 2010 – 2100

The MAVA model creates a system that moves together in all of its variables: land, population, technology, and GDP. To enable the creation of a working forward-looking model, this linked system is first fitted to historical data (1960–2010). This fit then enables us to see how the system has moved together across time. The manner and method of this fit is demonstrated and discussed in detail in [Lanz et al. \(2017\)](#). We run this fit forward to provide a baseline forecast for the remainder of this century (see [Fig. 2](#)).

Our projections for this century, 2010–2100, show that in 2100 we forecast an expected population of 12.4 billion, expected land use of 1.77 billion hectares, and a 300% increase in expected global GDP. These represent substantial increases over the current levels: 7.2 billion people, approximately 1.5 billion hectares of agricultural land, and 125 trillion USD in production.⁵ 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.

For purposes of public policies relating to land use, the most interesting feature of these forecasts is that they derive from a phenomenon of linked decline across all these sectors: population, production, land use and technology. That is, our forecast is in line with the view that economic growth is in broad decline and will tend toward a steady state in coming decades (see e.g. [Gordon, 2015](#)).

This phenomenon of the so called secular decline is demonstrated by the falling growth rates for the key economic variables of our model, as demonstrated in [Fig. 3](#). For purposes of land use policy, of all the variables in this linked system, agricultural

⁴ This view of land conversion in agriculture is consistent with recent studies ([Gibbs et al., 2010](#) and [Ramankutty, 2010](#)).

⁵ Our projections are in line with those forecasted by UN bodies: aggregate world population slightly below 10 billion by 2050 and converted agricultural lands around 1.7 billion hectares by 2050 ([Anon, 2013](#) and [Alexandratos and Bruinsma, 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 [Anon, 2013](#). Our projections also lie on the upper limit of the 95% confidence interval implied by the probabilistic projections reported in [Lutz and Samir \(2010\)](#).

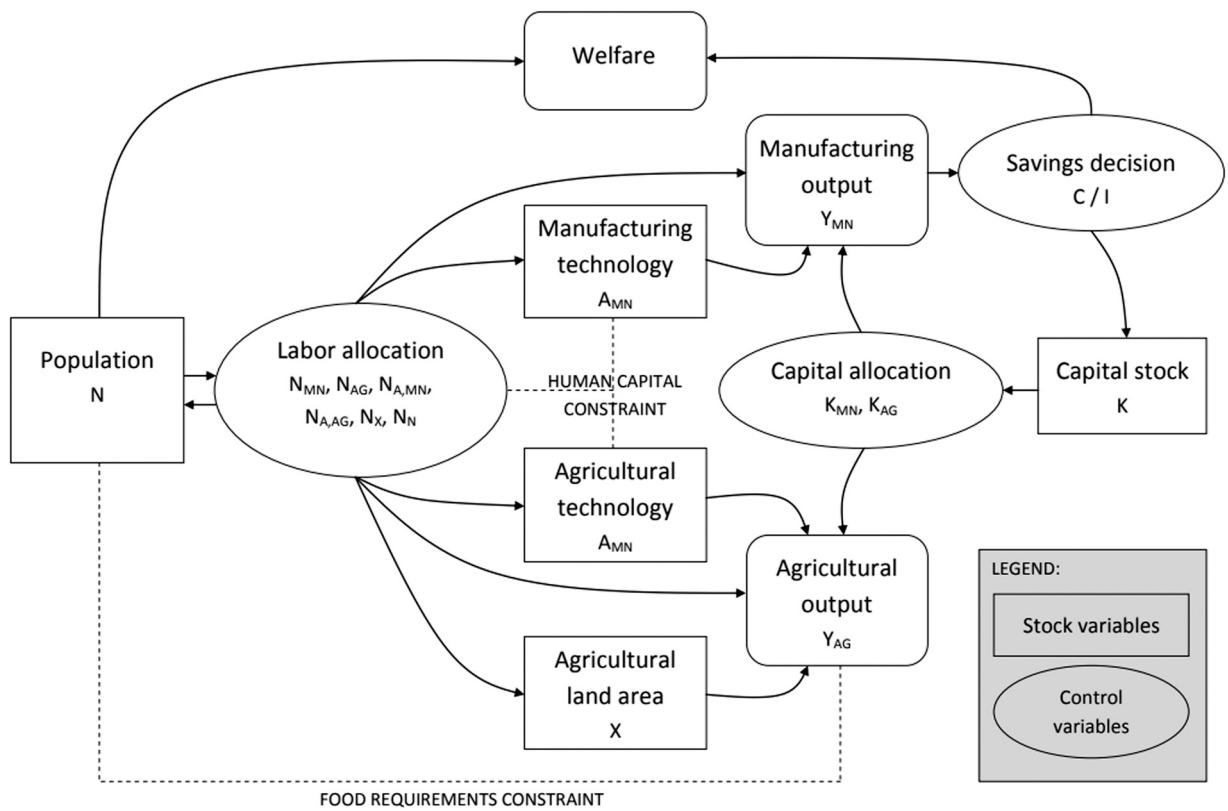


Fig. 1. Schematic representation of the model.

land is the first to reach an approximate steady state—its growth rate becomes negligible by 2050 and is approximately zero thereafter. Nevertheless, in the absence of any continued expansion in land use (Fig. 2), agricultural output increases by 67% between 2010 and 2050 and by 31% from 2050 to 2100.⁶

The results of our forecasting exercise indicate that the general direction of the economy is toward reduced growth—in terms of population, capital, GDP, and hence in all of the important inputs into the economy. For purposes of the macroeconomy (at least as it has existed over the previous fifty years), the reliance on the expanded use of land in agriculture is in a state of long run decline. This phenomenon is already apparent in land use trends in the developed world, and with adequate investment it should be possible to replicate the trend elsewhere.

The results set out in this forecast make it easier to contemplate dramatic changes in the amount of future land use in agriculture, and to ascertain how policy might move society more rapidly down that pathway.⁷

4. Managing land use in global agriculture

In this section, we describe the way in which the model can adjust to imposed land constraints for agricultural production and present estimates for their associated welfare loss.

At present, the amount of agricultural land in use is about 1.6 billion hectares, and we project a maximum level of use of about 1.77 billion hectares during the coming century. What is the cost of constraining agriculture to a much lower level of land use? For example, what if society requires that land allocated to global public goods, such as climate mitigation and biodiversity conservation, increases to 0.1 b, 0.2 b, or even 0.3 billion hectares off of baseline agricultural use? We can use the MAVA model to estimate the costs of moving to these lower levels of agricultural use and the associated higher levels of potential global public good provision.

⁶ This is in line with other studies, e.g. Alexandratos and Bruinsma (2012) projected a 72% increase in global agricultural output between 2010 and 2050.

⁷ Note that our forecasting exercise is motivated by taking historic economic patterns and projecting them forward. The past fifty years have seen substantial technological change in agriculture in 1960–2010 that drives much of what is seen in our data, but this has occurred primarily in the developed world. The forecasted outcomes in 2100 are most likely to come into existence if the developing world now replicates that pattern of development that occurred in the developed previously.

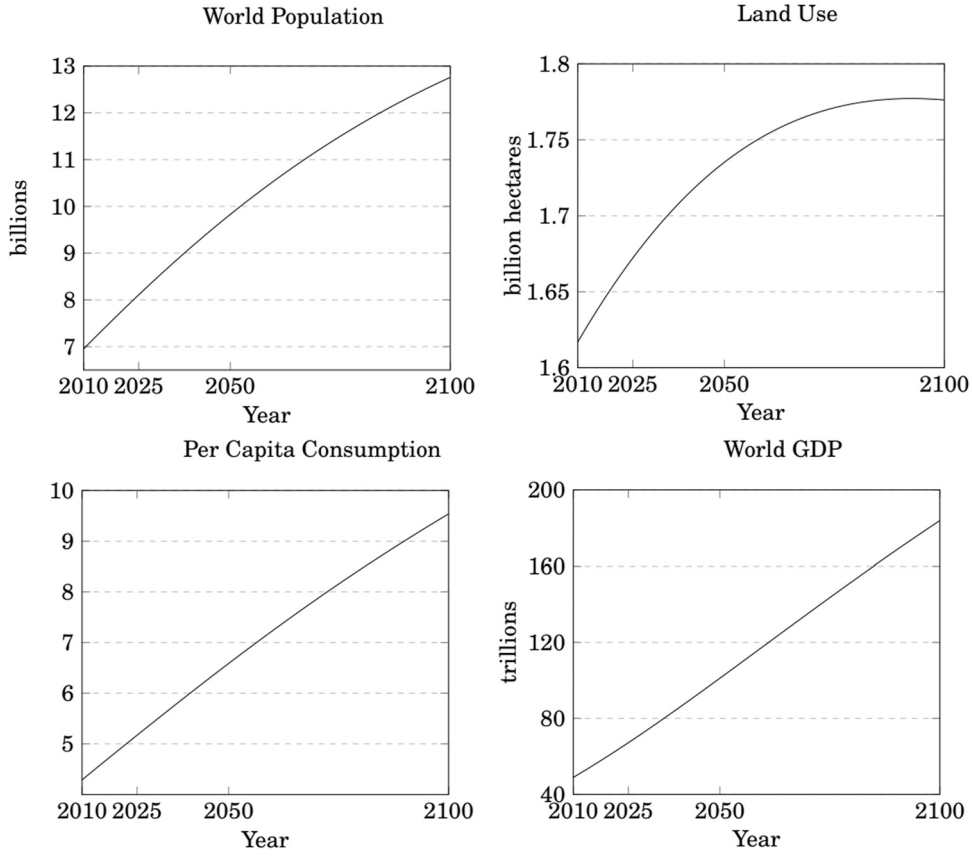


Fig. 2. Projections: 2010–2100.

To investigate the costliness associated with such higher levels of global public good provision, we compute the social welfare costs arising from food requirements when agricultural land inputs are constrained. As we described above, the concept of a *food requirement* is a key component of the dynamic problem solved by the MAVA model. As a first step, the model considers the total quantity of food needed to sustain the extant population, then it allocates labour in a fashion that both meets this requirement and maximises consumption-based societal welfare.

In each period of our simulations, society must meet a global food requirement, which is represented in the system by the following constraint,

$$N_t \bar{f}_t = Y_t^{ag}(A_{t,ag}, K_{t,ag}, N_{t,ag}, X_t) \tag{1}$$

where N_t is total population and Y_t^{ag} is agricultural output, which is a function of agricultural productivity $A_{t,ag}$, capital allocated to agriculture $K_{t,ag}$, labour allocated to agriculture $N_{t,ag}$ and stock of available land X_t .

Food demand \bar{f}_t increases with income according to,

$$\bar{f}_t = \xi \cdot \left(\frac{Y_{t,mn}}{N_t} \right)^\kappa \tag{2}$$

where ξ is a scale parameter, $\kappa > 0$ is the income elasticity of food consumption, and $Y_{t,mn}$ is the manufacturing output, which is a function of productivity in manufacturing. From this equation, we see that, as long as the technological level of society keeps increasing, food demand will continue to increase.

Our definition of a food requirement is met when the amount of food produced, is equal to society's needs $N_t \bar{f}_t = Y_t^{ag}$. Since this constraint must be satisfied in every period of our optimisation, the system is always, by definition, meeting the food requirement to be able to run. We are here interested in knowing the costs of meeting the food requirement constraint when agricultural land use is restricted.

The baseline forecast generated in Section 3 illustrates that land use is a declining factor in the generation of economic growth. It is declining in use, as with all other factors, on account of declining growth in general; however, it is also seen there that agricultural land use is the first economic factor to reach an approximate steady state in this general pattern of global

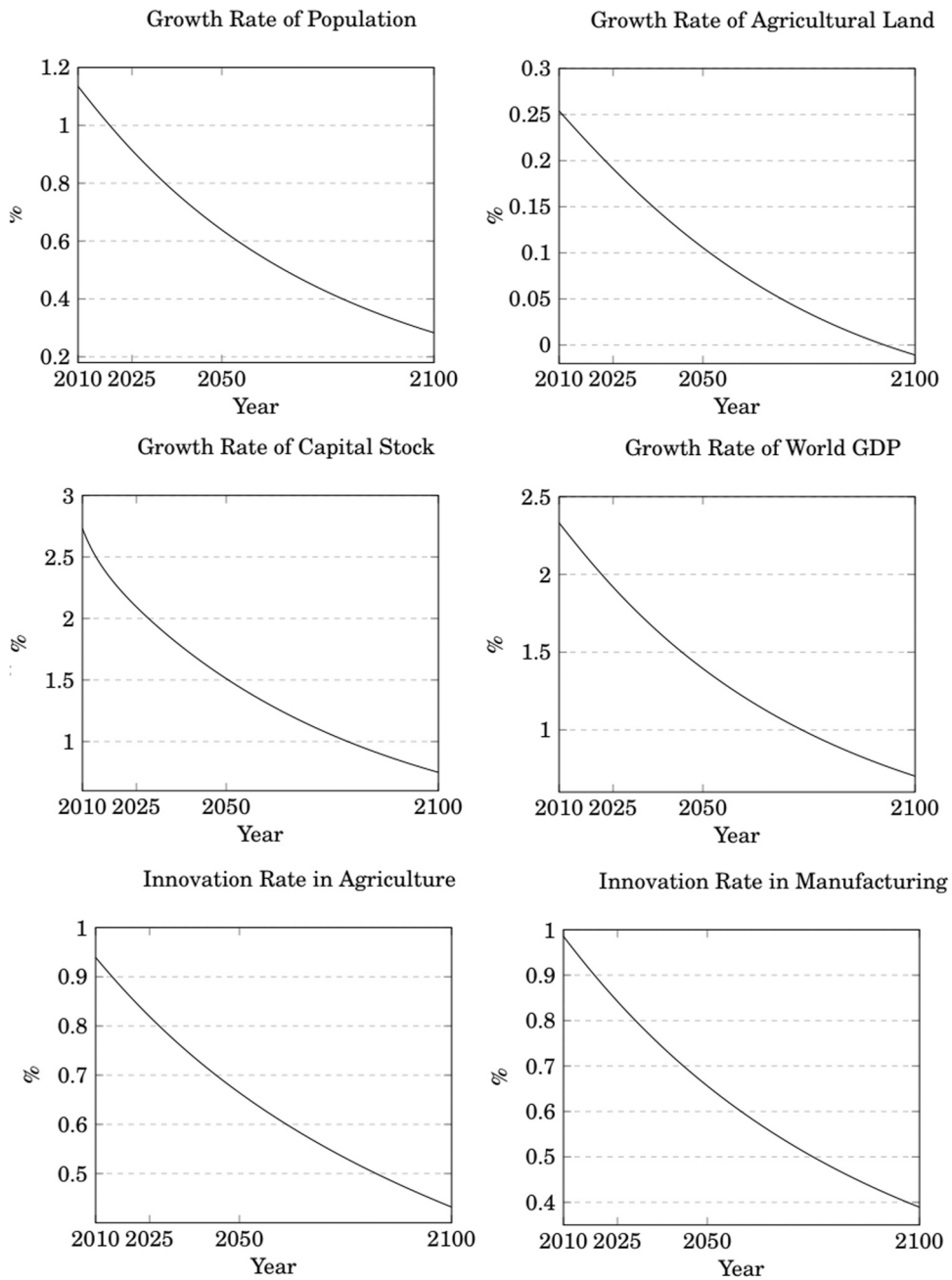


Fig. 3. Projected Growth Rates: 2010–2100.

decline in growth. For this reason it would seem it a priori reasonable to assume that pushing land use in the direction in which it is already moving would not be an overly costly policy pursuit.

To demonstrate this idea more precisely, we impose a series of land constraints on our model and run simulations under these constraints. In this context, a land constraint is equivalent to imposing a maximum available stock of land on the system \bar{X} , which will be binding in a specified target year. Results are presented in Table 1.⁸ The percentage values in this table are the welfare losses of each scenario as compared to the baseline simulation; the years portrayed in Table 1 represent the year in which each land constraint takes place in our simulations.

⁸ For a more detailed discussion of the impact of these land constraints on the global economy, see Naso et al. (2020).

Table 1
Change in Welfare under Alternative Land Use Constraints.

Land Constraint	2100	2050	2035	2025
1.6 billion hectares	-0.01%	-0.04%	-0.05%	-0.06%
1.5 billion hectares	-0.02%	-0.09%	-0.12%	-0.14%
1.4 billion hectares	-0.04%	-0.19%	-0.25%	-0.29%
1.2 billion hectares	-0.10%	-0.45%	-0.59%	-0.73%
1.0 billion hectares	-0.17%	-0.88%	-1.18%	-1.59%

Notes: Welfare losses are calculated using the social welfare objective function $\sum_{t=0}^T \beta^t N_t^{(1-\gamma)} \frac{c_t^{1-\gamma} - 1}{1-\gamma}$ as a percentage difference between its baseline value and the constrained scenarios.

Our results show that social welfare losses associated with the land constraints are not substantial. For a constraint of 1.0 billion hectares, binding in 2025, the total welfare loss incurred is around 1.59%. The situation is slightly better when we consider lighter constraints—if a constraint of around 1.4 billion hectares is imposed, in 2025, social welfare loss is approximately 0.29%. These results indicate that, if society were to impose a land constraint because of global public provision, it could do so (and meet long run food requirements) at a relatively minor cost.

Fig. 4 describes welfare losses for the range of feasible land constraints that might be imposed by the year 2050. The system cannot converge when we impose land constraints that are below 1 billion hectares, which suggests that society is not able to achieve that outcome (i.e. it is not feasible to meet extant food requirements with this land use constraint in that amount of time). The figure confirms, however, that welfare costs associated to global land constraints in 2050 range from about nearly 0% (no constraint) to 0.9% (1 billion hectares constraint).

How is this possible? To meet food requirements in the long run with a reduced available stock of land, the global economy needs to reorganise. As we show elsewhere (Naso et al., 2020), this is achieved by a reallocation of labour across sectors—the labour share of child rearing and land clearing decreases in the face of such constraints whereas agricultural R&D increases. If allowed to meet the constraint through its own forces, the model elects to shift toward labour allocations that increase agricultural productivity.⁹

Here we have demonstrated that potentially socially beneficial outcomes are achievable from imposing constraints on land use in the agricultural economy.¹⁰ By combining sound policies and investment in agricultural innovation, changes in agriculture may be able to achieve a superior equilibrium for society as a whole. This of course assumes that the provision of 0.1–0.5 billion hectares of land for the supply of global public goods is of a value greater than the approximately 1% of global GDP it could cost the economy.¹¹

In the remainder of this paper, we examine the nature of some possible policies that might be used to implement such changes in the economy. We find that a broad array of policies have the potential to alter the amount of land used in agriculture and that, given the manner in which this linked system moves together, it is possible to intervene in unexpected ways in order to achieve these broader global land use objectives.

5. Implementation of macroeconomic policies for public good provision in global land use

In this section, we examine how society might implement the land constraints we discuss above, by considering the use of a broad range of policy options. These policies all work in a similar way: they change the incentives society faces when allocating labour across sectors. Any reallocation of labour will move the entire economy onto a potentially different pathway in regard to the key variables of concern (population, production, technology and land use).¹²

It is problematic to consider a concept such as global land use management because the global economy is not centrally managed, and in regard to land use, management consists of many distinct sovereign states with their own policies and own decision-making processes. Nevertheless, it is possible to envision the adoption of particular policies by some or many individual states, and to ask the question concerning what would happen if the aggregate impact of such individual decisions were to cause the global parameters to shift somewhat in the direction indicated.¹³

In the following subsections, we pursue simulations by implementing variations in the parameters used in the MAVA model, to reflect the effects from the possible adoption of policies that would result in such parametric shifts. The goal of each policy

⁹ Enabling the model to reallocate labour in an unrestricted manner, and the allocations it then elects, demonstrates the dominance of technology-focused solutions to this joint problem, and points to the sorts of macro-policies that might be used to address it. We return to this point in Section 6, below.

¹⁰ Recent work has shown that some developing countries have been successful in combining land constraints (for environmental services) with food production (Lambin and Meyfroidt, 2011)

¹¹ There has been much work demonstrating that the potential costs of climate change or biodiversity loss may be much greater than 1% of GDP (for a literature review of the economic impacts of climate change, see e.g. Tol, 2018).

¹² For an analysis of specific policies concerned with land retention, other authors have reviewed their existence and feasibility (Hertel, 2017). Here we examine the idea of intervention to attain much lower levels of land use in agriculture.

¹³ We are analysing the model by assuming that shifts in parameters may be obtained by means of partial adoption globally, through individual state adoption and advocacy. Other papers have assumed that land use policies may be pursued via use of global policies and instruments, e.g., a carbon tax (Golub et al., 2009).

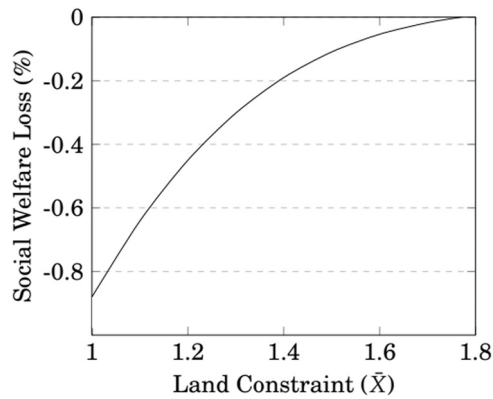


Fig. 4. Social Welfare Losses as a Function of Imposed Land Constraints (constraint effective as of 2050).

change is to effect the re-allocation of labour toward or away from the indicated activity. In this way, we can examine how the economy adjusts to the policy-instigated labour re-allocation, and where the new equilibrium will reside.

We examine how policies impact upon the economy if they are intended to shift labour: a) away from land conversion activities; b) away from child-rearing activities; or c) towards R&D services.

5.1. Policies for restriction of labour allocated to land conversion

The most straightforward approach to thinking about land conservation policy is to consider how policy interventions might directly impact upon the labour allocated to the tasks of clearing land in agriculture. We start by demonstrating precisely how we model this policy change within our simulations, and then discuss how such a parameter change (or its effect) might be accomplished through policy change.

Equation 3 describes how the amount of converted land evolves over time:

$$X_{t+1} = X_t(1 - \delta_X) + \psi \cdot N_{t,X}^\epsilon \tag{3}$$

Converted land X_t depreciates at a constant rate δ_X , and increases according to land clearing labour share $N_{t,X}$, its productivity ψ and its elasticity ϵ .¹⁴

The policy change we wish to investigate here is the creation of an incentive for the re-allocation of labour away from this activity. We do so by positing a change in labour productivity. In our simulations, this is accomplished by reducing the parameter ψ so that it requires more labour to convert the same amount of land relative to the baseline value.

This renders land conversion a less productive activity, and results indirectly in the reallocation of labour toward other uses. This re-allocation of labour results in both reduced amounts of land conversion and increased amounts of labour available for other pursuits. This change affects the scale at which land is cleared in every period and, because of the cumulative nature of this process, has a substantial impact on the amount of land cleared. Fig. 5 shows that the introduction of reduced productivity in land clearance results in a significant decrease in land conversion. Restrictions that reduce productivity by 30% drive agricultural land use to 1.4 billion hectares, and restrictions that reduce it by 50% drive agricultural land use toward 1.0 billion hectares.

These changes in the economy are accomplished at minor costs in social welfare. This is seen by the fact that these parameter shifts have little impact on the optimal paths of the important macroeconomic variables (population, production and consumption)—while the amount of land in agricultural use is much reduced.¹⁵ Thus, this sort of policy does not impose any broad labour re-allocation upon the system, while effecting significant change in land use. Equally important, the shift in this parameter is also the most direct means of reducing (rapidly) the amount of land used in agriculture, as Figure 5 demonstrates.

What sorts of policies can achieve this sort of shift in the productivity of land clearance in the economy? This parametric shift could be achieved, for example, by policies restricting the use of certain technologies or land uses in that enterprise (e.g. restrictions on the use of chain saws, bulldozers, fire). Restrictions on combining capital with labour in this sector (e.g. large machinery) would work direct reductions in the productivity of the sector, and thereby reduce the allocation of labour there.

Therefore, the most direct macroeconomic policy for land use management is to reduce land clearance through the re-allocation of labour away from this sector. This has the obvious benefit of working most directly on the desired objective, while doing so through direct labour re-allocation. The model demonstrates that this may be accomplished by reducing the relative productivity of labour in that sector, thereby moving labour toward other sectors of the economy. And this may be achieved through policies restricting combinations of capital and labour applied within this sector.

¹⁴ The natural rate of depreciation for cleared land is assumed to be 2%.

¹⁵ This is due to the fact that a small amount of the global labour share is allocated to land clearing in the baseline simulation—approximately 0.5%.

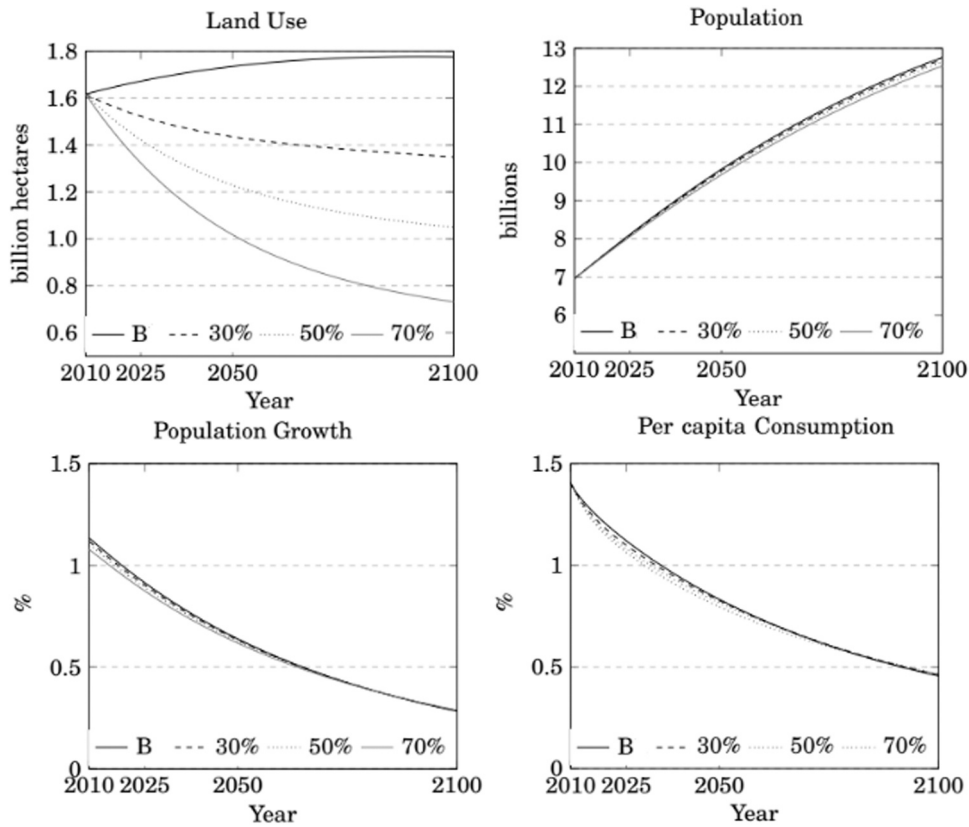


Fig. 5. Reduced Productivity in Land Clearing. Notes: The impact of reduced productivity in land clearing was calculated by decreasing the coefficient ψ , which determines how much land is cleared for one unit of labour employed in land clearing (see Appendix A).

This result is in part assumed. This is because the MAVA model does not consider costs of implementation, such as policing costs involved—the prospect of command and control instruments implies associated labour re-allocation costs that are not included within the model. For this reason, it may be preferable to utilise policy instruments based more on economic incentives than policing (and the implied labour allocations of command and control).¹⁶

5.2. Policies mandating the amount of labour allocated to the production of human capital

In contrast with the previous section, we now consider a much more wide-ranging policy impacting upon the amount of land used in agriculture. Here we examine how it might be possible to substitute policies creating much broader shifts in the economy, including those emphasising increased investments in human capital, and observe how these changes are capable of shifting the economy onto a less land-intensive pathway. These sorts of policy shifts result in much more dramatic changes in the economy, which may be preferred over those that are more narrowly focused upon land use objectives alone.

In the MAVA model, human capital is accumulated in a labour-formation stage, during which the current generation must allocate a certain share of its current labour force in order to create a next generation that becomes an effective labour force via this investment. Given the need for labour allocations to create additional effective labour units, it is possible to introduce policy change by means of any requirement that commands that more current labour units be used to generate future ones. This is a direct form of policy making regarding fertility—it alters decision making via changes in the investment required in raising a child.

Equation 4 describes the process used to produce new units of labour in our model:

$$N_t n_t = \chi^t N_{t,N}^s / A_t^\omega \tag{4}$$

¹⁶ In Appendix D, we discuss a different land conversion management policy, a tax on land clearing labour. Similar to the policy discussed in this section, a tax would allocate labour away from land services, reducing land use.

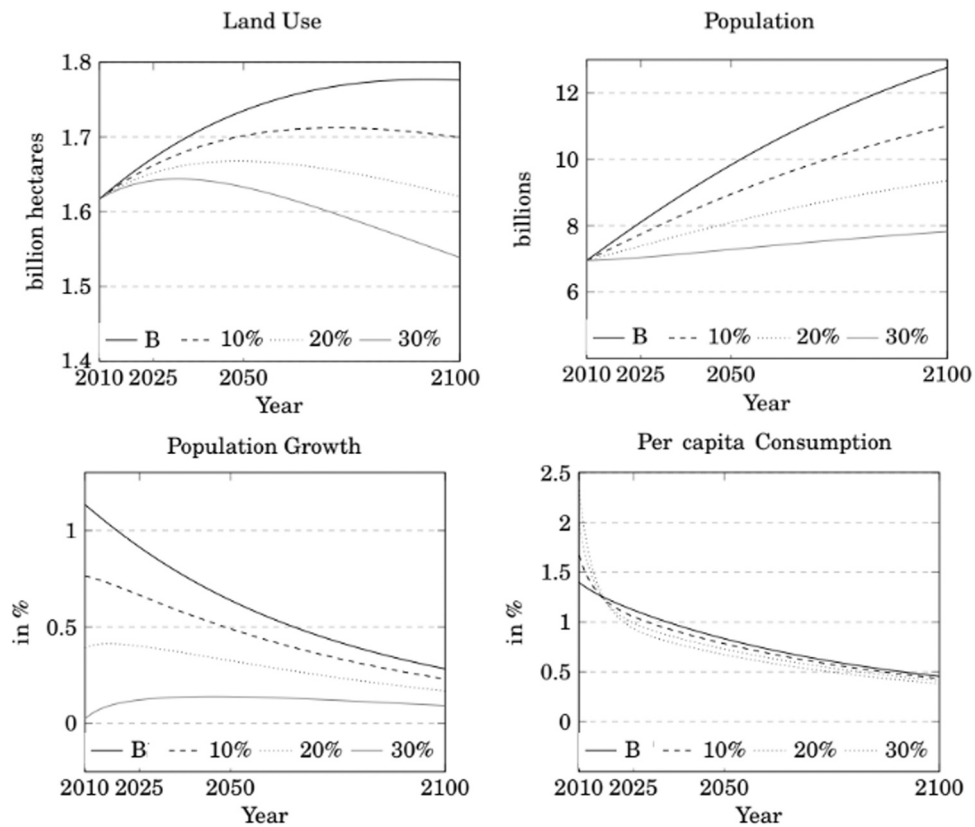


Fig. 6. Increased Cost of Child Rearing.

The variable n_t is the fertility rate, $N_{t,N}$ is the child rearing labour share, A_t is the technology index, ζ and ω are elasticity parameters, and χ is the productivity parameter. In line with the endogenous growth literature, we assume that the costs of fertility are increasing in the scale of technology.

In the simulations of this section, we reduce the parameter χ . A reduction in this parameter has the effect of reducing the productivity of labour in child rearing, and so renders it a relatively less beneficial sector for the economy.

In Fig. 6, we are able to see how reductions in this productivity parameter impact upon the macroeconomy (expressed in terms of the shift in the required costs of child-rearing). A shift in labour requirements increasing mandatory child investment costs by 30% results in population levels remaining at about 9 billion at the end of the century. In turn, this results in land use requirements of under 1.6 billion hectares.

Compared to the parameter shift investigated in the previous section, this is a shift that is able to reduce land use in agriculture but only through very substantial changes in other parts of the economy—especially the reduction in the population implied here. This in turn implies a substantial decline in the scale of the aggregate economy, and a relative decline in the growth of per capita consumption.

This is because this indirect manner of implementing land use change requires a very substantial re-allocation of labour in the economy.¹⁷ As the cost of child rearing increases, the share of labour dedicated to child rearing decreases, from around 60% to 52%. The labour shares of land clearing, agriculture and agriculture R&D also decrease due to reduced population size and reduced food requirements. Finally, the labour share of manufacture increases from around 21% to 27%. This happens because the system attempts to compensate for reduced population with increased consumption.¹⁸ Overall, the costs of this approach are much enhanced by reason of the broad-based disruption that it implies within the overall economy.

What sort of policy intervention is capable of influencing the costs of child rearing in this manner? Most directly, fertility policy is impacted by any change in required investments into children, such as compulsory education or child labour laws; or

¹⁷ See Fig. 8 in Appendix D.

¹⁸ Recall that the objective function for the MAVA model is a classical utilitarian one combining the product of population and per capita consumption. Of course this assumes that, in a model in which population is a choice, the maximisation of the level of population is part of the objective. Given that the problems addressed here (food provision, biodiversity losses, climate change) arise in part on account of population levels, it is arguable that the objective function might be better stated.

Table 2
Effect of an increased cost of child rearing on the amount of land used for agriculture (billion hectares).

Cost higher by	Cost of child rearing (years)	2010	2025	2035	2050
	17.65	1.62	1.67	1.70	1.73
10%	19.36	1.62	1.62	1.63	1.64
20%	21.41	1.62	1.66	1.68	1.71
30%	23.91	1.62	1.65	1.66	1.67
40%	27.08	1.62	1.64	1.64	1.63
50%	31.22	1.62	1.63	1.63	1.60
60%	36.89	1.62	1.62	1.61	1.57
70%	45.17	1.62	1.61	1.59	1.53

Notes: The impact of an increased cost in child rearing was calculated by decreasing the coefficient χ , which determines how many years are necessary for raising a child.

any change that increases the opportunity cost of the labour used in child rearing, such as increasing the rates of female education and female labour participation. These sorts of policies will have the implicit effect of reducing the productivity of labour allocated to child rearing, in that an effective labour unit will now take a larger labour allocation to produce.¹⁹

Table 2 shows how these policies mandating an increased costliness of child rearing (in terms of current labour-years required for the production of future labour) are able to alter the amount of land used in agriculture. It demonstrates that fertility policy indirectly impacts upon land use requirements through macroeconomic changes that impact much more directly on population levels. These broad changes in the economy move it far from the existing pathway. This represents a cost to society, in terms of the MAVA model's objective function, but it might in fact be a benefit if population reductions themselves help to address the policy objectives being pursued (i.e. biodiversity conservation and climate change).

Overall, it appears that a policy operating through fertility and human capital accumulation can have a larger impact upon population levels, and a smaller one on land use, through a broader redirection of the economy. The policy investigated here has the effect of altering the general pathway of the economy, encouraging the general movement toward a low quantity but high quality demographic equilibrium.²⁰ This sort of shift may be costly in terms of disruption to the current pathway, but it may be in furtherance of the overarching objectives being pursued by global land use policies. The macroeconomic approach is important for demonstrating how broader economic change may be considered and implemented within the context of land use policy.

5.3. Policies increasing the labour allocated to R&D

In this last subsection, we consider policies that target the reallocation of labour towards R&D in order to facilitate increases in agricultural productivity over time. The rationale is that technological change in agricultural production will enable substitution of other and fewer inputs for the land used in agricultural production. In particular, this may be viewed as a means of subsidising the transfer of technologies from the frontier (where land is already being substituted) to those countries within the frontier.

To capture this idea, we change the parameters of the MAVA model that determine the advance of agricultural technology. In our model, agricultural TFP increases along a technology ladder, driven by the accumulation of innovations within this sector. The rate at which innovations arrive in agriculture is given by the following equation,

$$\rho_{t,ag} = \lambda_{ag} (N_{t,Ag} / N_t)^{\mu_{ag}} \quad (5)$$

where λ_{ag} is the productivity parameter, $N_{t,Ag}$ is the agriculture R&D labour share and μ_{ag} is an elasticity.

To demonstrate the impact of a changed allocation of labour to agricultural R&D, we decrease the elasticity associated to the labour share of agriculture R&D, μ_{ag} . By doing that, we increase the marginal return of labour applied to R&D, increasing in turn the share of labour allocated to agriculture R&D.²¹ Fig. 7 presents the results of our simulations. Land use decreases in the medium and long run as the return to agricultural R&D increases, which reduces the reliance on land for food production. Population growth and population levels increase slightly, for two reasons. First, it becomes easier to meet the food requirement condition because of enhanced agricultural productivity. Second, the labour re-allocation occasioned by the shift toward R&D results in the removal of labour from land clearance and agricultural production. This has the effect of increasing the amount of labour available for child rearing.²²

¹⁹ In Appendix D, we discuss an alternative fertility policy, a tax on child rearing labour. Similarly to the policy discussed in this section, a tax would increase the cost of child rearing, decreasing population size and reducing land use.

²⁰ Our results are supported by the recent discussion on the impact of reproductive health services and contraceptive technologies on population growth and environmental services (Crist et al., 2017).

²¹ This approach is equivalent to a technology subsidy that increases the share of people working with R&D in society. An alternative type of technology policy would be to simply increase the productivity of the labour applied to agriculture R&D, λ_{ag} . We present simulations for this alternative in Appendix D. Results are somewhat similar to what we present in this section, although land use reduction in the long run is smaller with the second policy.

²² See Fig. 9 in Appendix D.

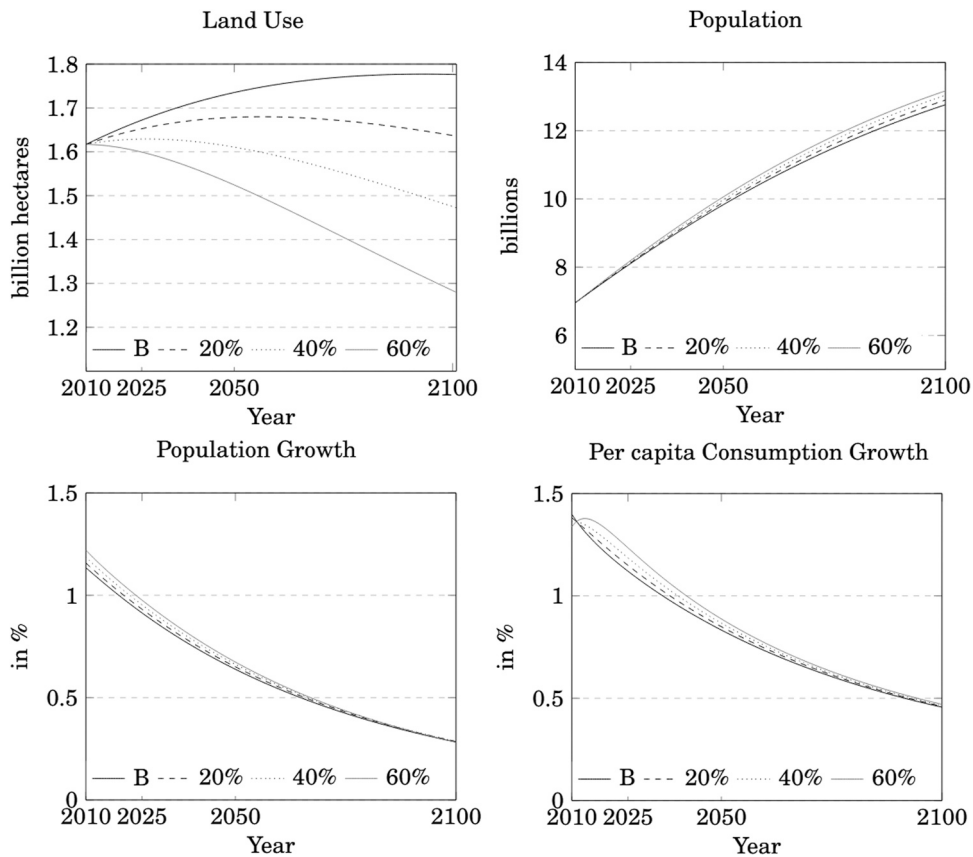


Fig. 7. Increased Labor Share in Agriculture R&D.

This policy might be implemented by subsidising the allocation of labour to agricultural R&D in developing countries, thereby providing the impetus for the transfer of technologies to them from the frontier (where agriculture is already relatively technology-intensive). This could be done, for example, by a policy of educational subsidies to developing countries, such as studentships at western agricultural universities.²³ This is a phenomenon that is already occurring to an extent, and the encouragement of this trend would enable developing countries to move more rapidly to a less land and labour-intensive form of agriculture.²⁴

Macroeconomic policy at the global level will always have a role for “catching up” when there are large differences between those countries on the frontier and inside of it. In the case of global land use, this is clearly the case. Developed countries have for many decades been releasing lands from agricultural use, while developing countries continue to expand their use of land. Agricultural production is very different in these differing parts of the world—one focusing on land- and labour-intensive production and the other on capital and technology. This section demonstrates that there is an important role to be played in subsidising agricultural R&D for purposes of transforming agriculture (and so society), and especially for purposes of driving down land use in the near term. This is a phenomenon that is likely to occur in any event in the long run, but it is important to encourage its adoption now in order to preserve the public goods on which we rely.

6. Global land use and policy – discussion

In this section, we provide a simple framework within which we consider the impacts of the policies outlined in Section 5. We focus on two criteria: the costs associated with implementing the various policies, and the time required to reach the land use target. We also briefly describe the broader societal benefits potentially associated with the pathways generated by each of them.²⁵

²³ There appears to be a decline on this type of initiative and on the formation of local centres for agricultural research (Byerlee and Lynam, 2020). The reinstatement of these sorts of technological transfers programmes could promote the type of policies we discuss here.

²⁴ To complement our analysis, we have also simulated an increase in both manufacture and agriculture TFP relative to the baseline. We do that by decreasing the elasticities of the innovation rate function in both sectors. The results, presented in Appendix D, are somewhat similar to the ones presented in this section.

²⁵ We analyse each of these policies separately for the sake of exposition, but they could be combined and implemented at the same time. At least in theory, society can decide the intensity of these various policies and decide exactly how much land it will devote to global public good provision, and at what cost.

Table 3
Evaluation of Global Land Use Policies – Years to Reach Targeted Land Use, Welfare Variation and Variation in Per Capita Consumption (PCC).

Policy	1.6b	1.5b	1.4b	Welfare	PCC
	Years	Years	Years		
<i>Land Use Restrictions</i>					
20%	5	92	–	-0.29%	-0.60%
40%	2	12	26	-0.67%	-1.50%
60%	1	7	14	-1.23%	-3.09%
<i>Human Capital</i>					
10%	–	–	–	-8.23%	-5.57%
20%	–	–	–	-16.10%	-11.02%
30%	64	–	–	-23.58%	-16.27%
<i>Technology Transfer</i>					
20%	–	–	–	0.61%	2.50%
40%	47	90	–	1.80%	5.38%
60%	15	47	71	2.85%	9.12%

Notes: Welfare variation are calculated by estimating the percentage difference in welfare value between baseline and each policy scenario. Note that these estimates do not take into account costs of implementation. Variation in consumption per capita ('Cons:') is calculated by estimating the percentage difference in the change in per capita consumption between baseline and each policy scenario. Note that these estimates do not take into account implementation costs. They can be interpreted then as gross variations.

The MAVA model enables us to estimate, for each global policy, the amount of time required to reduce land use, the welfare variation, and the variation in consumption per capita. Table 3 presents these estimates for the three macropolicies examined in this paper.

As the first set of results show, land use restrictions tend to reduce land use in a short amount of time at a relatively low welfare cost, as compared to the other policies. The entire range of possible targets—from 1.6 to 1.4 billion hectares—are attainable within this century at a welfare cost of around 1%. Moreover, most of the welfare cost associated with it comes from a reduction in consumption per capita and not so much from a reduction in population levels. Land use restriction policies alter the use of land in agriculture directly, with minimal disruption to the other parts of the economy. It is this finely-tuned nature of the instrument that renders it most efficient.

Human capital oriented policies have much broader implications for the development of economies. They focus on encouraging the demographic transition through the substitution of quality of inputs for quantity and not on other outcomes, such as land use. This is shown in our Table 3 by the fact that most land use targets are not even feasible under these policies, and they come at substantial cost. However, it may be the case that these sorts of policies are preferred for reasons other than land use management, for example, for the elimination of child labour in developing countries, and that land use objectives may be viewed as an ancillary benefit.²⁶

Finally, technology transfer policies generate welfare gains in the long run. Like the human capital policies, they do not act as directly as land use restriction policies, but they increase humanity's capacity to produce food for the same amount of agricultural inputs. Overall, we can think about these policies as encouraging the world down an already-existing pathway—toward reduced land- and labour-intensive agriculture. The main disadvantage of using these policies as compared to direct policies, however, is the pace at which land use targets would be met.

The main conclusion that emerges from this preliminary evaluation is that time is a key decision variable. If time is a crucial factor for policymakers—because of the imminence of catastrophic climate change, for example—land restriction policies should be used; if, on the other hand, time is not a major factor, then technology transfer policies appear to be more beneficial for society as a whole in the long run.²⁷

However, our conclusion might change when we consider costs that are not included within the MAVA model. Costs of implementation, such as monitoring and enforcement costs, vary from policy to policy, and may play an important role in evaluating each of these policies.

Land restriction policies require command and control methods of implementation, which can be expensive, specially in developing countries.²⁸ Moreover, these policies usually set up a contest between those wanting to convert land and those wanting to preserve public good functions, which would increase implementation costs even further.

Finally, it is important to note the generally limited nature of the estimates provided in Table 3, in regard to the costs and benefits associated with each policy there. This is because our model does not consider all of the costs or benefits of each policy concerned, but only the costs/benefits from the impact of the policy relative to the baseline path. For example, to make technology transfers effective (e.g. by moving scientists from the developed to the developing world), there may be significant

²⁶ One issue that mandated allocations of labour to child-rearing and education raises relates to the entities usually providing these services, and any additional burden this implies. For this reason, we prefer to conceptualise these as compulsory education policies, rather than additional fertility measures, which do not necessarily increase the burden of any particular segment of the population.

²⁷ Note that we do not consider the impacts of climate change in our simulations. However, the MAVA model was previously used to model uncertainty related to TFP accumulation (Lanz et al., 2018b) and that scenario could be helpful to understand the potential impacts of climate change to global land use.

²⁸ See e.g. de Souza Cunha et al. (2016) for an assessment of costs associated to forest conservation policies in Brazil.

subsidies required to achieve this. Then the costs of the policy (i.e. the subsidies) might cancel out the welfare gains of technology transfer policies showed in Table 3. Similarly, the MAVA model does not take into account the loss of labour implied in mandatory investment in human capital, which could make the welfare loss associated to human capital policies even more negative.²⁹

7. Conclusion

In this paper, we have investigated ways in which society can respond to the trade-off between food requirements and global land use. By employing a global land use model in which several sectors move in a co-integrated way, we simulate the baseline path—that is, the business as usual scenario for this century—and propose some macropolicies that can help society reduce land use in the long run. Our results show that significant improvements in food production (using the same stock of land) are achievable by means of policies that induce relatively minor labour re-allocations.

We also show that this reorganisation of the global economy does not come with major welfare losses. The global economy appears to adjust well to the imposition of land constraints—even more stringent constraints, such as 1.0 billion hectares, have a cost of no more than 1.6% of total welfare over almost one hundred years. This means that, if society were to impose a mix of the land use policies studied here, it could reduce land dependence while meeting food requirements at minor costs.

Society faces two types of long term challenges related to land use. The first one is to be able to increase food production to meet increasing requirements. As we show in section 3, without considerable improvement in agricultural productivity, this will require an expansion in global land use. The second is to reserve land to environmental services, such as climate change mitigation and biodiversity provision—more generally, global public good provision.

This paper shows that society may be able to implement certain macroeconomic policies that then induce broad labour shifts across economic sectors, targeting the combined objective of both food requirements and global public good provision. The policies can be as narrow as those focusing on a very specific task or activity (such as land use restrictions) but they may also be incredibly broad and general (such as compulsory education requirements).

A broader macroeconomic approach appears even more promising. We recommend the transfer of agricultural technologies from developed to developing countries, encouraging the migration of these technologies for the replacement of land- and labour-intensive agriculture in the developing world. This can be combined with a policy of human capital accumulation (via compulsory education requirements) to encourage the developing world down the development path it is already on, while hastening the day that the lands there are made available for the provision of a wide range of important public goods.

Conflict of Interest

We declare that there is not conflict of interest related to the manuscript: A Macroeconomic Approach to Global Land use, submitted to Resource and Energy Economics.

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Appendix A: Model details

Models' equations

This appendix lists all the equations of the MAVA model. For a comprehensive description of the model, see Lanz et al. (2017).

Preferences

We employ Barro and Becker (1989)'s dynastic utility function, where fertility n_t and the utility of children are complements in the parents' utility function. Our objective function is derived from their recursive formulation and is given by:

$$U_0 = \sum_{t=0}^T \beta^t N_t^{(1-\gamma)} \frac{c_t^{1-\gamma} - 1}{1-\gamma} \quad (6)$$

²⁹ Another important factor to consider is the inequalities that might be created by each of these policies. Unfortunately, our model does not enable us to estimate any distributional effects. But policymakers should take them into consideration to assure that disadvantaged groups in society will not be disfavoured even more by these policies.

N_t is the size of the population at time t , β is the discount rate in the economy, γ is the elasticity of marginal utility of consumption of the manufactured good, η is an elasticity determining how the utility of parents changes with fertility, and c_t is per capita consumption.

Production and capital accumulation

The MAVA model has two sectors: manufacture and agriculture. In the manufacturing sector, aggregate output is represented by a standard Cobb-Douglas production function:

$$Y_{t,mn} = A_{t,mn} K_{t,mn}^\vartheta N_{t,mn}^{1-\vartheta} \tag{7}$$

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 (i.e. food production) requires land X_t as an input. We employ a nested constant-elasticity-of-substitution (CES) to represent it:

$$Y_{t,ag} = A_{t,ag} \left[(1 - \theta_X) (K_{t,ag}^{\theta_K} N_{t,ag}^{1-\theta_K})^{\frac{\sigma-1}{\sigma}} + \theta_X X_t^{\frac{\sigma-1}{\sigma}} \right]^{\frac{\sigma}{\sigma-1}}, \tag{8}$$

where $\theta_{X,K} \in (0, 1)$, σ is the elasticity of substitution between a capital-labour composite factor and agricultural land, $A_{t,ag}$ is an index of productivity in agriculture, $K_{t,ag}$ is physical capital allocated to agriculture and $N_{t,ag}$ is the workforce allocated to agriculture.

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

$$Y_{t,mn} = C_t + I_t, \tag{9}$$

where C_t and I_t are aggregate consumption and investment respectively.

The accumulation of capital is then given by:

$$K_{t+1} = K_t(1 - \delta_K) + I_t, \quad K_0 \text{ given}, \tag{10}$$

where δ_K is a per period depreciation rate. Note that this equation describes the accumulation of total physical capital in this economy: $K_t = K_{t,ag} + K_{t,mn}$.

Population dynamics

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

$$N_{t+1} = N_t(1 - \delta_N + n_t), \quad N_0 \text{ given}. \tag{11}$$

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 the child rearing activities as well as the prevailing level of technology:

$$N_t n_t = \chi N_{t,N}^\zeta / A_t^\omega, \tag{12}$$

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.

Population dynamics are further affected by food availability, as measured by agricultural output. Food production equals food consumption, which is proportional to population size:

$$Y_t^{ag} = N_t \bar{f}_t \tag{13}$$

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

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

$$\bar{f}_t = \xi \cdot \left(\frac{Y_{t,mn}}{N_t} \right)^\kappa \tag{14}$$

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

Agricultural 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:

$$X_{t+1} = X_t(1 - \delta_X) + \psi \cdot N_{t,X}^\epsilon, \quad X_0 \text{ given}, \quad X_t \leq \bar{X}, \tag{15}$$

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.

Innovations and technological progress

In each period sectoral TFP evolves as:

$$A_{t+1,j} = A_{t,j} \cdot (1 + \rho_{t,j} S), \quad j \in \{mn, ag\}. \tag{16}$$

where S is the maximum growth rate of TFP and $\rho_{t,j} \in [0,1]$ is the arrival rate of innovations.³⁰

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

$$\rho_{t,j} = \lambda_j (N_{t,A_j} / N_t)^{\mu_j}, \quad j \in \{mn, ag\}, \tag{17}$$

where N_{t,A_j} is labour employed in R&D for sector j , $\lambda_j > 0$ is a productivity parameter and $\mu_j \in (0, 1)$ is an elasticity. This formulation implies that TFP growth increases with the share of labour allocated to the R&D sector.

Solution and optimal control problem

We consider the planner’s problem of selecting the allocation of labour, capital and savings rate to maximise the utility of a representative dynastic household. More specifically, a representative household chooses paths for N_t , K_t and C_t by maximising,

$$U_0 = \sum_{t=0}^T \beta^t N_t^{(1-\gamma)} \frac{C_t^{1-\gamma} - 1}{1-\gamma}$$

subject to equations 7, 8, 9, 10, 11, 15, 16, and the constraint for labour:

$$N_t = N_{t,mn} + N_{t,ag} + N_{t,A_{mn}} + N_{t,A_{ag}} + N_{t,N} + N_{t,X} \tag{18}$$

The numerical model is solved as a constrained non-linear optimisation problem. It then mimics the welfare maximisation programme by directly searching for a local optimum of the objective function subject to the constraints of the problem.

Equation 18 summarises the six types of labour that we have in our model: manufacture, agriculture, manufacture R&D, agriculture R&D, child rearing and land clearing. The MAVA model responds to the global policies we propose in this paper by reallocating labour across these tasks.

Appendix B: 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 more details about the fitting procedure see Lanz et al. (2017). Table 4.

Appendix C: Observed and simulated data

The table below reports both observed and simulated data from 1960 to 2100, by 10-year intervals. Table D.1.

Appendix D: Land use policies

Increased fertility cost – labour share allocation

See: Fig. 8.

Increased returns to agriculture r&d – labour share allocation

See: Fig. 9.

³⁰ In the original work of Aghion and Howitt (1990) 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.

Table 4

List of parameters of the model and associated numerical values.

<i>Imposed parameters</i>		
θ	Share of capital in manufacturing	0.3
θ_K	Share of capital in capital-labour composite for agriculture	0.3
θ_X	Share of land in agriculture	0.25
σ	Elasticity of substitution between land and the capital-labour composite	0.6
δ_K	Yearly rate of capital depreciation	0.1
S	Maximum increase in TFP each year	0.05
$\lambda_{mn,ag}$	Labour 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
<i>Initial values for the stock variables and calibrated parameters</i>		
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
<i>Estimated parameters</i>		
μ_{mn}	Elasticity of labour in manufacturing R&D	0.581
μ_{ag}	Elasticity of labour in agricultural R&D	0.537
χ	Labour productivity parameter in child rearing	0.153
ζ	Elasticity of labour in child rearing	0.427
1ω	Elasticity of labour productivity in child rearing w.r.t. technology	0.089
ψ	Labour productivity in land conversion	0.079
ε	Elasticity of labour in land-conversion	0.251

Table D.1

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

Alternative land use policies

We briefly present three alternative land use policies here. Our goal is to discuss different ways in which the macropolicies we propose might be implemented.

Increased cost of land clearing via a tax

An alternative to imposing restrictions on land conversion technologies is to directly restrict the amount of land clearing labour. We implement such a policy in our model by means of the application of a tax on land clearing labour.

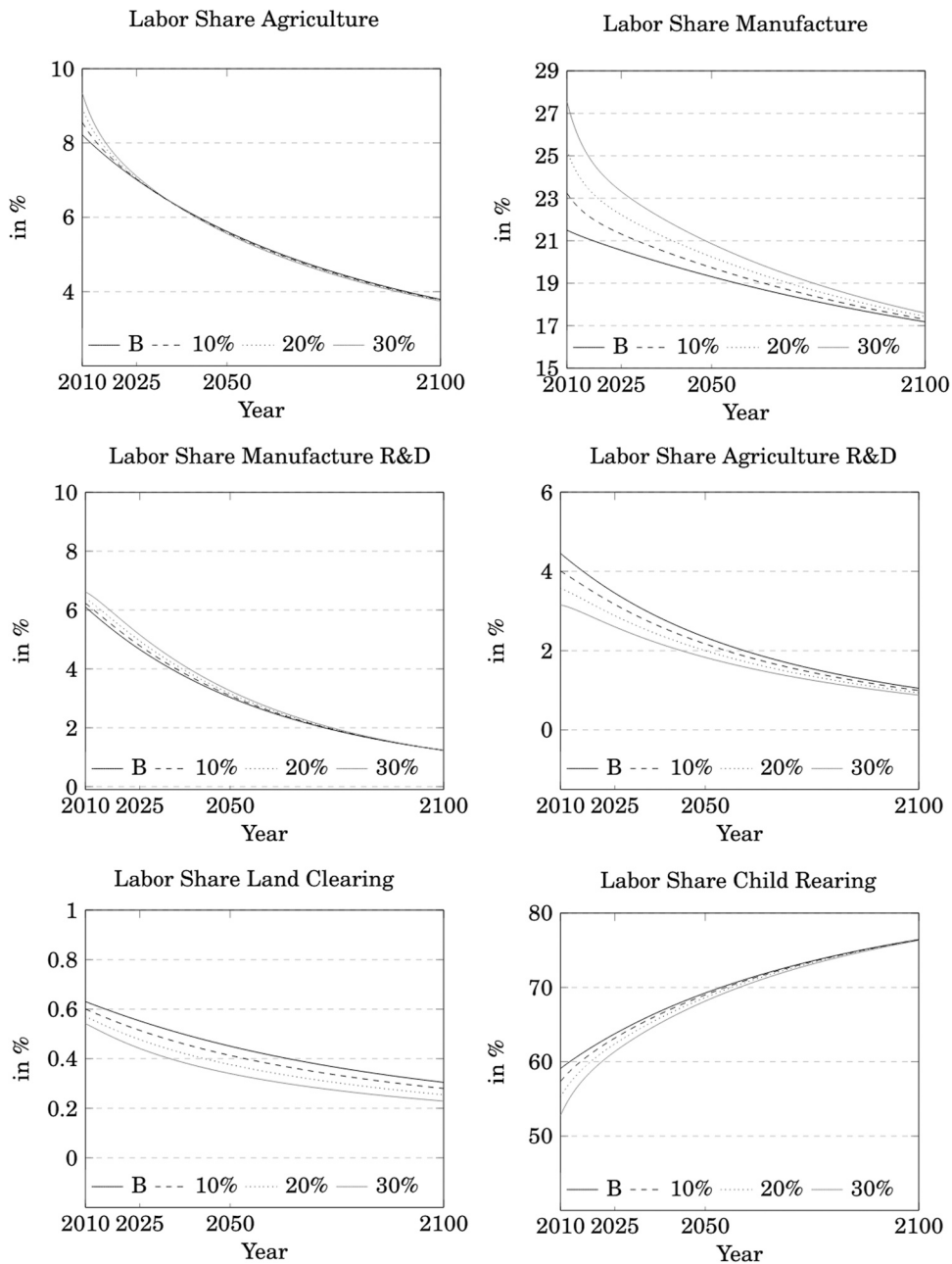


Fig. 8. Labor Share Allocation – Increased Fertility Cost.

As our model does not incorporate prices, we are only able to model a tax as an example of a policy that would reallocate labour away from the taxed activity. This of course assumes some amount of elasticity of labour supply. We also do not reallocate the labour that is shifted away from conversion to other activities, thus leading to a dead-weight loss in the economy resulting from the tax. In general, the results in this section should be viewed as illustrative of the impact of the shifting of labour away from land clearing, rather than a description of the new macroeconomic equilibrium that would result with a tax.

This type of policy creates a distortionary incentive and reduces the marginal benefit of employing labour in land clearing. Because, in equilibrium, the marginal benefit of all labour forms are equal, a decreased marginal benefit of labour in land

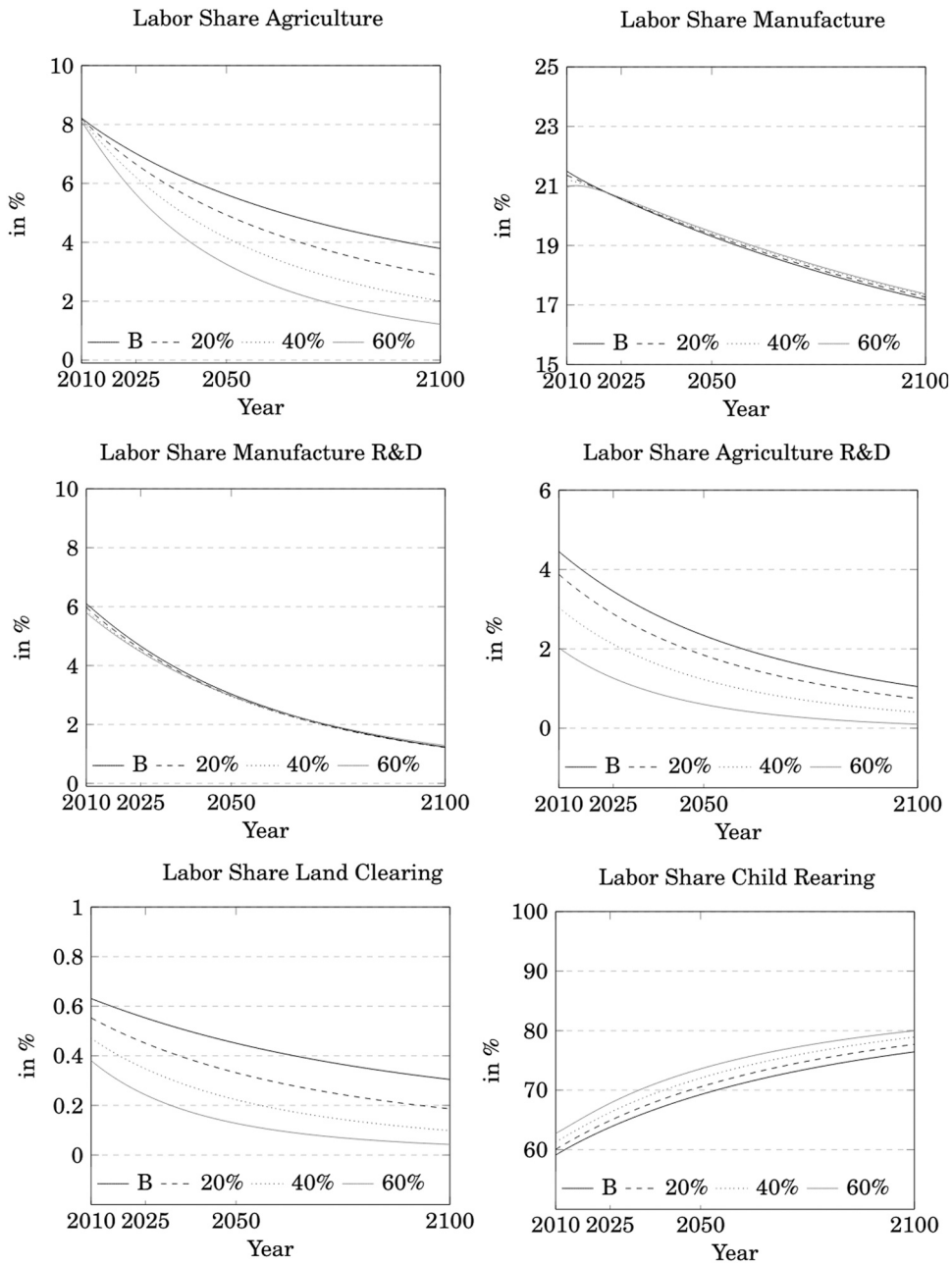


Fig. 9. Labor Share Allocation – Increased Share of Agriculture R&D Labor.

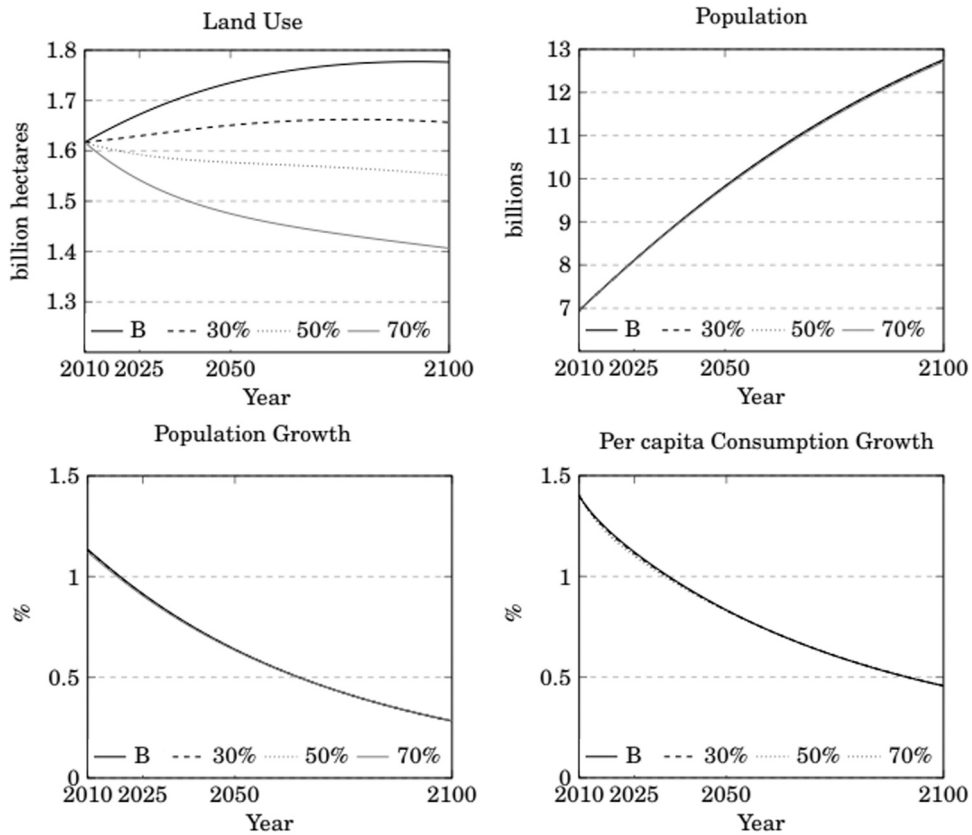


Fig. 10. Tax on Land Clearing. Notes: The impact of the land conversion tax was calculated by subtracting a fraction of the optimal amount of labor employed in land clearing at every period ($N_{t,x}(1 - \tau_x)$). This simulates the way in which a tax would work by generating distortionary incentives and a deadweight loss.

clearing results in a reallocation of labour to other sectors and a reduction in land use. However, the share of labour applied to land clearing is small as compared to other sectors, which substantially reduces the impact of this policy. Fig. 10 describes the implications of a tax on land clearing. We see that this is a very direct means of restraining land use in agriculture. We describe pathways resulting from policies that have the effect of restricting labour in land conversion by the amounts of 30%, 50% and 70%. In all cases, the optimal path for the economy remains virtually the same as the baseline, but with less land use in agriculture.

Note that this policy would only be able to reduce the amount of land use substantially if the tax on land conversion was extremely high. According to our results, the only way to cause land use to decline to 1.4 billion hectares by 2050 is to apply a 70% tax.

Increased cost of fertility via a tax

An alternative to increasing the investment requirement of human capital is to increase the cost associated to child rearing. Similarly to what we do with land clearing, we now model this fertility policy as having the same sort of impact as a tax on labour applied to child rearing, resulting in the withdrawal of labour from the activity.

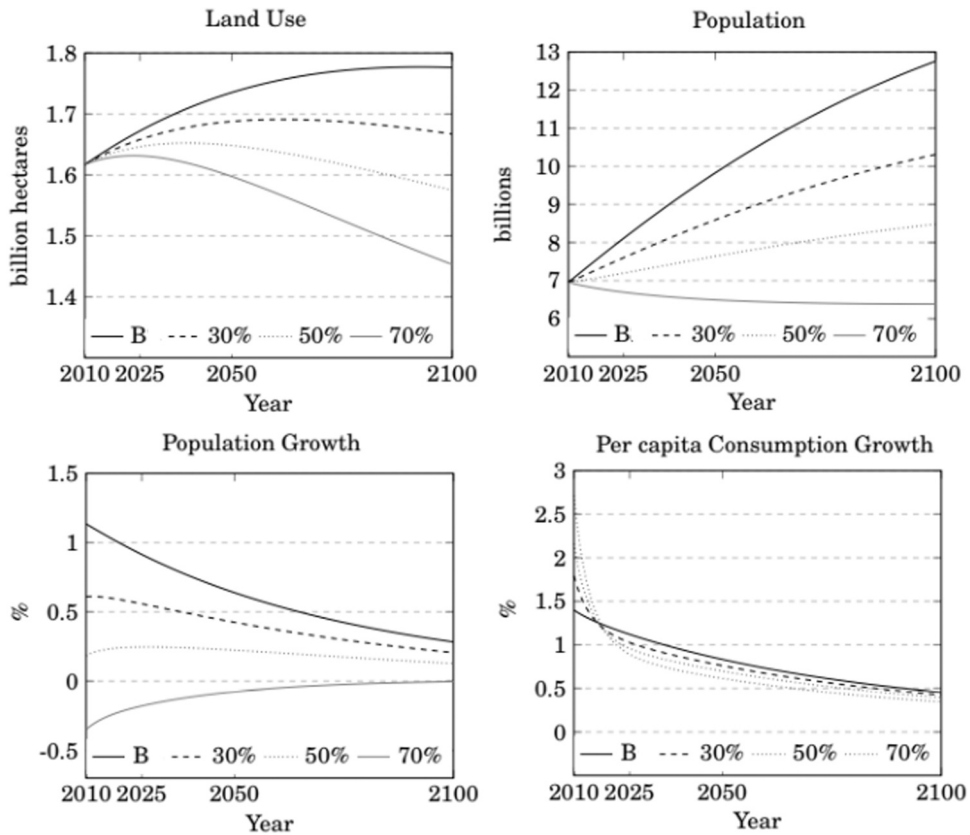


Fig. 11. Tax on Fertility. Notes: The impact of the fertility tax was calculated by subtracting a fraction of the optimal amount of labour in child rearing at every period ($N_{t,N}(1 - \tau_N)$). This simulates the way in which a tax would work by generating distortionary incentives and a dead-weight loss.

As expected, the main result is that aggregate population is shifted below the optimal pathway (see Fig. 11). The direct impact is to reduce population levels precipitously, causing aggregate population to decline potentially to half the baseline path (with a 70% increase in labour costs). At more modest increases in the “fertility tax” (of 30%) the decline in population is instead to about 10 billions or about 15% off the baseline. This implies that a very substantial increase in fertility tax can reduce land use to approximately 1.4 billion hectares.

The weakness of this approach lies in the fact that the impact on land use is being induced through population reductions, and these population reductions have the additional impact of reducing the labour supply for technological growth and development. In fact, the overall welfare level achieved under this policy constitutes a 30% reduction on the baseline path, simply because of the reduced size of the human economy.

Increased productivity of agriculture R&D

An alternative policy to increasing the returns to R&D is increasing labour R&D productivity directly. This intervention can be interpreted as a technology subsidy that enables researchers to buy better machines, for example. To implement it in our model, we increase the productivity parameter λ_{ag} .

As Fig. 12 shows, an increase in productivity of labour in agriculture R&D reduces reliance on land, increases population size and per capita consumption. The results are similar to the ones presented in section 4.3, promoting a technology subsidy via elasticity changes. However, society requires much larger increases in productivity to attain the same level of land use reduction attained with decreases in elasticity.

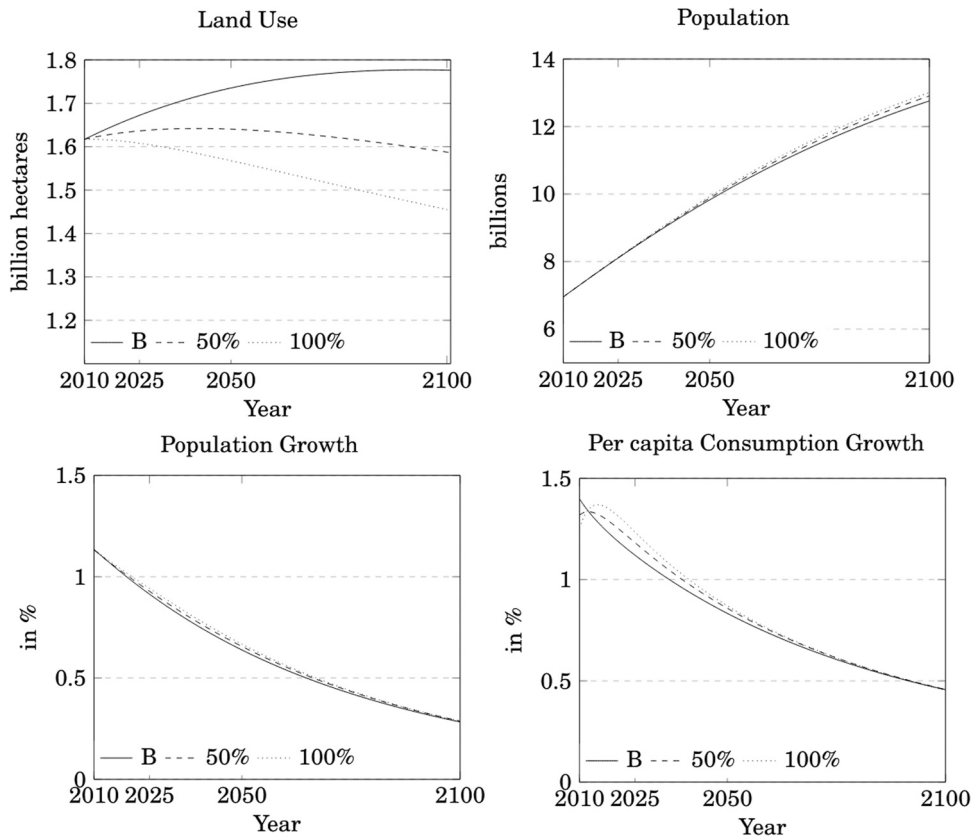


Fig. 12. Increased Productivity of Agriculture R&D Labor. Notes: The impact of this technology subsidy was calculated by decreasing the productivity of the labour share in agriculture R&D, λ_{ag} .

Increased labour share in both manufacture and agriculture R&D

Another type of technology subsidy that could be used to reduce society's reliance on land use is an intervention that stimulates both manufacture and agriculture R&D. The idea behind it is that a more advanced manufacture sector would free up labour to other sectors. Fig. 13 shows results for this policy. They are similar to the results presented for increases in the labour share of only agriculture R&D, presented in section 5. However, the system does not converge for a combined increase in the elasticity parameters that is larger than 15% of the baseline value. This suggests that the economy would not be able to accommodate such a policy—in other words, this policy of a combined technology subsidy of more than 15% would drive the economy too far away from the baseline path.

The labour re-allocation that this policy requires is somewhat similar to the policy presented in section 5. Labour applied in the agricultural sector—agriculture, agriculture R&D and land clearing—decreases as compared to the baseline. However, with this combined subsidy, labour applied to the manufacturing sector also decreases. The result is that this intervention increases more the share of the population working on child rearing than the single technology subsidy.

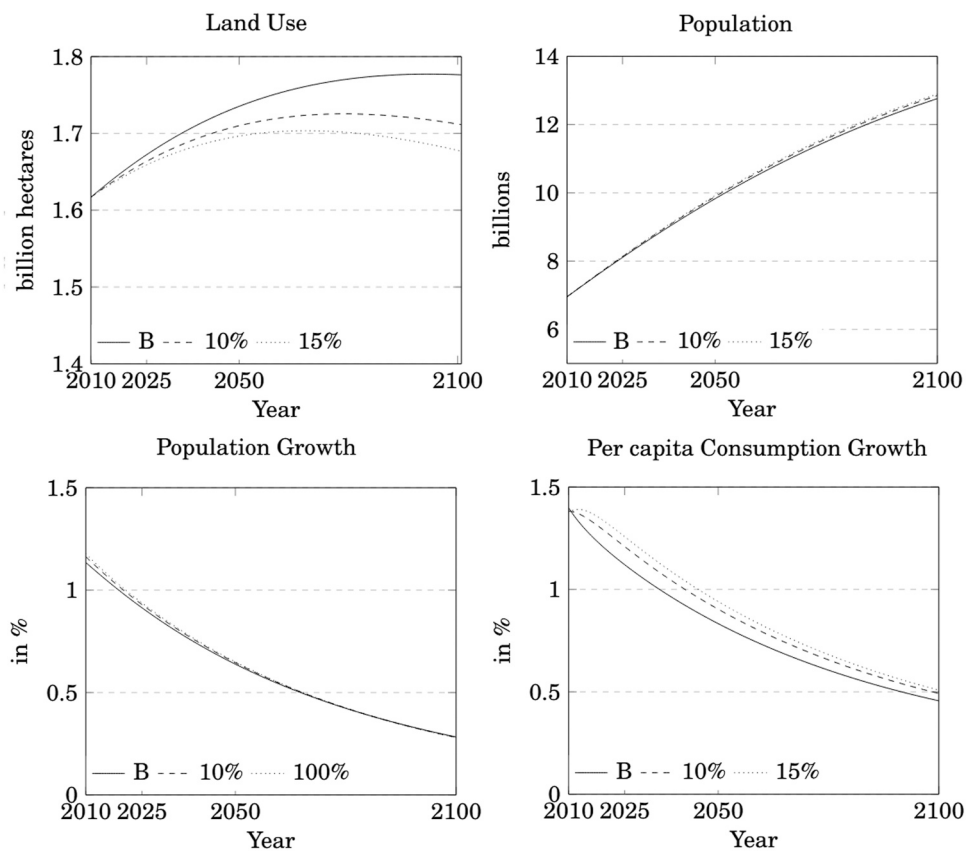


Fig. 13. Increased Labour Share in Manufacture and Agricultural R&D. Notes: The impact of this technology subsidy was calculated by decreasing the elasticities associate to the innovation rate functions of both sectors, μ_{ag} and μ_{mn} .

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