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FOOD SECURITY IN THE LONG-RUN: A MACROECONOMIC APPROACH TO 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 security and environmental services in the long run. We first show that it may be possible to provide for food security with very substantial constraints on the amount of land used in agriculture with relatively minor welfare losses. We then show that global policies that reallocate labour across sectors of the economy may have the capacity for directing the economy toward reduced reliance on land in agriculture. Focusing on education, research and development, and fertility costs may be the best way to meet these combined goals.

Keywords: Food Security, Land Use, Unified Growth Theory.

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1 Introduction

As recent studies in economics and environmental sciences have demonstrated (Foley et al. (2011), Cai et al. (2017), Hertel (2015) and Steinbuks and Hertel (2016)), there will be critical land use challenges arising out of agriculture in the coming century. The FAO has projected that food demand will rise by 60% by 2050, while Tilman et al. (2011) predict a 100% increase in global crop demand from 2005 to 2050.[1] These increased food requirements imply significantly increased land use, given continued reliance on existing agricultural systems.

However, the increasing pressure on land resources will not come from rising food requirements alone. Global public good provision also demands an increased allocation of land (Hertel (2017)). Forests are the reservoirs of much of global biodiversity and agricultural land use remains an important contributor to global carbon emissions. Steinbuks and Hertel (2014) demonstrate that both agriculture and environmental services, such as climate change mitigation, will require substantial amounts of land in the medium and long run. Lasting solutions will recognise that the two problems—agriculture and environment—must be addressed together (Foley et al. (2011)).

In this paper we are interested in the questions of whether it will be possible for land resources to meet the combined objectives of global public good and food security, and also the nature of the policies able to do so. We employ a novel macroeconomic model, derived from the unified growth theory, to examine ways in which humanity might be able to reduce reliance on land use in the next one hundred years. We first conclude 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.[2] [3]

Union or European Commission are accountable for the content of papers. It also has been presented at workshops or seminars at the International Union for Conservation of Nature (IUCN - Gland), World Economic Forum (WEF), University of Cambridge Centre for the Environment, and various meetings of BioEcon in Cambridge. We are grateful for comments on our previous work, and from seminar participants. We are also grateful to the MAVA Foundation for funding of the project.

[1] This projection is in line with other recent studies (see e.g. Cirera and Masset (2010) and Kearney (2010)).

[2] 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 role of macroeconomic policies in achieving this outcome.

[3] Note that we do not model explicitly public good provision in our simulations. We examine global policies that are able to reduce (agricultural) land use in the long-run and conjecture that part of the non-used land might be employed in global public good

Then we demonstrate that this important outcome may be attained via macroeconomic policies designed to induce particular labour market allocations—in order to effect societal change in terms of education, technology, and fertility. To this end, we demonstrate the impact of policies related to direct land-clearing activities, but also look at less direct interventions working through fertility services (such as education or child-rearing costs) and/or technology transfer and subsidy. The importance of our approach is that it first recognises that food security and global public goods comprise an important composite problem and, secondly, that this joint problem may be addressed through recognising the broad impacts of certain types of global policies.

We proceed as follows: In section 2, we present the literature review and use it to explain what we are trying to accomplish in terms of land use modelling. In section 3, we produce the results of those forecasts from other papers (the Baseline scenario) (Lanz et al. (2017)) and describe the food security and land use trade-off analytically. In section 4, we examine various policy instruments available for reducing land use in the long run, including taxes on various activities (such as land conversion) and broader macroeconomic policies for effecting the same outcomes. Section 5 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 100 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 (see section 3). Second, we add land to the agricultural production function. To produce food, society must use and clear land, which then may be 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.[4]

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provision. Our work offers a conceptual framework that enables us to examine the impacts of global policies on land use reliance in the long-run.

[4] 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 (Naso et al. (2020)). We do not

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. 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 to agriculture is probably unnecessary after mid-century.

Our study benefits from the insights and results of these three papers. The primary distinction between our work and theirs is that we are interested in additionally considering what we call 'macropolicies'—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.[5]

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 challenges (environmental and of food production) 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 do.

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? Finally, Cai et al. (2017)

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discuss in detail all the components of the MAVA model in the main text of this paper, but only give a general overview of how it works. For a detailed description of how the model was built, we advise readers to refer to Appendix A.

[5] We also consider the effect of policies that operate more directly on land use for comparison purposes.

study 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”. This is in line with the last policy analysed in this paper, a technology subsidy. By increasing the minimum share of labour in agricultural R&D, society might be able to guarantee an increased food production in the next 100 years, and reduce land dependence.[6]

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 policy impacts that achieve the outcomes being advocated throughout this literature.

3 The MAVA model

The model we use in this paper builds on long run land use modelling of the global macroeconomy.[7] The MAVA model is based on the insight that four key economic variables (population, land use, technology and production) are likely to move together across time as an inter-linked socio-economic system. By fitting the model to historical data, we are able to see both how this system has moved across the past 50 years, and we then forecast how we would expect the system to move in the future, and under varying policy scenarios. Here we examine how various policy interventions might have an impact on the economy as a whole, in the long run.

The literature that examines land use allocation and land availability in the long-run is vast. Our work benefits from recent work that has extensively examined the question of 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)).[8] We in-

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[6] In technology policy and fertility policy, reduced land use in agriculture is compatible with the outcomes from those policies; however, a reduction in population or land use may not necessarily be optimal. In short, we will be examining the outcomes from policies as being “costly” in the sense of the extent of the deviation from current baseline.

[7] For a detailed description of our model and a review on the work done on the modelling of long-term land use, see Lanz et al. (2017) and Lanz et al. (2018c).

[8] There are many 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)).

corporate elements of the models developed in these studies, and some of their insights. The main distinction of our approach is that our modelling uses the unified growth theory[9] 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.

The MAVA model is an endogenous growth model with an added agricultural sector that must produce the food required to sustain society's extant population. It functions by determining the optimal level of population at every period (necessary to produce food and manufactures) and then by allocating shares of that population to all of the various economic sectors required to sustain the population and the production system in that period: (i) land clearing; (ii) food production; (iii) manufactures production; (iv) child rearing; (v) agricultural R&D; and (vi) manufactures R&D.

Figure 1: Schematic representation of the model

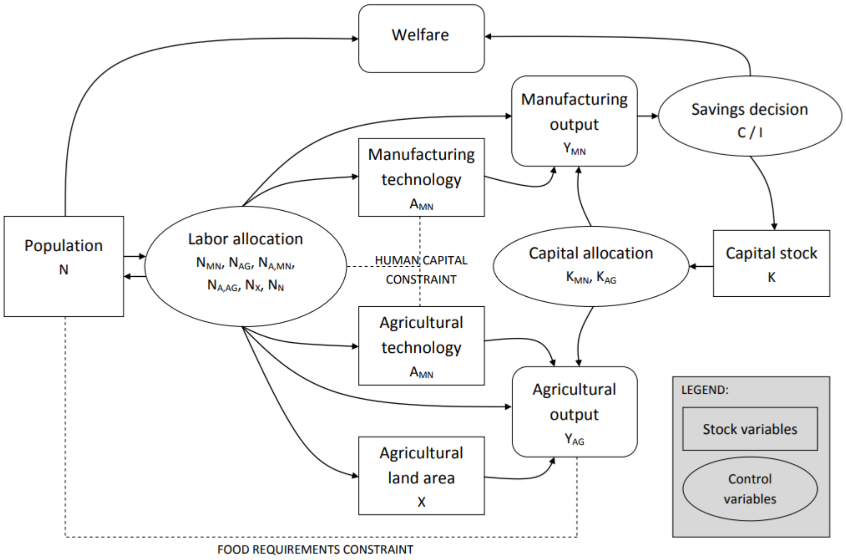

Figure 1 illustrates how our model works. Society's welfare is maximised subject to available labour—that is, the total amount of individuals performing each task. The manufacture sector produces consumption goods, whereas the agricultural sector provides society's food requirements. Land must be cleared for food production and depreciates at a constant rate. Finally, population increases with investments in fertility via a quality-quantity trade-off.[10]

A dynamic, forward-looking optimisation framework is used in looking at long term land use issues in FABLE (Steinbuks and Hertel (2013)).

[9] See e.g. Galor and Weil (2000) and Galor (2011).

[10] This means that fertility choice is determined by the costs of child-rearing. As technology advances, more education is required to train a new individual to be ready for

The objective of society in this modelling is utilitarian—the program pursues the path that provides the greatest utility for the greatest number of people. Utility is obtained by consumption, which comes from goods produced at the manufacturing sector; whereas population creation is determined by the necessary amount of labour to sustain the extant population (food production) and the costs associated to raise new members (child-rearing costs).[11]

3.1 Baseline Projections: 2010 – 2100

The MAVA model creates a system that moves together in all of its stock variables: land, population, technology, and GDP. To create a reasonable baseline forecast for the coming century, this linked system is fitted to historical data (1960-2010) for these observed variables. This fit then enables us to see how the system has moved across time and to project how it would continue to function if it worked in the same way over the next century.[12]

Our projections for the next 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 per cent increase in expected global GDP (see Figure 2). 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.[13] 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.

Our projections corroborate recent findings of most growth economists—economic growth is slowing down and will eventually reach a plateau (see e.g. Gordon (2015)). Overall, it appears that the global economy has entered a new phase of reduced growth—both in terms of population and

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employment. This technological effect increases costs of child-rearing, but, at the same time, makes new individuals more productive at the end of the training as compared to the earlier generation.

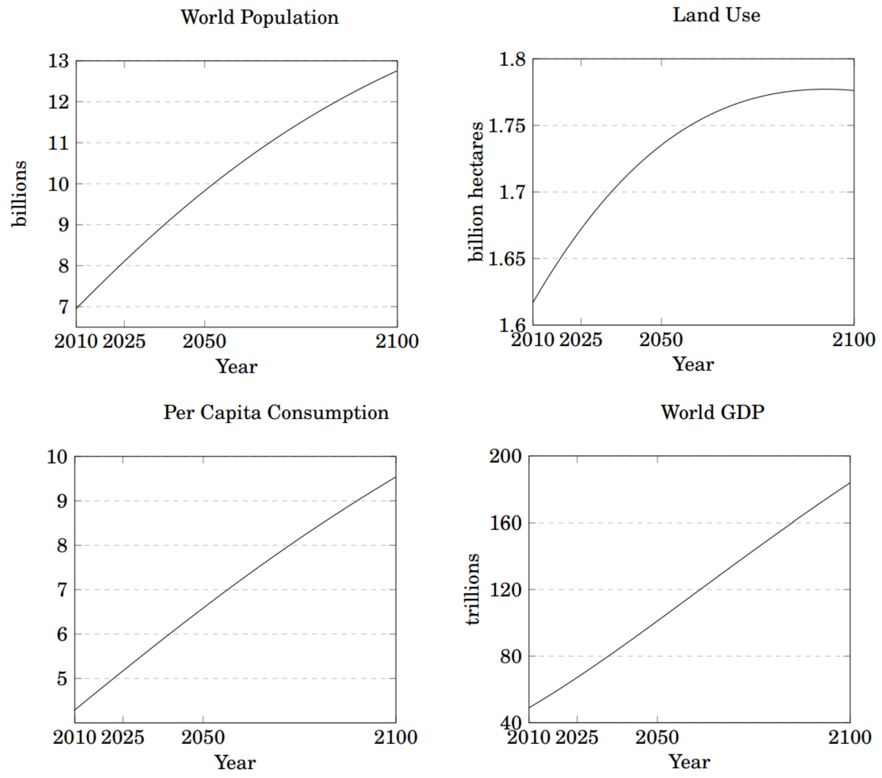
[11] Appendices A, B and C describe the MAVA model in detail. We encourage readers to check these Appendices for a better comprehension of the model. For more information and analysis, see Lanz et al. (2017).

[12] See Appendix B for parameters utilised in the fit of the model.

[13] Our projections are in line with those with forecasted by UN bodies: 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).

economic variables.

Figure 2: Projections: 2010–2100



This phenomenon of the so called secular decline is shown in Figure 3. Growth rates of the six most important variables of our model can be described by a downward exponential curve that reaches a value close to zero at the end of the century. However, among all these variables in this system, agricultural land is the first one to reach an approximate steady state—that is, its growth rate becomes negligible by 2050 and is approximately zero thereafter. What is interesting to note here is that, in the absence of any continued expansion in land use (Figure 2), agricultural output increases by 67 percent between 2010 and 2050 and by 31 percent from 2050 to 2100.[14]

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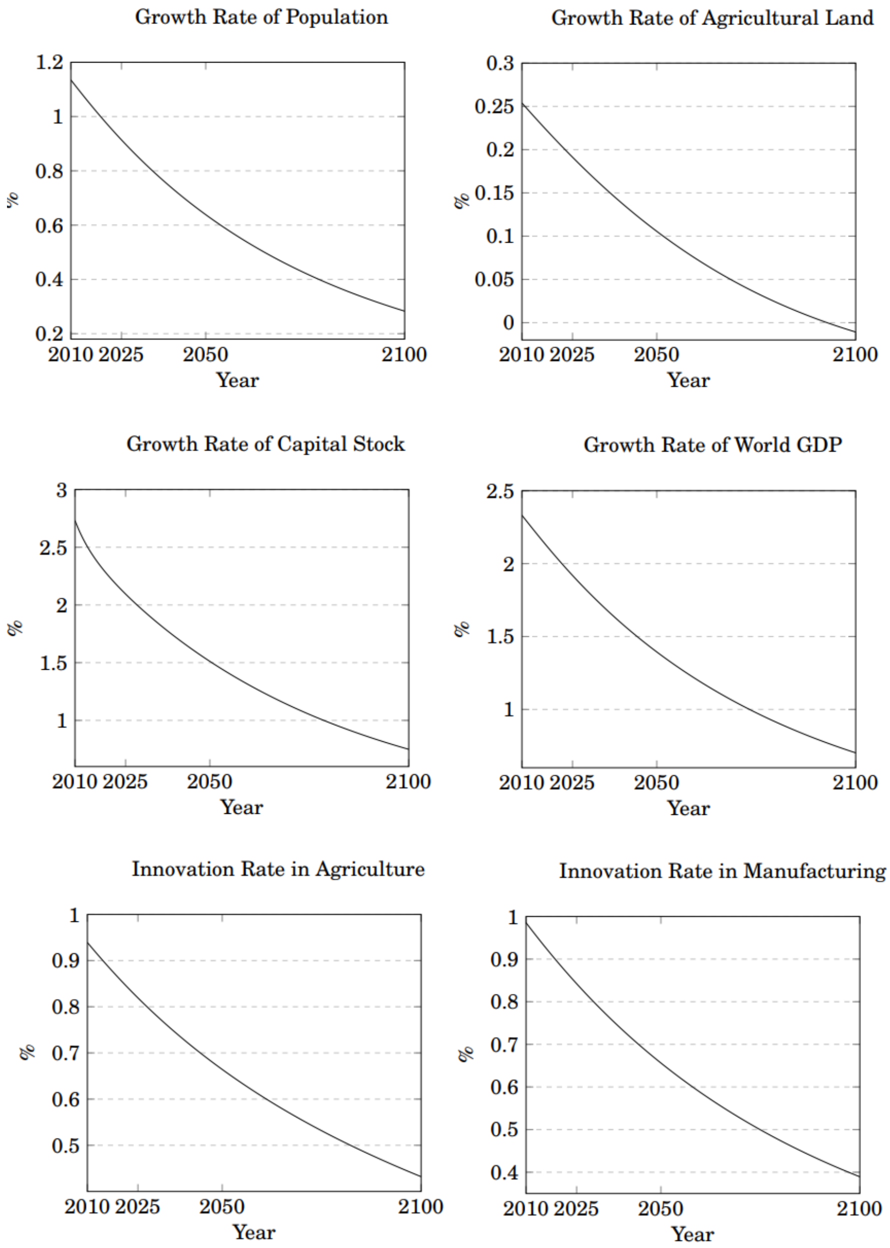
[14] This is in line with other studies, e.g. Alexandratos et al. (2012) projected a 72 percent increase in global agricultural output between 2010 and 2050.

Figure 3: Projected Growth Rates: 2010–2100



The results of our forecasting exercise indicate that the general direction of the economy is toward reduced growth—in terms of stocks of population, capital, GDP, and hence 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. 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.[15]

3.2 Choosing the Amount of Land in Long Run Agriculture

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

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

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.[16] Food demand $\overline{f}_t$ increases with income, according to,

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

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. Therefore, as long as the technological level of society keeps increasing, food demand will continue to increase.

Our definition of food security descends from the constraint we impose that the society's agricultural output must meet the needs of the projected population in every period. In other words, food security is achieved when the amount of food produced $Y_{t,mn}$, is equal to society's needs $N_t \overline{f}_t = Y_t^{ag}$. Agricultural output is an increasing function of the available stock of land, implying that, ceteris paribus, the larger the amount of land available to agriculture, the easier is for society to meet food requirements.

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[15] 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. Otherwise, it is unlikely that land conversion and population can become decoupled from growth at the global level.

[16] For details, see Appendix A.

Since this constraint must be met in every period in our simulations, the system is always, by definition, food secure—in other words, the model would not converge to an equilibrium if society were not able to always provide food to every individual. We are here interested in estimating the social costs of meeting this requirement; more specifically, we ask: what is the welfare loss associated to having a food secure society when land use in agriculture is restricted?

This provides the framework within which we consider the issue of the extent to which the other inputs (technology, labour, capital) can substitute for land, if we constrain land's availability for agricultural use.[17] A constraint on land use in agriculture is the means by which it would then be made possible to make land available for public good uses.

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.[a]

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

Our analysis demonstrates that there is little cost to imposing land constraints on the economic system in this way. This is because, at bottom, our Baseline projections show that additional agricultural land does not appear to be an important contributor to economic growth or agricultural output in the coming century.

To demonstrate this more precisely, we impose a series of land constraints to our model and run simulations under these constraints.[18] The results are presented in Table 1.[19]

Our results show that social welfare losses associated to the land constraints are relatively minor. For a constraint of 1.0 billion hectares (note that, at the moment, we use approximately 1.6 billion hectares),

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[17] An allocation of labour (clearing land) is required to move land into agriculture. This view of land conversion in agriculture is consistent with recent studies (Gibbs et al. (2010) and Ramankutty (2010)).

[18] The imposed constraint means that our system cannot use a greater stock of land than what we impose from a starting year to the final period, 2100.

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

binding in 2025, the total welfare loss over almost one century 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 low cost.

Figure 4: Social Welfare Losses as a Function of Imposed Land Constraints

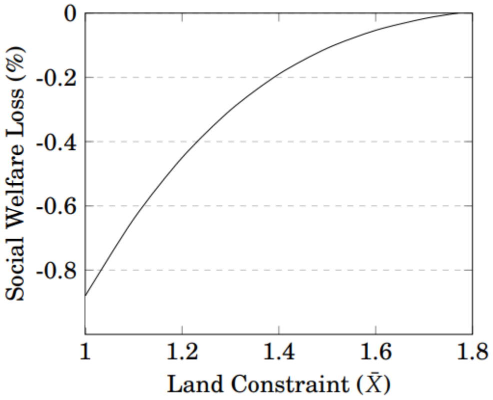

Figure 4 describes welfare losses for the range of feasible land constraints that might be imposed (i.e. the maximum land allocated to agriculture in millions of km squared).[20]

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 decrease whereas agricultural R&D labour share increases. This reorganisation is costly to society because it drives the economy off the optimal (Baseline) path—and that is why we observe welfare losses.

Here we have demonstrated the relatively socially beneficial, although hypothetical, outcomes achievable from imposing constraints on land use in the agricultural economy. By socially beneficial, we mean that the costs from moving off the Baseline path are more than offset by the benefits from providing land for use in global public good production.[21]

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[20] The range of constraints are feasible in the sense that constraints that required agricultural land use to be below 1.0 sq. km. generated unstable outcomes within the MAVA model. Here we present information on the cost of the constraint when imposed with effect from the year 2050. See Table 1 for the costs of other scenarios examined.

[21] 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)). By combining sound policies and investment in agricultural

This assertion is an assumption of our work, i.e. that the provision of 0.5 million hectares of land for global public goods is of a value greater than the 1% of global GDP it could cost the economy.[22]

In the remainder of this paper, we analyse policies that could be used to decrease the pressure the global economy exerts on land use. We consider both the potential for land availability from these various policies, and their potential costs (both in terms of the cost of movement off of the Baseline or optimal pathway and in terms of the cost of implementation). We find that a broad array of policies have the potential to alter the amount of land used in agriculture, and that it is important to consider all of these cost factors in considering how to implement a land use constraint in agriculture.

4 Implementation of Land Use Policies

In this section, we examine how society might implement the land constraints we discussed 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. This change in incentives induces labour shifts and, ultimately, changes our projected Baseline path.[23]

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 model we are examining.[24] This is how we proceed here to examine the aggregate impact of individual state policy-making regarding land use.

In the following subsections, we pursue simulations with variation in the parameters used in the MAVA model, to reflect the possible adop-

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innovation, these countries have achieved a superior equilibrium for society as a whole.

[22] 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)).

[23] 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, both the basic nature of those interventions and the potentially broad basis for them.

[24] 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 advocation. 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)).

tion of policies that would result in such parametric shifts. The precise nature of the simulated parametric shift being simulated is indicated in the notes to each of the tables in the section.

4.1 Land Conversion Management

The most straightforward approach to thinking about land conservation policy is to consider how policy intervention might directly impact the amount of land conservation (or, equivalently, reduce the rate of land conversion). We consider this within our framework as a policy intervention where the costs of conversion are increased, e.g. through either a tax on the application of labour to land conversion (land clearing) or a restriction on the technologies used in conversion. We consider each in turn.

4.1.1 Tax on Land Conversion

First, we study the impact of a policy that restricts the amount of labour applied to land conversion, e.g. by means of the application of a tax to such labour.[25]

This type of policy creates a distortionary incentive, and reduces the marginal benefit of employing labour in land clearing or land conversion. Because, in equilibrium, the marginal benefit of all labour forms have to be equalised, a decreased marginal benefit of labour in land conversion 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 quite small as compared to other sectors (mainly because not much labour is needed to clear land), which substantially decreases the impact of this policy.

Figure 5 describes the implications of a tax on land clearing for land use, population, and per capita consumption. It is straightforward to 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. Ac-

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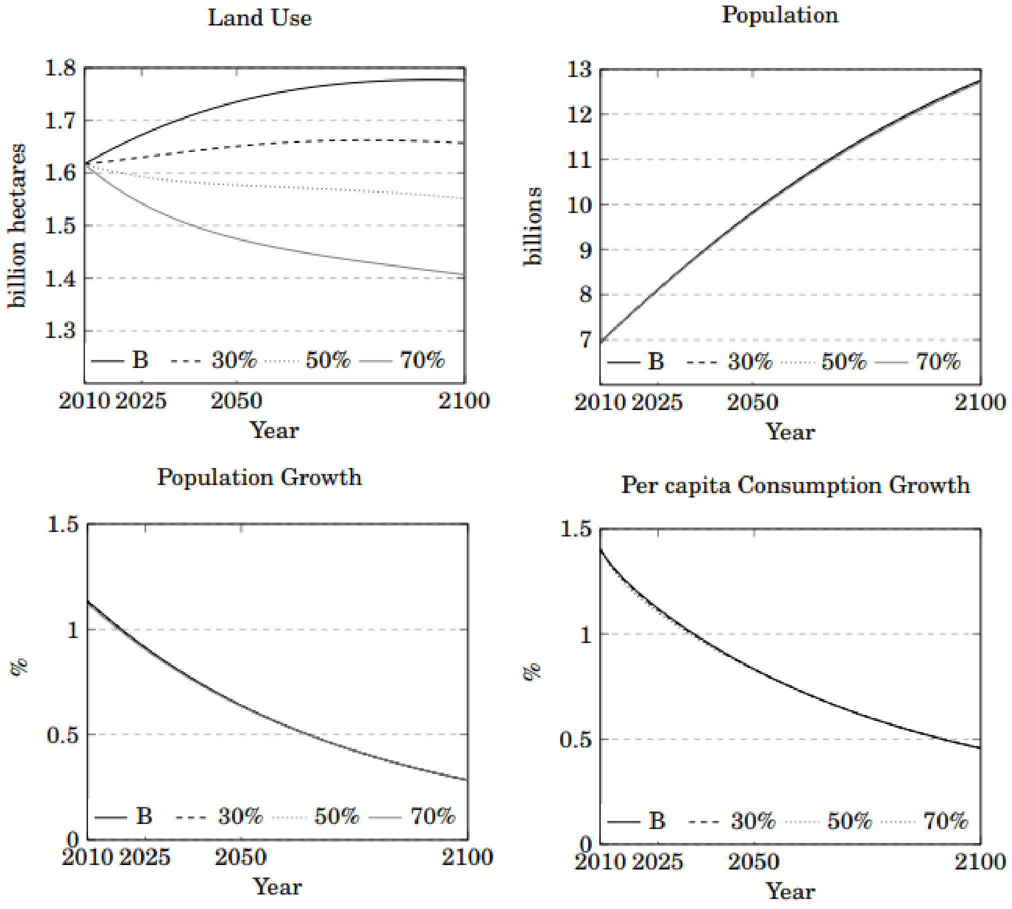
[25] As our model does not incorporate prices, we are only able to model a tax as an example of a policy that would reallocate labour away from the taxed activity. This of course assumes some amount of elasticity of labour supply in the specific activity. We also do not reallocate the labour that is 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 the designated activity, rather than a description of the new macroeconomic equilibrium that would result with a tax.

cording 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.

Figure 5: 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.

In conclusion, our first and most direct policy for land use management is to simply allocate labour away from it within the economy. The optimal path is easily obtainable despite the re-allocation, even at relatively high rates of re-allocation. The weakness of this policy lies in the fact that only a relatively small amount of land is removed from production by reason of the removal of labour from land conversion, given an assumed rate of reforestation of 2% per annum. The policy can remove 0.4 billion hectares from production along the baseline path, however, more significant constraints (e.g. 1.2 billion or 1.0 billion hectares) cannot be easily achieved by application of this policy.[26]

4.1.2 Land Use Restrictions

An alternative to the direct regulation of labour allocations to land conversion is the restriction on the use of certain technologies or land uses (e.g. chain saws, bulldozers, fire). This we view as a reduction in the productivity of labour being applied to land clearing, and so a reduction in that parameter in the model.

Rendering land conversion a less productive activity will result indirectly in the reallocation of labour toward other uses, resulting in both reduced amounts of land conversion and increased amounts of labour available for other pursuits. However, unlike taxes on land clearing, this policy is not purely distortionary; it affects the scale—or order of magnitude—at which land is cleared in every period. It then has a much greater impact than the former policy, which was constrained to be only a fraction of labour of land clearing and subject to diminishing returns. Hence, in this scenario, it is possible to attain much lower land use constraints.

As expected, the introduction of land use restrictions (which have the direct effect of increasing the cost of land conversion and the indirect effect of re-allocating labour toward other activities) will result in a significant decrease in land conversion. Restrictions that reduce productivity by 30 per cent drive agricultural land use to 1.4 billion hectares, and restrictions that reduce it by 50 per cent drive agricultural land use toward 1.0 billion hectares.

Otherwise, these land use restrictions have little impact on the feasibility of the optimal pathway—so the optimal levels of population, production and consumption remain the same—while the amount of land in agricultural use can be much reduced. Such a policy intervention is a highly effective way in which to attain relatively substantial constraints on land use.[27]

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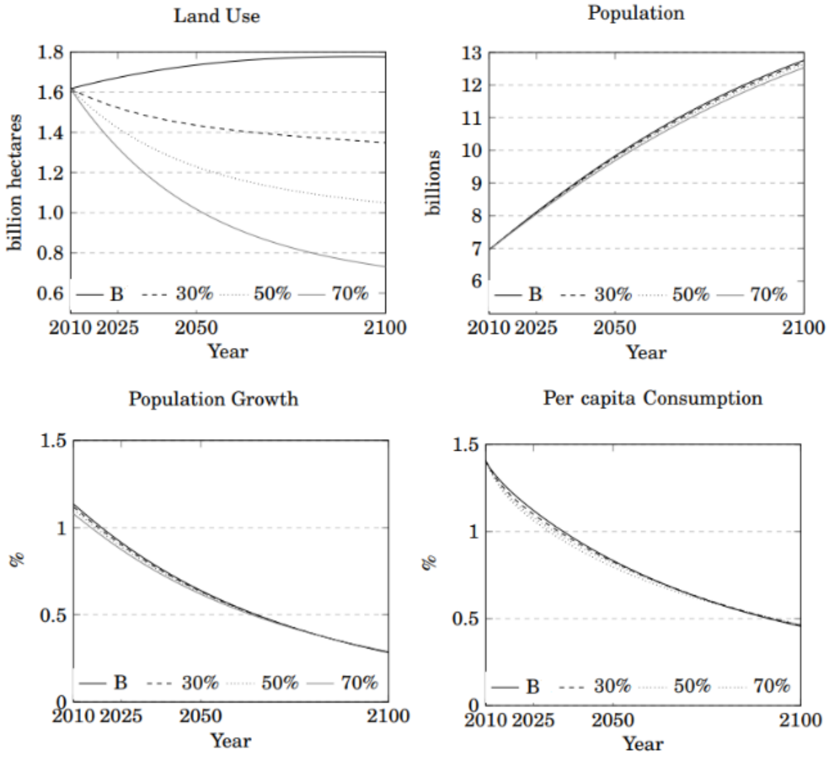
[26] This outcome is also a result of the assumption that no more than 2% of non-agricultural land can be returned to its natural state in a given year absent a labour allocation, and so can be altered substantially if it is assumed to be possible to return large amounts of land to "natural state" simply through non-use.

[27] The important caveat here is that the model assumes that these restrictions may be implemented in a highly cost-effective manner. The model does not make provision for labour allocations to "management" or "enforcement", so the policy assumption in this case is that the land use restrictions may be attained without resource implications.

Figure 6: 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 labor employed in land clearing (see Appendix A).

4.2 Policies Impacting Fertility Decision Making (female labor participation, female education, child education, child labor laws)

To demonstrate the benefit of using a macroeconomic model in analysing these issues, we will now consider much more wide-ranging policies that might have an impact on the amount of land used in agriculture. In this section, we examine how it might be possible to substitute policies emphasising increases in human capital, for those policies that were discouraging conversions of land.

In the MAVA model, fertility is a matter of labor allocation, in that the current generation must allocate a certain share of its labor force in order to make the next generation into "productive labor". That is, the cost of producing the next generation includes both child rearing and education costs, so that the new generation of workers can be allocated between agricultural production, manufacturing production, R&D, land clearing and child rearing/education. Therefore, each generation must use a certain share of its labor resources to make the next generation productive, and this we term the cost of fertility.

An indirect form of policy intervention would work through increasing the cost of fertility. If the cost of bearing and raising an individual child is increased, then this has the effect of causing some re-allocation of the labour currently used in that endeavour. This has the effect of both reducing the population and increasing the number participating in the labour force, thereby increasing production while reducing food requirements.

The policy interventions to do this could operate through increasing opportunity cost. Any policy intervention that increases the implicit cost of labor supplied in child rearing or reduces the benefits from child rearing will be effective in raising fertility costs (e.g. increasing rates of female education and female labor participation).

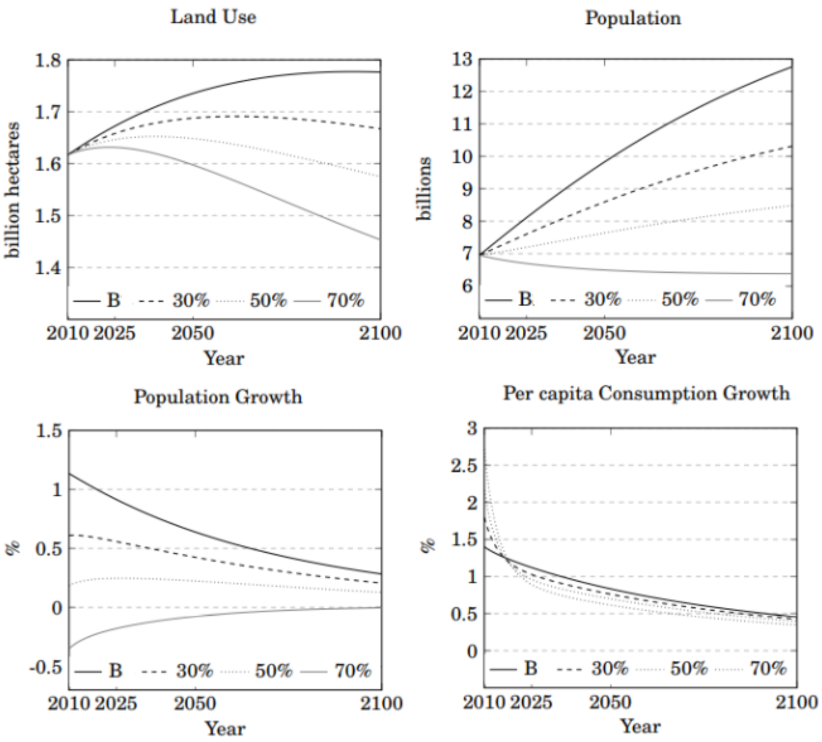
4.2.1 Increased Cost of Fertility – Increased Opportunity Costs

Such policies would take the form of anything that makes a labour allocation to child-rearing more costly in terms of labour supplied. In this case, we model the 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.

As expected, the main result of a tax on labour in child rearing is that aggregate population is shifted below the optimal pathway (on account of the re-allocation of labour). 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. Indirectly, the impact on land use due to the decreased food requirements corresponds proportionally to the population decline. 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, and even though per capita consumption is minimally affected.

Figure 7: Tax on Fertility



Notes: The impact of the fertility tax was calculated by subtracting a fraction of the optimal amount of labor 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 deadweight loss.

4.2.2 Increased Cost of Fertility – Increased Investment Requirements

The alternative to increasing the cost of labour in fertility is an increase in the required investment in any child. Each generation makes provision for an allocation of some part of its time to prepare the next generation for labour, and increasing that amount (the number of person-years dedicated to each child) will simultaneously reduce fertility in the current generation and increase human capital in the next. A reduced population will reduce food requirements, and an increased human capital stock will make it possible to reduce land requirements.

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 (see Appendix A).

This is the more direct form of policy making regarding fertility, and alters decision making regarding fertility via changes in the relative cost of raising a child. In terms of macroeconomic theory, it consists of any policies that mandate increased investments in human capital, e.g. by mandating a given level of compulsory education or a specified level of investment in higher education. These policies might also restrict the ability to take benefits from children of education age, e.g. through restrictions on child labour. Any such policies will increase the amount of time or labour required by the current generation in the production of the next generation (see Table 2).

As we see in Figure 8, a policy increasing mandatory child investment costs by 30%—a requirement of 24 person/years invested per child—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. Again, this is a policy that results in a substantial decline in the size of the human population—by reason of the required investment in children. This in turn implies a substantial decline in the scale of the aggregate economy, although growth in per capita consumption remains positive but in decline.

In sum, policies operating through fertility choice can have the most dramatic impact upon population and land use, through a fundamental redirection of the economy. The policies investigated here have the effect of altering the manner in which societies develop and grow, moving rapidly toward a low quantity but high quality demographic equilibrium.[28]

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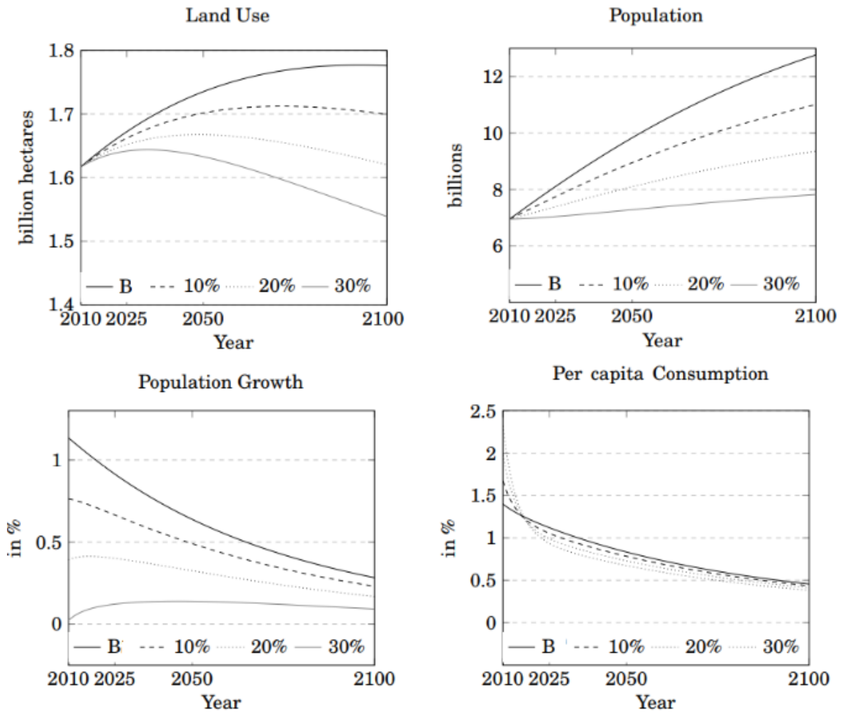
[28] Our results are supported by the recent discussion on the impact of reproductive health services and contraceptive technologies on population growth and environmental services (Crist et al. (2017)).

Figure 8: Increased Cost of Child Rearing



4.3 Technology Subsidy Policy

There is a third group of policies that do not target land use directly or fertility choices, but focus on the rate of agricultural innovation. In this last subsection, we consider a technology subsidy policy, that is, a policy that aims to facilitate increases in agricultural productivity over time. The rationale is that, with an increased level of technology, agricultural production will require a smaller stock of land to produce the same amount of food.

To capture this idea, we constraint the model to allocate a fixed share of the total labour force towards agricultural R&D sector. We force society to allocate first 50 percent and then 100 percent more R&D labour than it would at the Baseline path.

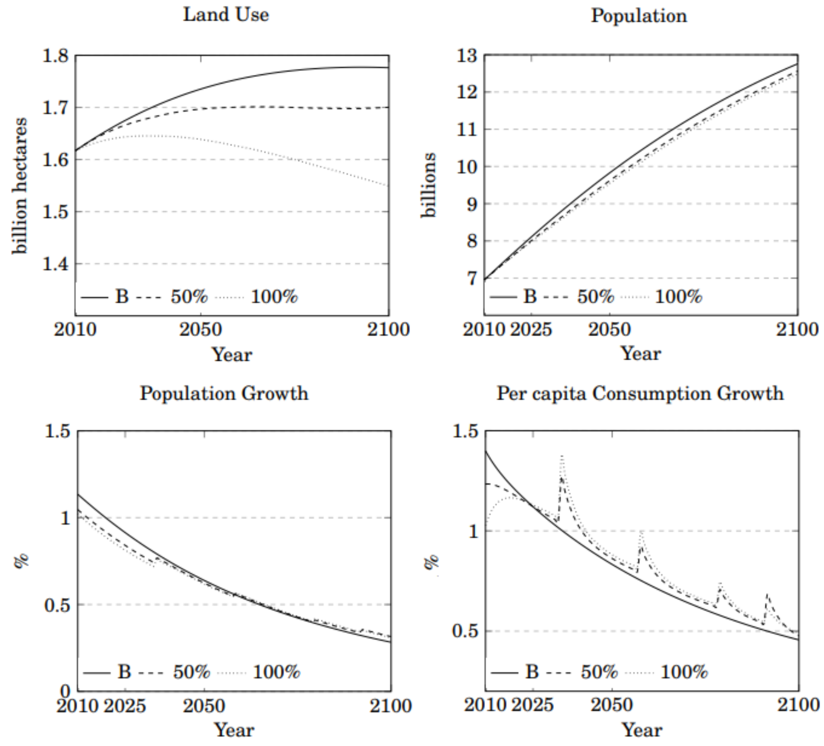
Table 3 shows that increased allocations of resources to the R&D sector do in fact decrease long run land use. The allocation of a 100% increase in labour resources to R&D generates an increase of over 81% in TFP, and reduces the amount of aggregate land used in agriculture by approximately 13%.

Table 3: Simulations for Exogenous Shifts of Labour Resources to Agricultural R&D

Variable	Baseline	50% Increase	100% Increase
R&D	100%	150%	200%
TFP	4.57	6.72	8.31
Land	1.77	1.70	1.54

Notes: This table presents simulations with an increased share of labour into agricultural R&D as compared to the baseline. The aggregate land use is presented in billion hectares.

Figure 9: Land Use and Agricultural TFP with increased labour share in agricultural R&D


Land Use

Population

Population Growth

Per capita Consumption Growth

Figure 9 describes the economic outcome of society moving resources to R&D. There is a small decrease in population levels—due to the fact that most of the labour share towards R&D comes from child-rearing labour—and a slightly increase in per capital consumption growth.[29].

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[29] The kinks we observe in the diagram of per capita consumption growth come from the manner in which we force the system to allocate labour to the R&D sector. In our code, we determine minimum shares of R&D labour that have to be met periodically.

This observed increase in per capita consumption is the result of an influxes of child-rearing labour into R&D, increasing the productivity of the whole economy.

As our simulations show, this type of policy does not drastically decrease land use—as some of the other policies studied in this section—but, at the same, does not change considerably population levels or per capita consumption either. Compared to other macropolicies, this seems to be less disruptive to the global economy.

4.4 Global Land Use Policies – Discussion

This section studies macropolicies that could be used to implement the land constraints we discussed in section 3. We focus on three main groups of policies: land clearing, fertility services and technology subsidies. These policies change the optimal allocation of labor shares as compared to the baseline path. By shifting labour (i) away from land clearing, (ii) away from fertility services and (iii) towards agricultural R&D, society is able to reduce its dependence on land use in the long run.

We analyse each of these policies separately here 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.

The macropolicies we investigate here can be divided into two groups, with regard to their effects upon the existing baseline. The first group, land clearing policies and technology subsidies, does not result in major movement off of the baseline path, and so (in this respect) they appear to be very low-cost comparatively. This can be seen in the way that they have little effect on population and per capita consumption relative to the baseline path. The second group, consisting of policies relating to fertility services, however, does result in more substantive change in society (even though per capita consumption is relatively unchanged). This is so because fertility disincentives decrease population levels—and total utility, that is, per capita consumption multiplied by total population, declines.[30]

The interesting result from our analysis of these policies for managing global land use is the extent to which optimal land use moves with the general equilibrium. If we pursue a society with more highly edu-

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Because these shares are different from the optimal shares the system is always trying to deviate from this constraint.

[30] Although the model imposes a cost for deviating from the baseline path, the issue here is whether it makes sense in this context to apply the classic utilitarian method of computing societal welfare as the product of global population and per capita consumption.

cated individuals, then a corollary of this policy pursuit is a reduced population and reduced requirement for land use in agriculture. The same is potentially true of an economy built on higher levels of technology. To some extent, the level of global agricultural land use is a measure not so much of the requirements of agriculture, as it is a measure of the sort of society we wish to be.

5 Conclusion

In this paper, we have investigated ways in which society can respond to the trade-off between food requirements and global land use in the long run. 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 proposed 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 100 years. This means that, if society were to impose a mix of the land use policies studied here, it would 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 one is to reserve available land to environmental services, such as climate change mitigation and biodiversity provision— global public good provision. It is difficult to predict the exact amount of land necessary for these environmental services, but it is generally agreed that the lands required will compete with food production. This paper shows that society can implement certain tools at the global level to induce labour shifts across sectors, and then accommodate both food requirements and global public good provision in the long run.

Appendix A: Model Details

Models' Equations

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

Economy

Manufacturing output:

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

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 (i.e. food production):

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

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

Macroeconomic identity:

$$Y_{t,mn} = C_t + I_t, \tag{3}$$

where C_t and I_t are aggregate consumption and investment respectively.

Capital accumulation:

$$K_{t+1} = K_t(1-\delta_K) + I_t, \quad K_0 \text{ given}, \tag{4}$$

where δ_K is a per period depreciation rate.

Population Dynamics

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

$$N_{t+1} = N_t(1-\delta_N + n_t), \quad N_0 \text{ given}. \tag{5}$$

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:

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

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.

Food production equals food consumption, and is proportional to population:

$$Y_t^{ag} = N_t \overline{f}_t$$

where $\overline{f}_t$ 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:

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

, 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 $\overline{X}$, thus over time, the stock of land used in agriculture develops as:

$$X_{t+1} = X_t(1 - \delta_X) + \psi \cdot N_{t,X}^{\varepsilon}, \quad X_0 \text{ given}, \quad X_t \leq \overline{X}, \tag{6}$$

where $N_{t,X}$ is labor allocated to land clearing activities, $\psi > 0$ measures labor 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:

$$A_{t+1,j} = A_{t,j} \cdot (1 + \rho_{t,j} S), \quad j \in \{mn, ag\}. \tag{7}$$

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.[31]

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

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

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[31] In the original work of Aghion and Howitt (1990) time is continuous and the arrival of innovations is modeled 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.

where N_{t,A_j} is labor employed in R&D for sector j, $\lambda_j > 0$ is a productivity parameter and $\mu_j \in (0,1)$ is an elasticity.

In agriculture the dynamics of TFP are augmented to include the depreciation due to biological problems:

$$\tilde{A}_{t+1,ag} = \tilde{A}_{t,ag} \cdot (1 + \rho_{t,ag}S - \phi_t S)\,, \tag{8}$$

where ϕ_t measures the rate at which man-made R&D depreciates and is given by:

$$\phi_t = \lambda_D \left(X_t\right)^{\mu_D}\,, \tag{9}$$

with $\lambda_D \geq 0$ and $\mu^D > 1$.

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 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 4: 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 C: 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 only available for 2005.

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

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