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Deforestation, Land Taxes and Development

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Deforestation, Land Taxes and Development

February 6, 2015

Abstract

This paper combines neoclassical growth theory with the von Thünen approach of land conversion to model deforestation and land allocation decisions in an intertemporal general equilibrium context suitable for developing countries. Analyzing the impact of several forest conservation policies, including international transfers under a REDD+ scheme, emphasized the role of taxes on non-forest land as effective and powerful policy that has been largely neglected so far. The findings of our equilibrium analysis are in stark contrast to the conventional economic wisdom that taxes on land are allocation neutral. As we model deforestation as one investment decision besides investment into physical capital stocks, land taxes may not only increase forest conservation levels but also overall capital stocks and output. We identify the conditions that lead to this double-dividend effect and apply them to data for a set of countries, concluding that forest conservation, e.g. implemented by land taxes, can have this positive effect for many developing countries. Additionally, we re-assess Borlaug's hypothesis and Jevons' paradox in a general-equilibrium context and design a land tax scheme that is robust to agricultural yield increases.

1 Introduction

Biodiversity loss due to deforestation of tropical forests is a major concern as these forests contain the majority of all species of the world: Prolonging tropical forest clearance can eliminate several billion species per year (Pimm and Raven, 2000). As many species are still unknown and the potential uses of unknown or known species for pharmaceutical, agricultural or other domains is largely unknown as well, the value of this loss is yet not assessable. As tropical forests are located in developing countries with high poverty rates and dependence on agricultural production, opportunity costs of conservation are perceived high in these countries and forest protection does often not enjoy a high political priority.

This paper takes a new attempt to model important drivers of deforestation in the context of development. It provides a general theoretical framework within a Ramsey-type growth model of intertemporal utility and profit maximization that

Forest type	Carbon (tC/ha) (Above ground)	Share of species exclusively in forest type		
		Trees and lianas	Birds	Amphibians
Primary forest	120–680	60%	40%	39%
Secondary forest		8%	11%	5%
Plantation	60–300	$< 1\%$	6%	$< 1\%$

Table 1: Ecosystem benefits according to forest type in the tropics. Sources: Carbon content for above-ground biomass: IPCC (2006); species: Barlow et al. (2007).

allows discussing how several structural factors of the economy as well as policies influence the steady state level of the forest cover. One particular emphasis is given on land taxes as one instrument to reduce deforestation. As we will show, land taxes can have an additional beneficial impact on the (economic) wealth of the economy, implying an important 'double dividend' aspect. This major finding depends, however, on the technology of the economy. We derive a simple criterion that will also be applied to available data to answer the question whether land taxes spur or deteriorate total GDP.

The classical economic models on deforestation treat (standing) forests as assets with a high (or perfect) degree of appropriation possibilities of the social benefits they generate (Bohn and Deacon, 2000; Foster and Rosenzweig, 2003; Arcand et al., 2008). Within this setting, the impact of property rights, trade and discount rates can be analyzed and deviations from the social optimum assessed. This approach, however, typically misses the fact that many benefits of (virgin) forests cannot be appropriated like the various local and global ecosystem services (water household, carbon sequestration) as well as biodiversity conservation. Additionally, managed and degraded forests provide these benefits to a substantially lower extent (Gibson et al., 2011): Carbon storage in above-ground biomass is only half for tropical forest plantations compared to tropical primary forest; likewise many species are habituated only on primary forests (see Tab. 1).Therefore, in the conventional framework the undersupply of biodiversity-rich forests cannot be modeled appropriately as removing property-rights related market failures will give an efficient forest cover.

In this paper, we take the opposite perspective by neglecting any possibility of appropriating the social benefits of virgin forests by forest owners. We will distinguish two types of land—virgin forests and agricultural land—and managed forests will just be treated as 'agricultural' land without any differentiation. While this is an admittedly polar view, it helps to focus on the biodiversity aspects of virgin forests that are most seriously and irreversibly affected by advancing deforestation. The question that arises is then: what determines the conversion of virgin forests without private value to (valuable) agricultural land (including managed forests) and how can this conversion be contained?

If (undeveloped) virgin forest has no market value and is in many cases a de-facto open access resource which can be appropriated and converted to agricultural land with value, how have virgin forests sustained for so long and why do they still sustain? The answer to this question was already given by von Thünen (1826): Only areas close to cities and settlements are cultivated while in

the far distance wilderness prevails as its cultivation would be too costly. It is the geographical dimension, mainly the costs of transportation and accessibility of remote areas, that prevents the immediate and complete human appropriation of cultivatable land. This so-called 'passive protection' is typically modeled in von Thünen type models where a cultivation frontier is established when land rents become zero with increasing distance to the settlement area (e.g. Beckmann, 1972; Angelsen, 1999, 2007, 2010).

The mentioned von Thünen-type models are, however, predominantly static models which furthermore do not embed the agricultural sector in the whole economy and, thus, take only a partial equilibrium perspective. Contrary, multi-sector growth models—if considering land as production factor at all—take agricultural land exogenously (e.g. Irz and Roe, 2005). This paper therefore combines the neoclassical growth theory with the von Thünen approach of endogenous land allocation.

The main propositions derived from this model will identify the conditions where land taxes can increase conservation *and* economic wealth. Conventional economic wisdom predicts no distortive allocation effects of land taxes within the economy as land is seen a fixed resource with inelastic supply. By modeling endogenous deforestation and land allocation decisions, however, the neutrality of land taxes is lost. As workers migrate between the agricultural and industrial sector, land allocation decisions also affect overall capital stocks with implications for total economic output.

2 The model

The economy considered consists of a household sector who invests into capital and allocates labor in two production sectors, the manufacturing and the agricultural sector. While the manufacturing sector uses also capital for production, the agricultural sector uses land besides labor. Fig. 1 illustrates the considered sectors of the economy, their objective functions and exchanges. The sectors are explained in detail below.

2.1 The sectors of the economy

The representative manufacturing firm maximizes instantaneous profits

$$\pi^Y = \phi^Y Y(K, L^Y) - wL^Y - (r + \gamma)K + \gamma\bar{K} \tag{1}$$

where ϕ^Y denotes the level of technology, K capital input, L^Y sectoral labor input, w wage rate, r interest rate and γ an investment risk parameter (or, expropriation rate) caused by an environment of insecure property rights (if we think of expropriation, the expropriated capital γK is lump-sum transferred back to the representative firm at the same level, i.e. $\bar{K} = K$). The parameter γ can also have another interpretation: If there exist positive spillovers of investment

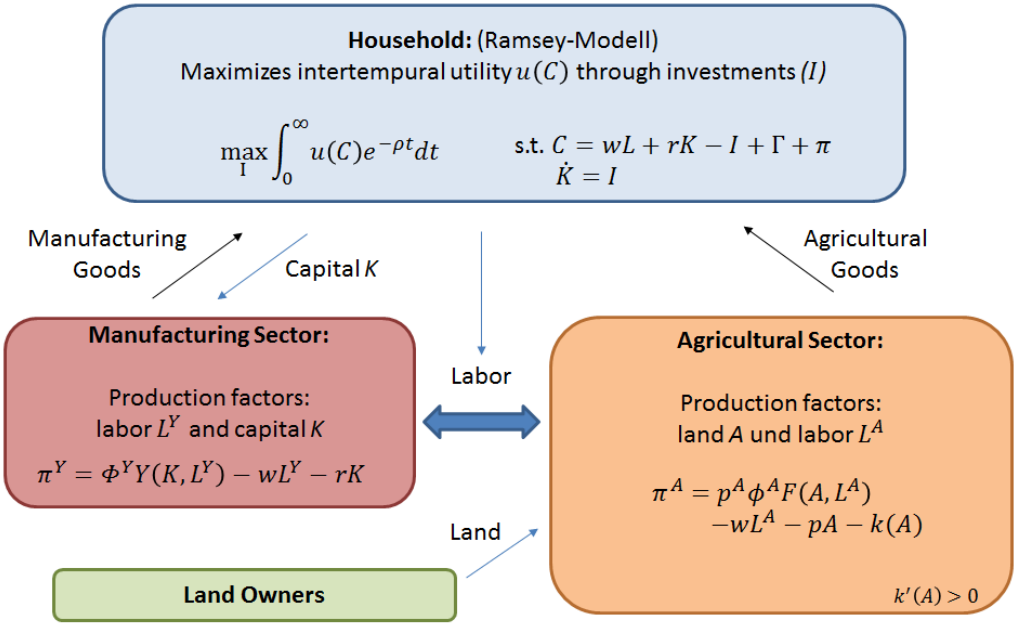

Figure 1: Sectors of the economy, objective functions and flows of goods.

into firm capital to economy-wide knowledge stocks ('learning-by-doing'), the social returns of investments are reduced by the amount γ giving the private return of investment for the firm.[1] Thus, γ can also be associated to institutional factors impeding the capture of the entire benefits of investments into physical, human and intellectual capital. $Y(\cdot)$ is assumed to be a standard neoclassical production function (homogeneous of degree one and concave in each argument). The first-order conditions are

$$\phi^Y Y_K = r + \gamma \tag{2}$$

$$\phi^Y Y_{L^Y} = w \tag{3}$$

where $F_X := \partial F / \partial X$ denotes the partial derivative of function F with respect to X.

The representative agricultural firm maximizes instantaneous profits

$$\pi^A = p^A \phi^A F(A, L^A) - wL^A - pA - k(A) \tag{4}$$

where p^A is the price of agricultural goods, ϕ^A is the technology level, L^A sectoral labor input, A the area of agriculturally used land and p its rental price. In case of perfect substitutes between agricultural and manufacturing goods, we can simply normalize p_A to one as differences in production technology are refelcted in ϕ^A and ϕ^Y. In case of a small open economy, p^A refers to the terms-of-trade of

[1] See Arrow (1962) and Barro and Sala-i Martin (2003, Ch. 4.3) for a formal development of the learning-by-doing model and its implication on (under)investment.

agricultural goods relative to manufacturing goods on the world market.[2] As a crucial feature of the von Thünen model, transportation costs $k(A)$ arise as agricultural output has to be brought to consumers in every period. Transportation costs are highly relevant for (low value) agricultural commodities as they form a substantial share of the commodity price (see, for example, Salin (2013) for the case of Brazilian soybean). As travel distance increases in area A, we assume $k'(A) > 0$. The first-order conditions are

$$p^A \phi^A F_A = p + k'(A) \tag{5}$$

$$p^A \phi^A F_{L^A} = w \tag{6}$$

The representative landowner maximizes intertemporal (discounted) profits

$$J_H = \int_0^\infty \pi_H e^{-rt}\, dt \tag{7}$$

$$\pi^H = pA + q(A)H - \tau A \tag{8}$$

where land A increases by deforestation activities H according to $\dot{A} = H$. Deforestation activities induce additional positive or negative payments per unit deforested $q(A) := p^H - k^H(A)$ where p^H is the price for timber and $k^H(A)$ the direct logging and transportation cost that again increase in area, hence, $\partial k^H(A)/\partial A > 0$ and $q'(A) < 0$. Note that $q(A)$ can be positive or negative, implying that deforestation may be profitable even without renting out the land or it may be a costly investment into land acquisition. In this paper, we will in particular consider the case where $q(A) < 0$, i.e. deforestation is an investment into agricultural land expansion. This is justified by the high transportation costs in remote areas, the wide-spread use of slash-and-burn practices (as professional deforestation is often too expensive) and the fact that $q(A) > 0$ would imply an immediate deforestation of all available non-protected forests which is add-odds to existing unprotected forests.

For simplicity, we assume that there is a fixed amount of land $Q = A + W$ which can be divided between agricultural use and not used primary forests, or wilderness, W. Deforestation reduces the primary forests W by $\dot{W} = -H$ and generates agricultural sites (which can used for crop and forest plantations). The landowners may face a unit tax τ on their agricultural land. Forest conservation policies can additionally be modeled by employing a land constraint $\tilde{Q}$ with $A \leq \tilde{Q} \leq Q$. Hence, agricultural area cannot increase beyond $\tilde{Q}$.

With λ the co-state variable for A and θ the Lagrange multiplier for the land constraint $A \leq \tilde{Q}$ (with $\tilde{Q} = Q$ in case of no conservation areas), we obtain as

[2] The case of a closed economy (without trade) and imperfect substitution of agricultural and manufacturing goods is not considered here as it adds substantial complexity to the analysis which distracts attention to the fundamental dynamics of land conservation.

first-order conditions:

$$\lambda = -q(A) \tag{9}$$
$$\dot{\lambda} = r\lambda - (p + q'(A)H - \tau - \theta) \tag{10}$$
$$\lim_{t\to\infty} \lambda A e^{-rt} = 0 \tag{11}$$
$$\theta(\tilde{Q} - A) = 0 \tag{12}$$

The representative household maximizes discounted utility

$$J_W = \int_0^\infty u(C, W)e^{-\rho t}\, dt \tag{13}$$
$$C = wL + rK - I + \Gamma + \pi_H \tag{14}$$
$$\dot{K} = I \tag{15}$$

where the total amount of labor $L = L^Y + L^A$ is given and normalized to one and Γ covers lump-sum transfers (i.e. tax revenues τA or international transfers for deforestation policies). The primary forest W is an open-access resource providing potentially benefits for the household. If local external benefits of primary forest conservation are small, $u_W(C, W) \approx 0$ despite possibly large global external benefits. As primary forest conservation is beyond the control of the household, benefits of forest conservation are neglected in the market economy.

Applying the maximum principle with μ as co-state variable for K, the intertemporal first-order conditions are:

$$u_C = \mu \tag{16}$$
$$\dot{\mu} = \rho\mu - r u_C \tag{17}$$
$$\lim_{t\to\infty} K\mu e^{-rt} = 0 \tag{18}$$

2.2 Market equilibrium and steady state

Substituting and re-arranging the first-order conditions, the intertemporal market equilibrium is fully characterized by:

$$\phi^Y Y_K = \rho + \gamma + \eta\hat{C} \tag{19}$$
$$\phi^Y Y_L = p^A \phi^A F_L \tag{20}$$
$$-\frac{dq(A)}{dt} = -(\rho + \eta\hat{C})q(A) - [p^A\phi^A F_A - k'(A)] - q'(A)H + \tau + \theta \tag{21}$$
$$\lim_{t\to\infty} K u_C e^{-rt} = 0 \tag{22}$$
$$\lim_{t\to\infty} -q(A)Ae^{-rt} = 0 \tag{23}$$
$$\theta(\tilde{Q} - A) = 0 \tag{24}$$

In the steady state, area A, capital stock K and consumption C are constant (constant area implies also that $H = 0$ and $\dot{H} = 0$). The market equilibrium therefore reads:

$$\phi^Y Y_K = \rho + \gamma \tag{25}$$
$$\phi^Y Y_L = p^A \phi^A F_L \tag{26}$$
$$p^A \phi^A F_A = \Phi(A) + \tau + \theta \tag{27}$$
$$\theta(\tilde{Q} - A) = 0 \tag{28}$$

where $\Phi(A) := -\rho q(A) + k'(A)$ is a measure for the marginal costs of land conversion and cultivation. As we assumed $q'(A) < 0$ the sign of $\Phi'(A)$ depends on crucially on $k''(A)$. In terms of linear transportation costs, $k''(A) = 0$ and, thus, $\Phi'(A) > 0$.

Equation (25) describes the capital market, (26) the labor market and (27–28) the land market in the steady state.

3 Endogenous land allocation, land rents and protected areas

3.1 Base case

An inspection of Eqs. (27–28) allows already gaining some insights into the dynamics of the endogenous land allocation. In the absence of protected areas, $\tilde{Q} = Q$. The entire wilderness will be converted into agricultural land and $A^* = Q$ if the land constraint is binding, i.e. the land rent is strictly positive ($\theta > 0$). Contrary, if marginal conversion and cultivation costs Φ or land taxes are higher than the marginal productivity of land, we obtain an interior solution, some primary forests remain and land taxes fall to zero. This duality is illustrated in the upper panel of Fig. 2. The interior solution $A = A^* < Q$ is in particular relevant when transportation costs are high, e.g. due to bad infrastructure. It explains why primary forest is still existent in countries like the Democratic Republic of Kongo where active protection by the government is low but missing infrastructure increases the costs of conversion and cultivation.

In case of strict protected forest areas, available land reduces to $\tilde{Q} < A^*$ and a land rent $\tilde{\theta} > 0$ emerges (see lower panel of Fig. 2). An *additional* land tax $\tau \leq \tilde{\theta}$ will have no allocative effects besides revenue generation for the government. If $\tau = \tilde{\theta}$, the land tax will lead to the same conservation level $A^* = \tilde{Q}$ even if there is no explicit area protection.

3.2 International transfers and REDD+

Current international policy proposals on reducing emissions from deforestation and forest degradation (REDD+) in developing countries focus on a per-area

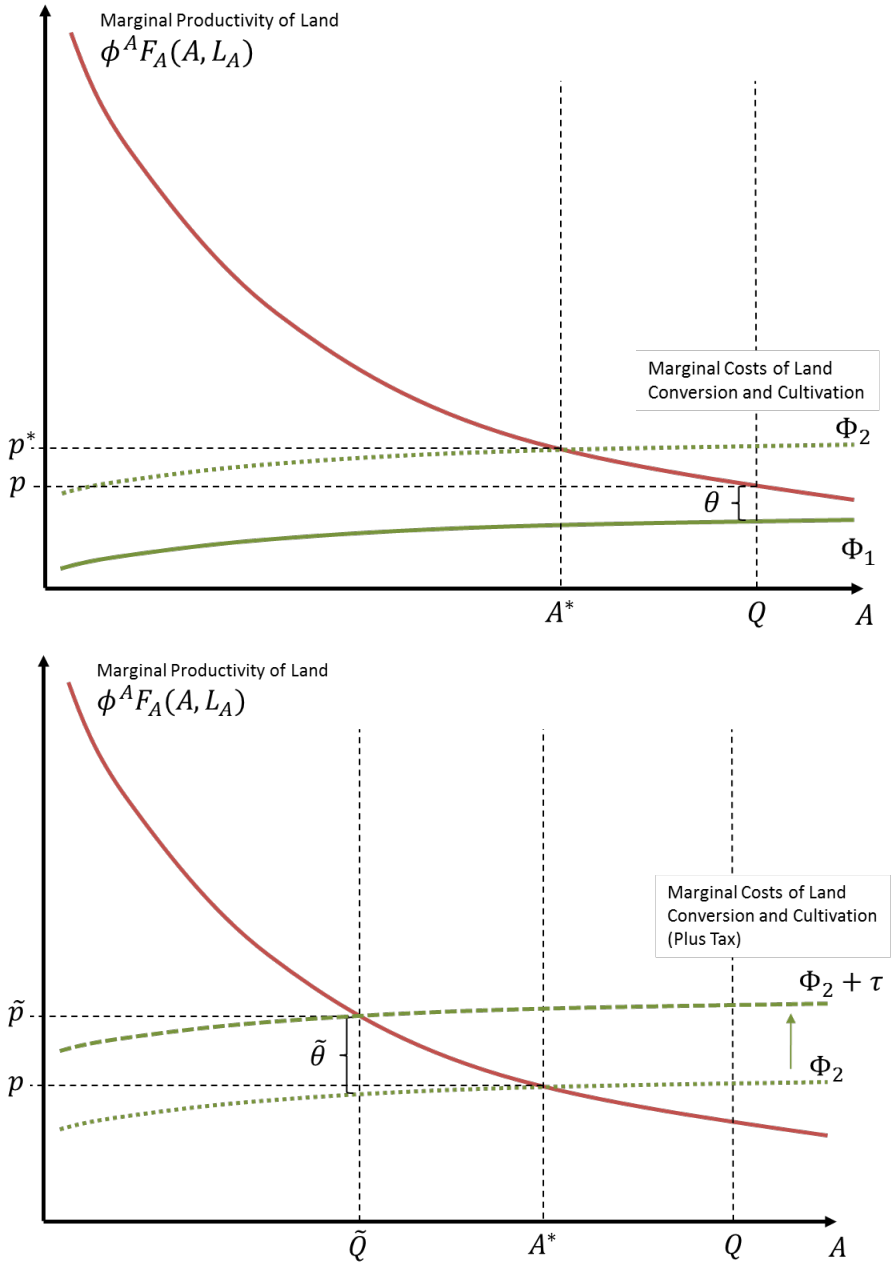

Figure 2: Endogenous land allocation. Upper panel: interior versus corner solution; lower panel: protected area versus land tax.

transfer s for standing forests W above a pre-determined baseline W^B. Thus, total transfers amount to $T = s(W - W^B) \geq 0$. If the forest area falls below the baseline level, the subsidy becomes zero (instead of being negative) as countries cannot be forced to pay taxes on deforestation. With $Q = W + A$, the transfer can be re-written as (assuming always positive subsidies):

$$T = s(W - W^B) = s(Q - A - W^B) = s(Q - W^B) - sA \tag{29}$$

As Q and W^B are not determined by allocation decisions, the subsidy on forest conservation is basically a tax on agricultural area sA with $s(Q - W^B)$ being a non-distortive lump-sum transfer to ensure participation.

The government of the transfer receiving country can implement a domestic tax on agricultural area equal to the per-area REDD+ payment $\tau = s$. In that case, the government would receive two sources of revenues – one from the international REDD+ mechanism $s(W - W^B)$, the other from the domestic land tax $\tau A = \tau(Q - W)$. Equivalently, the government could create protected areas of the same size and without the implementation of a land tax. As shown in Sec. 3.1, land rents would increase to the benefit of land owners and government revenues would be accordingly lower. Hence, the consideration of endogenous land rents provides an important rationale for governments to implement domestic land taxes *additionally* to international transfers for forest conservation instead of relying on protected areas only: They can generate revenues without distorting the economic allocation negatively.

4 Determinants of forest area without conservation policies

This section analyzes how structural parameters of the economy influence the steady state level of forest area. This will help to identify driving forces of deforestation and, thus, determinants of the conservation costs. The analysis may also provide an explanation for different levels of forest conservation among countries. For the comparative static analysis of the steady state equilibrium, we neglect a specific conservation goal $\tilde{Q}$. We will further assume that marginal conversion and cultivation costs are positive, i.e. $\Phi'(A) > 0$; this assumption is crucial and considering falling marginal costs will reverse the sign of many marginal effects.

4.1 Basic comparative static analysis

The role of the pure time preference rate

Proposition 1. *In the steady state an increase of time preference rate ρ changes the land allocation according to:*

$$\Phi'(A)\frac{dA}{d\rho} + \frac{d\theta}{d\rho} = \underbrace{\frac{F_{AL}Y_{LK}}{F_{LL}Y_{KK}}}_{>0} - (G_H - q(A)) \tag{30}$$

Proof. See Appendix. □

Note that $\theta = 0 = \frac{d\theta}{d\rho}$ for an interior solution (where not all forest is converted to land). The proposition states that a higher pure time preference rate can even increase conservation (lower A) if marginal deforestation costs G_H are sufficiently high. The reason is that deforestation is basically an investment into future cultivated land. The higher the marginal deforestation costs G_H, the more expensive is the 'investment' into cropland expansion. Hence, higher discount rates discourage the investment into the development of land. Besides the investment effect, there is, however, an opposing effect: High discount rates shift production from the manufacturing sector (where capital is an important input factor) to the agricultural sector (where no capital is used). This leads to higher labor input in the manufacturing sector and, thus, increases the productivity of land. If the latter effect is stronger than the 'land investment' effect, more land is used and less forest conserved.

In case of a corner solution ($A = 1$ and $\frac{dA}{d\rho} = 0$), the land rand changes in the same direction as the agricultural land changes in case of an interior solution.

The role of capital market imperfections

Proposition 2. *In the steady state an increase in γ (risk premium of investment or external spillovers of private investment) increases deforestation as*

$$\Phi'(A)\frac{dA}{d\gamma} + \frac{d\theta}{d\gamma} = \underbrace{\frac{F_{AL}Y_{LK}}{F_{LL}Y_{KK}}}_{>0} \tag{31}$$

Proof. The proof is along the lines of the proof of Proposition 1. □

A higher γ reduces investment into the capital stock. As labor is a fixed factor, lower capital will be partly substituted by land to avoid strong decrease of consumption. Thus, either increases the agricultural land or (if all land is used) the land rent θ increases.

Land taxes and land rents

Proposition 3. *In the steady state an increase in the land tax reduces deforestation:*

$$\Phi'(A)\frac{dA}{d\tau} + \frac{d\theta}{d\tau} = -1 \tag{32}$$

Proof. The proof is along the lines of the proof of Proposition 1. □

For the corner solution case, where it simply reduces land scarcity rents without affecting other parts of the economy (i.e. $\frac{dA}{d\tau} = 0$ while $\frac{d\theta}{d\tau} = -1$ – hence, the tax simply absorbs the land rent).

Corollary 1. *(Henry George Land Tax) In case of a corner solution where all land is used for agricultural production, a change in the land tax τ simply absorbs the scarcity rent without affecting other economic variables (in particular, the land price remains unaffected).*

$$d\tau = -d\theta \tag{33}$$

The corollary takes up the famous Henry George (1879) proposal to use land taxes as a non-distortionary (incentive-neutral) way of raising public revenues. However, it also shows that a land tax is only incentive-neutral when land is indeed a fixed factor ($A = Q$) and no costly investments into land cultivation can be done.

The role of timber prices

Proposition 4. *High timber prices increase deforestation:*

$$\Phi'(A)\frac{dA}{dp^H} = \underbrace{\rho}_{>0} - \frac{d\theta}{dq} \tag{34}$$

Technological progress in agricultural and manufacturing sectors

The role of productivity increases in the agricultural sector on forest cover is controversially discussed among agricultural and environmental economists. Norman Borlaug (2002) suggested that crop yield increases, as for example brought by the Green Revolution, are the best way to reduce pressure on standing forests ('Borlaug hypothesis'). This view implicitly assumes a fixed demand for food that can be met with lower agricultural area as productivity increases. Contrary, there has been since Jevons (1865) a long-standing tradition of skepticism among economists on the positive direct conservation effects of productivity increases. Our model allows to consider the impact of productivity increases on forest conservation in both sectors.

Proposition 5. *Productivity increase in the agricultural sector increases deforestation:*

$$\Phi'(A)\frac{dA}{d\phi^A} + \frac{d\theta}{d\phi^A} = \underbrace{p^A\left(F_A - \frac{F_{AL}}{F_{LL}}F_L\right)}_{>0} \tag{35}$$

Proposition 6. *Productivity increase in the manufacturing sector decreases deforestation.*

$$\Phi'(A)\frac{dA}{d\phi^Y} + \frac{d\theta}{d\phi^Y} = \underbrace{\frac{F_{AL}}{F_{LL}}\left(Y_L - \frac{Y_{LK}}{Y_{KK}}Y_K\right)}_{<0} \tag{36}$$

Proof. The proof is along the lines of the proof of Proposition 1. □

Hence, while increases in industrial productivity reduce deforestation, increases in agricultural productivity accelerate deforestation if $\Phi'(A) > 0$. However, if marginal conversion and cultivation costs decrease with ongoing deforestation and, thus, $\Phi'(A) < 0$, the impact of productivity increases reverses in both sectors.

4.2 Biased technological shift and forest conservation

Corollary 2. *(Biased technological shift) Consider the case of an interior solution, i.e.* $d\theta/d\phi^Y = d\theta/d\phi^A = 0$ *and* $\Phi'(A) > 0$. *Consider furthermore an increase of productivity levels by the rates* $g_A := d\phi^A/\phi^A$ *and* $g_Y := d\phi^Y/\phi^Y$. *The technological shift can be forest conserving* ($dA < 0$) *or forest-consuming* ($dA > 0$) *depending on:*

$$dA < 0 \Leftrightarrow \frac{g^Y}{g^A} > \frac{p^A\phi^A}{\phi^Y}\frac{(F_{LL}F_A - F_LF_{AL})Y_{KK}}{F_{AL}(Y_KY_{KL} - Y_LY_{LL})} \tag{37}$$

Proof. Substitute $d\phi^A$ and $d\phi^Y$ by their growth rate in (35) and (36) and solve for the change in agricultural land dA. Summing both equation gives the overall effect on agricultural land which is negative if and only if (37) holds. □

Corollary 2 emphasizes the role of the relative size of technological change in both sectors. Overall technological change implies productivity changes in both sectors, not only in one. Depending on the relative total factor productivity growth rates g_Y and g_A, the forest-consuming effect of increasing productivity in the agricultural sector can well be overcompensated by the forest-saving effect of higher productivity in the manufacturing sector. For specific production functions, we can derive an even simpler condition:

Example 1. *Cobb-Douglas technology. For the case of the Cobb-Douglas production functions* $Y = K^\alpha(L^Y)^{(1-\alpha)}$ *and* $F = A^\beta(L^A)^{(1-\beta)}$, *a technological shift is forest-conserving* ($dA < 0$) *if and only if:*

$$\frac{g^Y}{g^A} > \frac{FL^Yp^A\phi^A}{Y\phi^Y(1-L^Y)} = \frac{GDP^A/L^A}{GDP^Y/L^Y} \tag{38}$$

where $GDP^A := p^A\phi^AF$ *and* $GDP^Y := \phi^YY$ *refer to agricultural and industrial value-added, respectively.*

Condition (38) says that for low labor productivity in the agricultural sector (i.e. the value-added per worker GDP^A/L^A is low compared to the industrial sector), even an equal technology shift in both sectors $g^A = g^Y$ will be forest-conserving.

4.3 Conservation policy and land tax response to productivity shifts

In case of a *ceteri paribus* change in the agricultural productivity ϕ^A, forest area is reduced according to Proposition 5. To avoid this impact, the government

could either use a quantity instrument like the establishment of protected areas or use land taxes that are indexed to agricultural productivity levels. Hence, the land tax becomes a function of agricultural productivity $\tau(\phi^A)$. With such a tax in place, the overall impact of a productivity change for an interior solution ($\theta = 0$) is:

$$\frac{dA}{d\phi^A} = \frac{\partial A}{\partial \phi^A} + \frac{\partial A}{\partial \tau(\phi^A)} \frac{\partial \tau(\phi^A)}{\partial \phi^A} \tag{39}$$

This allows to calculate the tax response $\tau^*(\phi^A)$ that neutralizes the productivity change, i.e. that yields $\frac{dA}{d\phi^A} = 0$:

$$\frac{\partial \tau^*(\phi^A)}{\partial \phi^A} = \frac{-\frac{\partial A}{\partial \phi^A}}{\frac{\partial A}{\partial \tau(\phi^A)}} \tag{40}$$

Substituting the partial effects on A from Propositions 3 and 5, we finally obtain:

$$\frac{\partial \tau^*(\phi^A)}{\partial \phi^A} = p^A \left(F_A - \frac{F_{AL}}{F_{LL}} F_L \right) \tag{41}$$

In case of a Cobb-Douglas technology, this simplifies to:

$$\frac{\partial \tau^*(\phi^A)}{\partial \phi^A} = p^A \frac{F}{A} \tag{42}$$

which gives after integrating the land tax:

Corollary 3. *(Productivity-indexed land tax) In case of a Cobb-Douglas technology the following tax rule ensures a constant forest protection level under changes in agricultural productivity:*

$$\tau^*(\phi^A) = p^A \phi^A \frac{F}{A} + \tau_0 = \frac{GDP^A}{A} + \tau_0 = \frac{\tilde{p}}{\beta} + \tau_0 \tag{43}$$

with τ_0 a constant that determines the overall conservation level, $\tilde{p} := p - k'(A)$ the net land rent (net of marginal transportation costs) and β the share of land income on agricultural value added (parameter of the Cobb-Douglas function).

Hence, if land taxes are indexed to the agricultural value added per agricultural area GDP^A/A – which is an easy to observe variable – changing agricultural productivity levels will not influence the forest cover. If the income share of land on total agricultural production β is known, the land tax can equally be indexed to the net land rent observable on the land market.

5 The impact of land taxes on the broader economy

5.1 Impact on production factors and factor prices

Proposition 3 indicated that land taxes do either reduce deforestation or – if all forest has been converted to agricultural land – land taxes reduce the land rent.

As the price of land is determined by the first-order condition (5) $\phi^A F_A = p$, land prices are in the latter case not affected. In case the land tax has allocative effects, the impact on land prices is determined by

$$\frac{dp}{d\tau} = \frac{d(\phi^A F_A)}{d\tau} = \phi^A \left(F_{AA} \frac{dA}{d\tau} + F_{AL} \frac{dL^A}{d\tau} \right) \tag{44}$$

Calculating the impact of a change in land taxes on land prices yields:

Proposition 7. *Land taxes do not change land prices, even if they have allocative effects. Hence,* $\frac{dp}{d\tau} = 0$.

Proof. Calculating the impact of the tax change on the labor force in the industrial sector gives

$$\frac{dL^Y}{d\tau} = -\frac{F_{AA}(1 + \frac{d\theta}{d\tau})}{F_{AL}(\rho G_{HA} + G_{AA})} > 0$$

Substituting this and the solution for $\frac{dA}{d\tau}$ from (32) into (45) and using the homogeneity property of the production function gives $\frac{dp}{d\tau} = 0$. □

This is a remarkable result. A lower availability of agricultural land is expected to increase land prices (i.e. the marginal productivity of land). As more workers shift, however, to the manufacturing sector, the marginal productivity of land decreases by the same amount. Thus, the net effect is zero.

Likewise, the impact of land taxes on wages is given from (6) by

$$\frac{dw}{d\tau} = \frac{d(\phi^A F_L)}{d\tau} = \phi^A \left(F_{LA} \frac{dA}{d\tau} + F_{LL} \frac{dL^A}{d\tau} \right) \tag{45}$$

with the same substitutions and transformations as in Proposition 7, we obtain

Proposition 8. *Land taxes do not change wages, even if they have allocative effects. Hence,* $\frac{dw}{d\tau} = 0$.

Together with the fact that interest rates remain unchanged as well (they equal the discount rate due to the Ramsey rule), we can conclude

Corollary 4. *All factor prices remain unaffected by land taxes – be they distortive or neutral (corner solution). As total labor is fixed, an increase in land taxes with allocative effects on land allocation leads to a stronger substitution of land by capital.*

Hence, the only factor that is affected by land taxes in the economy is capital: as land availability decreases, more capital is used to produce consumption goods.[3] The impact of tax changes on capital is

$$\frac{dK}{d\tau} = \frac{Y_{KL} F_{AA}(1 + \frac{d\theta}{d\tau})}{F_{AL} Y_{KK} \Phi'(A)} \geq 0 \tag{46}$$

In case of a corner solution, $\frac{d\theta}{d\tau} = -1$ and $\frac{dK}{d\tau} = 0$, otherwise a strict inequality yields and land taxes always increase capital stocks.

[3] It is important to note here that agricultural goods and manufacturing goods are perfect substitutes in our model economy.

5.2 Impact on sectoral and total GDP

From the findings above, it is also possible to calculate the impact of land taxes on agricultural output $GDP^A = \phi^A F$, industrial output $GDP^Y Y = \phi^Y Y$:

$$\frac{dGDP^A}{d\tau} = -\phi^A \frac{(F_A F_{AL} - F_L F_{AA})(1 + \frac{d\theta}{d\tau})}{F_{AL}\Phi'(A)} \leq 0 \tag{47}$$

$$\frac{dGDP^Y}{d\tau} = -\phi^Y \frac{Y_L F_{AA}(1 + \frac{d\theta}{d\tau})}{F_{AL}\Phi'(A)} \geq 0 \tag{48}$$

with the strict inequality again if no corner solution ($A < 1$) applies.

Corollary 5. *The impact on land taxes on total GDP is given by the sum of (47) and (48). The impact on total GDP is positive if the productivity ϕ^Y in the manufacturing sector is sufficiently high.*

The last result has a remarkable implication: Taxing land can increase total GDP due to higher industrial output. Land taxes promote the shift of an economy from a land-intensive (agricultural) economy to a capital-intensive (industrial) economy. Why does this shift not occur without the land tax? The capital stock is socially optimal if other market failures are absent (i.e. $\gamma = 0$, $\delta = 0$) and the pure time preference rate of investors ρ is socially optimal. In such a case, higher capital stocks are dynamically inefficient measured by the discounted utility function although consumption in the steady state is higher. There are, however, a variety of reasons why interest rates in developing countries are too high, capital markets distortive and investments too low: Interest rates are high due to low life expectancy and high investment risks because of inappropriate institutions (rule of law, property rights protection) or violent conflicts. Spillover effects of investment lead to further under-investment from a social perspective. In all of these cases which can be modeled by a distorted ρ or $\gamma > 0$ capital stocks are too low and land taxes provide a 'second-best' instrument to increase capital intensity of the economy and promote, thus, growth.

The output enhancing effect of land taxes depends, however, on the technology and production function:

Example 2. *Cobb-Douglas technology. For the case of the Cobb-Douglas production functions $Y = K^\alpha (L^Y)^{(1-\alpha)}$ and $F = A^\beta (L^A)^{(1-\beta)}$, the impact of tax changes on total GDP for an interior solution ($A < 1$) is:*

$$\frac{dGDP}{d\tau} = \frac{\phi^Y Y L^A - \phi^A F L^Y}{A L^Y \Phi'(A)} \tag{49}$$

$$= \left(\frac{1}{1-\alpha} - \frac{1}{1-\beta}\right) \frac{wL^A}{A\Phi'(A)} \tag{50}$$

where the last transformation uses the first-order conditions of optimal labor allocation in both sectors (Eqs. (3) and (6)). This implies that tax increases have positive impact on total GDP if and only if $\alpha > \beta$.

The result resembles slightly the well-known finding that constant consumption without technological change is possible in an economy with *exhaustible* natural resources if the income share of capital is higher than the income share of natural resources (Solow, 1974; Stiglitz, 1974). In our case, however, we have basically shown that a reduction of a (non-exhaustible) natural resource can be overcompensated by capital deepening and increase total output if the same condition holds.

Example 2 (continued)**.** *Denote with* $\tilde{\alpha} := \frac{rK}{GDP}$ *and* $\tilde{\beta} := \frac{pA}{GDP}$ *the income shares of capital and land rents on total GDP. Denote further with* $\vartheta := \frac{GDP^Y}{GDP}$ *the share of the industrial sector on total production (and* $1-\vartheta$ *the share of the agricultural sector accordingly). Then:*

$$\frac{dGDP}{d\tau} > 0 \Leftrightarrow \alpha > \beta \Leftrightarrow \frac{\tilde{\alpha}}{\tilde{\beta}} > \frac{\vartheta}{1-\vartheta} \tag{51}$$

$$\Leftrightarrow \vartheta < \tilde{\vartheta} := \frac{\tilde{\alpha}}{\tilde{\alpha}+\tilde{\beta}} \tag{52}$$

Example 2 illustrates that for a Cobb-Douglas technology land taxes have beneficial impact on total GDP if and only if the fraction of capital income share and land rent income share is higher than the fraction of industrial output share and agricultural output share. For countries with a large agricultural sector (ϑ very small) – which is the case for many least-developed countries – higher land taxes increase total GDP.

For a typical capital share $\tilde{\alpha} = 1/2$ and the rather ad-hoc land rent share of $\tilde{\beta} = 0.05$ the agricultural sector needs to be larger than 10% for land taxes to increase total GDP according to Example 2. Hence, in particular least-developed countries with high share of agricultural activities could benefit from land taxes.

5.3 Using land tax revenues for increasing investments

In our model we have assumed so far that land tax revenues τA are lump-sum transferred to the household and then allocated to consumption and investment according to the household's first-order condition. The revenues could, however, also used to subsidize investments and enhance capital stocks. A subsidy σ on capital basically changes the capital market distortion factor γ to $\gamma = \gamma' - \sigma$ where γ' is the original mark-up on interest rates introduced in (1) for expropriation and investment risks or (external) spillovers to investment. If all land taxes are used for subsidizing capital stocks, $\tau A = \sigma K$ or, alternatively, $\sigma = \tau A/K$. As long as $\sigma \leq \gamma'$, the land tax reduces the capital market distortion and brings the capital stock closer to its optimal level. There are, however, further equilibrium effects that apply: As γ is reduced by the capital subsidy, additional forest is conserved according to Proposition 2. As the land tax increases, the tax base (A) reduces which could have adverse effects on the capital subsidy rate. Also, the labor market could be affected due to changing investments. Nevertheless, the entire impact on increasing land taxes on conservation remains positive:

Proposition 9. *Subsidizing capital at the rate $\sigma = \tau A/K$, a change on the land tax τ influences agricultural area in case of an interior solution ($A < 1$) according to:*

$$\Phi'(A)\frac{dA}{d\tau} = \frac{K\Lambda\left(-\sigma\phi^Y Y_{LL} + \phi^A(A\phi^Y F_{AL}Y_{AL} - F_{LL}[\sigma - K\phi^Y Y_{KK}])\right)}{-K\Lambda\sigma\phi^Y Y_{LL} + \phi^A(\tau\phi^Y[KF_{AL}Y_{KL} + AY_{LL}F_{AA}] - K\Gamma F_{LL}[\sigma - K\phi^Y Y_{KK}])} \tag{53}$$

With the usual conditions on the signs of the derivatives of the neoclassical production function, it follows $\frac{dA}{d\tau} < 0$.

6 An empirical investigation on the impact of land taxes on GDP

This section applies Corollary 5 for the Cobb-Douglas case to estimated parameters for real-world economies. We want to analyze the empirical implications of the critical condition in Example 2 which only requires to know income and GDP shares.

Land rent income shares $\tilde{\beta}$ are difficult to estimate. They can be found in Social Accounting Matrices although data quality is in particular for developing countries a major concern. Table 2 shows parameters for a set of countries and whether they meet the critical condition in Example 2. As it turns out, land taxes have a negative impact on GDP in Brazil and Uganda (negative sign on the column $\frac{dGDP}{d\tau}$ but positive signs for the remaining countries. As can further be seen, the value of ϑ is close to the critical value $\tilde{\vartheta}$, implying that small parameter changes will change the sign of $\frac{dGDP}{d\tau}$. In order to address the uncertainty and measurement problems in determining income shares, we apply a Monte-Carlo simulation analysis assuming a normally distributed land income share β with mean equal to the reported values and standard deviations of $\sigma = 10\%$ and $\sigma = 20\%$ to account for measurement errors.[4] Finally, we report the frequency of a positive impact of land taxes on GDP, indicating the probability of a positive impact, given the uncertainty on β in the column $P[dGDP/d\tau > 0]$.[5] The last two rows of Table 2 use mean and median parameter values for the impact analysis. By and large, the results suggest that for many countries land taxes have a positive impact while the negative impact on Brazil is highly uncertain.

[4] We create a sample of one million observations.

[5] For the analysis we assumed that capital income shares are not uncertain as they are typically easier to measure. Nevertheless, considering the fact that income shares have to sum up to one, an error in β will translate to an error in α. Accounting for this inter-dependence does, however, only slightly change the calculated probabilities in the Table 2.

Country	Base year	$\tilde{\alpha}$	$\tilde{\beta}$	ϑ	$\tilde{\vartheta}$	$\frac{dGDP}{d\tau}$	$P[dGDP/d\tau > 0]$		Source for SAM
							$\sigma = 10\%$	$\sigma = 20\%$	
Bangladesh	1993/94	0.435	0.129	0.741	0.771	+	0.65	0.57	Fontana and Wobst (2001)
Brazil	1995	0.514	0.033	0.942	0.940	–	0.49	0.49	Cattaneo (2002)
China	2007	0.453	0.020	0.892	0.958	+	0.77	0.64	Zhang and Diao (2013)
El Salvador	2000	0.649	0.015	0.895	0.977	+	0.82	0.68	Acevedo (2004)
Ghana	2005	0.238	0.076	0.591	0.758	+	0.99	0.89	Breisinger et al. (2007)
Indonesia	1995	0.424	0.062	0.829	0.872	+	0.69	0.59	Bautista et al. (1999)
Kenya	2003	0.511	0.048	0.710	0.914	+	1.00	0.92	Kiringai et al. (2006)
Malawi	1998	0.336	0.108	0.644	0.757	+	0.95	0.78	Chulu and Wobst (2001)
Mexico	2008	0.652	0.014	0.967	0.979	+	0.55	0.52	Debowicz and Golan (2012)
Nigeria	2006	0.433	0.110	0.680	0.797	+	0.95	0.78	Nwafor et al. (2010)
Peru	2002	0.507	0.043	0.917	0.922	+	0.52	0.51	Nin-Pratt et al. (2011)
Tanzania	2001	0.397	0.041	0.671	0.906	+	1.00	0.95	Thurlow and Wobst (2003)
Uganda	1999	0.237	0.226	0.615	0.511	–	0.07	0.23	Dorosh et al. (2002)
Vietnam	1997	0.282	0.093	0.742	0.752	+	0.55	0.52	Nielsen (2002)
Zambia	2001	0.528	0.012	0.780	0.978	+	0.99	0.90	Thurlow et al. (2008)
Zimbabwe	1991	0.488	0.023	0.847	0.955	+	0.90	0.73	Thomas and Bautista (1999)
Mean		0.443	0.066	0.779	0.871	+	0.87	0.71	
Median		0.444	0.046	0.761	0.907	+	0.97	0.82	

Table 2: Impact of higher land taxes on total GDP. Data on income shares $\tilde{\alpha}$ and $\tilde{\beta}$ was calculated from Social Accounting Matrices (SAM) as cited. The share of the non-agricultural sector ϑ was taken from World Development Indicators for the respective base year of the SAM. The critical value for $\tilde{\vartheta}$ and the sign of the GDP impact $\frac{dGDP}{d\tau}$ was calculated using the condition in Example 2. $P[dGDP/d\tau > 0]$ refers to the probability of a positive impact on GDP under uncertain land income shares $\tilde{\beta}$ with σ as the standard deviation of the measurement error. For the last two rows, ϑ as well as GDP impacts (and probabilities) have bean calculated using mean and median values of $\tilde{\alpha}, \tilde{\beta}$ and ϑ over teh country sample.

7 Discussion and conclusions

This paper developed a multisectoral general equilibrium growth model with endogenous land conversion and forest conservation decisions. The model shed light on crucial aspects of deforestation, conservation policies and development. It first emphasizes the duality between land rents and land scarcity: Even without taxes, land rents can become zero if the marginal costs of converting and cultivating one additional unit of land is higher than its marginal productivity. Land taxes are only allocation neutral if they are less then the land rent that (that might be zero for high marginal conversion costs). Land taxes above this threshold, however, loose their allocation-neutral property which is at odds to conventional economic wisdom. In that case, land taxes increase forest cover and affect capital accumulation through general equilibrium effects on the labor market.

The forest-conserving property of land taxes makes them to an important instrument for forest protection which has hardly been considered so far. Although such taxes can be made equivalent to a quantity instrument like the establishment of protected areas, the tax generates public revenues while protected areas create windfall profits (rents) for land owners. This latter aspect is of great relevance for developing countries where governments often lack the financial resource for necessary investments and public good provision. Additionally, a land tax is a natural way to implement conservation policies within an international REDD+ regime: As international transfers are basically subsidies per area of forest conserved, an equally high tax on non-primary-forest area will internalize the positive global external benefits of forest conservation and result automatically in the optimal forest conservation level – provided that the REDD+ subsidy reflects the global benefits accurately. The establishment of protected areas, however, runs the risk of over- or underprovision of primary forests if the government cannot estimate the domestic marginal costs of forest conversion correctly.

While the Weitzman (1974) framework can in principle be used to analyze the welfare effects of price and quantity instruments under uncertainty, the partly allocation-neutral property of the land tax makes a hybrid approach particularly attractive: While the establishment of a conservation area provides a safeguard for forest conservation levels, a land tax equal to the (global) social benefits of forest conservation will either be allocation neutral (if it is lower than the land rent) or induce *additional* forest conservation if the opportunity costs of conservation are lower than anticipated (and the land rent is very low). In both cases, the tax generates public revenues.

The analysis of the determinants of deforestation also emphasized the role of infrastructure as important component of the marginal land conversion and cultivation costs. This might generate an important trade-off between economic growth in developing countries that is often hampered by bad or missing infrastructure and forest conservation. Likewise, low pure time preference, e.g. due to increased life-expectancy, may also increase deforestation which is contrary to the conventional view on resource conservation. High interest rates and

capital market imperfections, however, have a negative impact on forest cover as they re-allocate labor from the capital-intensive manufacturing sector to the land-consuming agricultural sector.

Our multi-sector general equilibrium approach provides also a new assessment of Borlaug's hypothesis and Jevons' paradox: If marginal conversion and cultivation costs increase in area cultivated, higher factor productivity in the agricultural sector is land-consuming and increases deforestation; if marginal costs decrease, the opposite holds. Hence, policies that increase crop yields should be complemented by additional conservation policies to avoid adverse effects on forest cover. We developed a land tax indexed to an easy-to-observe productivity indicator that is robust to productivity changes in the agricultural sector.

Many policies targeted at economic growth and poverty reduction focus on institutional factors and public goods like infrastructure, education, research and health services. These factors will in turn affect innovation rates and technological progress in *both* sectors simultaneously, the manufacturing and the agricultural sector. Increased productivity in the manufacturing sector has, however, the opposite effect on deforestation of productivity increases in the agricultural sector. A simultaneous technological shift in both sector will be forest-conserving if the labor productivity in the agricultural sector is lower than in the manufacturing sector, which is typically the case.

Finally, we explored the impact of land taxes on the capital intensity of the economy and aggregate output. Again contrary to the conventional view, land taxes can increase overall output by inducing a higher capital stock as a substitute for reduced land use. The positive effect depends on the relationship between land and capital factor shares and the size of the agricultural sector compared to the manufacturing sector. This increase in output above the dynamically optimal level reduces discounted utility. If tax revenues are used to subsidize capital in case of underinvestments, for example, due to capital market imperfections, welfare can also increase. An application to empirical data on factor and output shares revealed the output-increasing potential of land taxes for several countries. Admittedly, land taxes can have negative impacts on GDP for some countries and problems of measuring the factor share of land create substantial uncertainty on the GDP effect for some countries. Hence, a country-specific and differentiated analysis is required.

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A Proof of Proposition 2

Differentiating Eqs. (25–27) totally with respect to γ gives:

$$\phi^Y \left(Y_{KK} \frac{dK}{d\rho} + Y_{KL} \frac{dL^Y}{d\rho} \right) = 1 \tag{54}$$

$$\phi^Y \left(Y_{LK} \frac{dK}{d\rho} + Y_{LL} \frac{dL^Y}{d\rho} \right) = \phi^A \left(F_{LA} \frac{dA}{d\rho} + F_{LL} \frac{dL^A}{d\rho} \right) \tag{55}$$

$$(G_H - q) + \rho G_{HA} \frac{dA}{d\rho} = \phi^A \left(F_{AA} \frac{dA}{d\rho} + F_{AL} \frac{dL^A}{d\rho} \right) - G_{AA} \frac{dA}{d\rho} - \frac{d\theta}{d\rho} \tag{56}$$

Solving (54) for $dK/d\rho$ and substituting this into (55), we obtain by using further $dL^A/d\rho = -dL^Y/d\rho$ (labor constraint) and $Y_{LL}Y_{KK} = Y_{LK}^2$ (homogeneity of Y):

$$\phi^A F_{LL} \frac{dL^Y}{d\rho} = \phi^A F_{LA} \frac{dA}{d\rho} - \frac{Y_{LK}}{Y_{KK}} \tag{57}$$

Putting this into (56) and using $F_{LL}F_{AA} = F_{AK}^2$ (homogeneity of F), gives Eq. (30) after re-arranging.

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