A Closer Look at the Mechanism of Structural Transformation: the Role of Biased Technical Change in Agriculture

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Abstract

I analyze a simple model of structural change to investigate the effect of agricultural productivity on industrialization when technical change is biased. When food consumption is close to the subsistence level, the bias is irrelevant and any type of technical change fosters industrialization. However, when the economy develops and food consumption substantially exceeds the subsistence level, the effect of land- and labor-saving technologies on industrialization critically depends on the elasticity of substitution between land and labor. I calibrate the model to investigate the contribution of different types of technical change in practice. Consistent with empirical evidence, labor-saving technologies have a substantial role in later stages of development.

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1 Introduction

As stated recently by Rodrik et alii (2015), one the two broad challenges of today's developing countries is the "structural transformation" challenge, that is, a quick and continuous flow of production factors from traditional to modern economic activities. More specifically, the transition away from traditional agriculture has been perceived as sluggish in many of the world poorest countries (Alston and Pardey 2014). This persistence of agriculture throughout much of the developing world has raised interest in the theoretical underpinnings of structural change.

Some theories have stressed that the main cause for structural change is the relative speed of productivity growth among economic sectors. Sectors with relatively slow productivity growth end up concentrating most labor and valued-added in the aggregate economy (e.g. Baumol (1967), Ngai and Pissarides (2007)). Another strand of research argues that structural transformation originates in differences in the income elasticity of demand among consumption goods (e.g. Matsuyama (1992), Laitner (2000), Kongsamut, Rebelo & Xie (2001) and Gollin, Parente & Rodgerson (2002)). Engel's law in particular is highlighted as the main cause for the transition away from agriculture. Finally, more recent explanations focus on differences in the capital intensities (Acemoglu and Guerrieri 2008) or in the scale of productive units (Buera and Kaboski 2012) among sectors.

Irrespective of the main explanation chosen, a conventional view has emerged that the growth of agricultural productivity is a key determinant of structural transformation away from agriculture, at least in a closed economy.[1]. This view, already prominent in the work of earlier development economists such as Lewis (1954), Nurske (1953) and Schultz (1953), is that increased agricultural productivity releases labor for the industrial sector, and at the same time ex-

[1]Vollrath's 2011 model put forward the agricultural income share of labor, not agricultural TFP, as a long-run determinant of industrialization. Nonetheless, it belongs to the technology parameters of agriculture and can be understood as a loose form of agricultural productivity.

pands the demand for manufactured products by raising rural incomes. But the specific role of land- and labor-saving technologies in this process, of whether productivity improvements should primarily concern labor or land, has not been clarified so far. This distinction, however, is key to understand the development of modern agriculture.

Historically, as shown by Hayami and Ruttan (1985) and Ruttan (1977, 2002), countries that went through successful agricultural development experienced biased technical change in favor of the relatively scarce factor. For example, in Japan and Taïwan, where land is scarce, the priority was given to land-saving technologies such as the development of rice varieties that are respondent to fertilizer. In the United States, Canada and Australia, where land is abundant and the main constraint on production was the size of the workforce, the priority was given to the development of agricultural machines that substitute for labor. Today, Alston and Pardey (2014) observe that the productivity paths of world regions also diverge according to their level of development. Higher income regions like Japan, Europe and North America move in a relatively labor-saving direction under the effect of high wages, while low and middle-income regions, notably Sub-Saharan Africa, move in a relatively land-saving direction. These observations raise the question of the type of technical change involved in structural transformation.

Recently, two papers addressed this question using a different perspective. In the context of small open economies, namely Brazilian municipalities, Bustos, Caprettini and Ponticelli (2016) argue that while labor-augmenting technical change can be expected to speed up industrialization, land-augmenting technical change has the opposite effect. Land improvements are responsible for an increase in the marginal product of agricultural labor and therefore attract labor in agriculture. In the context of a closed economy, Leontief production functions and hidden unemployment in agriculture, de Souza (2017) argues that land-augmenting technical change contributes to industrialization via reduced unemployment and an increased demand for manufactures, while labor-augmenting technical change has the opposite effect.

My paper elucidates the effect of biased technical change on industrialization in the context of a closed economy and general specifications for the production functions. I develop a model that can be seen as a natural extension of Matsuyama's (1992) model in a closed economy, where the factor-bias of technical change has been taken into account. It is also strongly complementary to the work of Bustos, Caprettini and Ponticelli (2016), since their model of an open economy obtains as a special case of the more general model presented in this paper. In my model, I show that when food consumption is close the subsistence level, both types of technical change contribute to industrialization. However when food consumption substantially exceed the subsistence level, the type of technical change that foster industrialization depends on the elasticity of substitution between land and labor. A high elasticity of substitution will give more importance to land-saving technologies, while a low elasticity of substitution will give more importance to labor-saving technologies.

In a second phase, I calibrate a simplified model using country and regional level data to estimate (i) elasticities of agricultural labor with respect to land- and labor-augmenting technical change (ii) the rates of land- and labor-augmenting technical changes over 2005-2015. These two components are then combined to assess the contribution of different types of technical change to structural transformation. This calibration intends to be parsimonious in data and concepts, and the elasticities of agricultural labor are computed using just a few economic indicators, namely, the income share of land, food consumption and subsistence levels, the elasticity of substitution, and the share of food spending. My results suggest that labor-augmenting technical change is the main driver of structural transformation in developed regions, while developing countries achieve a relative balance between labor and land-augmenting technical change. In Sub-Saharan Africa where the overall level of technical change is low, the diminishing land per capita exerts a significant drag on structural transformation.

The remainder of the paper is organized as follows. Section 2 presents the model and gives the main theoretical results and intuitions. Section 3 derives formula for the elasticities of agricultural labor using a simplified model. Section 4 calibrates the elasticities of agricultural labor. Section 5 calibrates the rates of labor- and land-augmenting technical changes and gives a growth decomposition of agricultural labor per capita. Section 6 concludes and gives directions for further research.

2 A model of structural transformation with biased technical change in agriculture

2.1 Technology and preferences

The economy consists of two sectors of production. The traditional sector, agriculture (Y^A), uses augmented labor ($\hat{L^A} = A_L L^A$) and augmented land ($\hat{S} = A_S S$), where L^A, S stand for respectively agricultural labor and land and A_L, A_S their respective technical change components. I do not focus on land utilization through harvesting and simply assume that land enters the production function directly. A_L embodies technologies and inputs such as herbicides and agricultural machines, that extend the power of the labor force without affecting the amount of land used. A_S embodies technologies and inputs such as additional harvesting seasons, fertilizers and high-yielding crops that are akin to a land extension without affecting the labor force. As emphasized by Ruttan (2002), mechanical technologies on one side and biological technologies on the other reflect roughly these two directions. But there are exceptions: in the examples chosen above, herbicides are a biological technology but are more akin to a labor-saving technology since they save on the labor used to weed. In practice, new inputs or techniques may improve both components at the same time. For instance, a genetically engineered crop might be resistant to herbicides (and will therefore save on manual labor) and might also take less time for maturing, enabling the farmer to set up an additional planting and harvesting cycle (which amounts to land extension).

The agricultural sector is to be seen as the sector where most of the population would work initially, to provide for its own subsistence. The modern sector (Y^M) is identified with manufacturing and services and uses labor (L^M) as long as possibly other fixed inputs that are sector specific. Note that land does not enter the production function of the modern sector. This assumption relies on the observation that manufacturing and services activities are much less land-intensive than agriculture and generally take up a small proportion of the total land available for economic activities, though in particularly land-constrained area a conflict might occur[2]. Formally,

$$
\begin{aligned}
Y^M &= M\,F(L^M), \\
Y^A &= A\,G(\hat{L^A}, \hat{S}), \\
\hat{L^A} &= A_L\,L^A, \quad \hat{S} = A_S\,S.
\end{aligned} \tag{1}
$$

Inputs have positive returns, the production technology of the modern sector is concave, and the production technology of the traditional sector has constant returns to scale with diminishing returns to labor:

$$
\begin{aligned}
&(i)\ F, G \text{ are of class } C^2 \\
&(ii)\ F' > 0, \quad F'' \leq 0 \\
&(iii)\ G_{\hat{L^A}} > 0, \quad G_{\hat{S}} > 0, \quad G_{\hat{L^A}^2} < 0 \\
&(iv)\ G \text{ has constant returns to scale.}
\end{aligned} \tag{2}
$$

I assume the existence of a representative household taking prices as given. Its preferences are given by

$$
U(C^A, C^M) = (C^A - \lambda)^{\nu^A} (C^M)^{\nu^M}, \qquad \nu^A + \nu^M = 1,\, \lambda \geq 0 \tag{3}
$$

The Stone-Geary argument embedded in (3) is one of the simplest way to take into account Engel's law and was first used in the context of structural change by

[2]Land cover statistics for the European Union in 2015 reveal that human buildings use 4% of the land available while this proportion rises to 22% for cropland (Eurostat).

Matsuyama (1992). In the context of a representative household, the subsistence level λ is by aggregation a sum of the subsistence levels of all households. Though Cobb-Douglas preferences are somewhat constraining, Appendix B shows that the main ideas conveyed by this paper can be extended without difficulty to a framework with CES preferences, with the cost of an added layer of subtleties.

Finally, a minimal amount of agricultural productivity is required so that the economy can produce more than the subsistence level if the entire labor force is working in agriculture. Normalizing the labor force to one for simplicity, this yields:

$$AG(A_L, \hat{S}) > \lambda \tag{4}$$

2.2 Market equilibrium

The representative household owns the land and receives the real wage w. I normalize the price of the manufacturing good to one and denote the price of the agricultural good by p^A and the price of the rent on land by q. The budget constraint of the representative household is,

$$p^A C^A + C^M = w + qS + \pi, \tag{5}$$

where π denotes profit from the modern sector. Interior solution of utility maximization for the representative household implies:

$$\frac{U_{C^A}}{U_{C^M}} = p^A. \tag{6}$$

Production decisions in agriculture and manufacturing are taken by profit-maximizing entities, acting as price-takers. Since producers compete for the same pool of worker this yields:

$$\begin{aligned} M F'(L^M) &= w, \\ p^A A\, G_{\hat{L^A}}(\hat{L^A}, \hat{S})\, A_L &= w. \end{aligned} \tag{7}$$

Finally, market clearing needs to be clarified. I assume the economy lives in autarky. This yields:

$$\begin{aligned} L^A + L^M &= 1, \\ C^M &= Y^M, \\ C^A &= Y^A. \end{aligned} \tag{8}$$

I now solve for the equilibrium allocation of labor to study the implications of land- and labor-augmenting technical changes. Using equations (6) and (7),

$$\frac{U_{C^A}}{U_{C^M}} = \frac{M\,F'(L^M)}{A\,G_{\hat{L^A}}(\hat{L^A},\hat{S})\,A_L}, \tag{9}$$

the equality between marginal rate of substitution and marginal rate of transformation. Combining (9) with household preferences stated in (3) gives

$$\frac{\nu^A}{\nu^M}\frac{C^M}{C^A-\lambda} = \frac{M\,F'(L^M)}{A\,G_{\hat{L^A}}(\hat{L^A},\hat{S})\,A_L}. \tag{10}$$

Replacing C^M, C^A and L^M using (8) and (1) and rearranging yields

$$\frac{\nu^A}{\nu^M}\frac{F(1-L^A)}{F'(1-L^A)} = \frac{1}{A_L}\frac{G(\hat{L^A},\hat{S})-\hat{\lambda}}{G_{\hat{L^A}}(\hat{L^A},\hat{S})}, \qquad \hat{\lambda} = \frac{\lambda}{A}, \tag{11}$$

(11) is the key equation governing the allocation of labor in this economy. Since there is no market failure, this market equilibrium decentralizes the optimal solution of a social planner. The endogenous responses of this labor allocation to exogenous changes are summarized in Proposition 1 below. The proofs for this proposition as well as for Proposition 2 in Section 3 are given in Appendix A.

Proposition 1 *Consider a competitive market economy whose technology is characterized by* (1) *and* (2)*, whose representative consumer has preferences* (3) *and with market clearing* (8).

Denote σ as the (possibly nonconstant) elasticity of substitution between augmented labor and augmented land in agriculture, and s_S as the competitive income share of land in agricultural output.

Then, at an interior solution,

(a) the equilibrium allocation of labor L^A is unique[3]*and satisfies the following condition:*

$$\frac{\nu^A}{\nu^M}\frac{F(1-L^A)}{F'(1-L^A)} = \frac{1}{A_L}\frac{G(\hat{L^A},\hat{S})-\hat{\lambda}}{G_{\hat{L^A}}(\hat{L^A},\hat{S})}, \qquad \hat{\lambda} = \frac{\lambda}{A},$$

(b) the equilibrium allocation of labor L^A reacts to exogenous parameters as follows:

$$\frac{\partial L^A}{\partial \nu^A} > 0 \qquad \frac{\partial L^A}{\partial \hat{\lambda}} > 0,$$

if $\underline{\sigma < 1}$,

$$\frac{\partial L^A}{\partial A_L} < 0 \qquad \frac{\partial L^A}{\partial A_S} \lesseqgtr 0 \Leftrightarrow \frac{Y^A-\lambda}{Y^A} \lesseqgtr \sigma,$$

if $\underline{\sigma = 1}$

$$\frac{\partial L^A}{\partial A_L} < 0 \qquad \frac{\partial L^A}{\partial A_S} < 0,$$

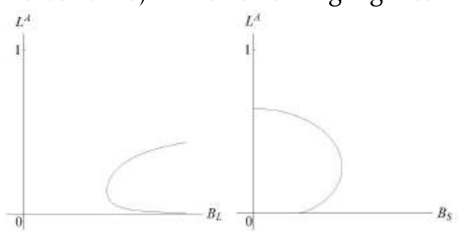
if $\underline{\sigma > 1}$

$$\frac{\partial L^A}{\partial A_L} \lesseqgtr 0 \Leftrightarrow \frac{Y^A-\lambda}{Y^A}\frac{\sigma - s_S}{1-s_S} \lesseqgtr \sigma \qquad \frac{\partial L^A}{\partial A_S} < 0,$$

$$\textit{furthermore, } \frac{\partial L^A}{\partial S} \textit{ has the same sign as } \frac{\partial L^A}{\partial A_S}.$$

The effects of a marginal increase in Hicks-neutral technical change (A), in the subsistence level (λ) or in the preference for food (ν^A) on the equilibrium value of agricultural labor are as expected and easily conceivable. In particular, the negative response of agricultural labor to Hicks-neutral technical change summarized in the sign of $\frac{\partial L^A}{\partial \hat{\lambda}}$, is the result of Engel's law as described in Matsuyama (1992). On the other hand, understanding the effects of an increase in labor- (A_L) and land-augmenting (A_S) technical change is more challenging and requires discussion. The effects of an increase in A_S, slightly more intuitive,

[3]For instance, L^A is *not* single-valued when Y^A is a CES with $\sigma < 0$ (the function fails to be concave). The following figures are examples of the shapes that arise in that situation.



are studied first. Also, since in the current framework land-augmenting technical change and land increase have the same consequences, the following discussion uses land increase as an illustration.

When land increases, a *price effect* and a *complementarity effect* can be identified. The *complementarity effect* is the result of a land increase when the price of agricultural goods is kept constant. Holding the price of food fixed, a land increase raises the marginal productivity of labor in agriculture[4]. This rise in the agricultural real wage (equation (7)) will immediately attract more labor in agriculture until the wage gap closes. The complementarity effect thus induces a rise in L^A. This mechanism is the only mechanism that govern labor in a small open economy, since such an economy act as a price taker with respect to world prices.

The *price effect* is the result of a land increase when the marginal productivity of labor (in both sectors) is kept constant. Holding the marginal productivity of labor constant, a land increase raises agricultural production, and under Cobb-Douglas preferences, this create a drop in food prices, affecting agricultural real wages negatively. Workers then move out of agriculture to prevent the agricultural real wage from falling. The price effect thus induces a drop in L^A.

Understanding the final movement of L^A amounts to asking which of the price and the complementarity effect will dominate the other. Proposition 1 states that if the elasticity of substitution between land and labor is greater than or equal to one, then the price effect always dominates. In case the elasticity of substitution is lower than one, the price effect dominates *provided the economy is close to a state of subsistence*.

To understand why proximity to subsistence matters, note that in equilibrium, the price of agricultural goods is related to agricultural output in a simple way:

$$\frac{\partial p^A}{\partial Y^A} = -\frac{\nu^A}{\nu^M}\frac{Y^M}{(Y^A-\lambda)^2}. \tag{12}$$

[4]Note that because the function G has constant returns to scale and diminishing returns to labor, its cross marginal product must be positive.

Imagine that Y^A comes close to the subsistence level λ. Then equation (12) tells us that the price effect will become arbitrarily large. The complementarity effect (i.e. the increase in the marginal productivity of labor), on the other hand, stays bounded, since the cross partial derivative $G_{\hat{S}\hat{L^A}}$ is finite by assumption, even close to a state of subsistence. This explains why the price effect always overcomes the complementarity effect when agricultural output is close to the subsistence level, and why agricultural labor is a decreasing function of land in this region. When agricultural output moves away from the subsistence level, the price effect diminishes and agricultural labor may become an increasing function of land: the relationship is possibly non-monotonic.

I now study the effect of labor-augmenting technical change on the allocation of labor. When there is labor-augmenting technical change, price versus complementarity is still the key idea. A difference however, is that the complementarity effect is now uncertain. Holding the price of food constant, labor-augmenting technical change can either raise or lower the marginal productivity of labor. This comes from the fact that it increases the efficiency of raw labor L^A and at the same time decreases the marginal productivity of augmented labor $\hat{L^A}$ on account of diminishing returns. As a result, the complementarity effect can either raise or lower agricultural labor. The price effect has the same orientation than before and results in a drop in the price of food and movement of labor out of agriculture. If $\sigma < s_S$, the complementarity effect drives labor out of agriculture and plays in the same direction as the price effect[5]. Otherwise, both effects play in opposite directions.

Fortunately, it is possible to sort out the general case in terms of the elasticity of substitution. When the elasticity of substitution is less than or equal to one, either both effects play in the same direction or the price effect dominates. This result in agricultural labor being a decreasing function of labor-augmenting technical change. When the elasticity of substitution is greater than one, the price

[5]An hypothesis termed as "strong complementarity between land and labor" by Bustos, Caprettini and Ponticelli (*ibid.*)

effect dominates only if the economy is close enough to a state of subsistence, following the same analysis as before.

Finally, it is worth taking time to compare the effect of biased technical change on this closed economy with the results of biased technical change on an open economy found by Bustos, Caprettini and Ponticelli (2016). Results in an open economy are akin to taking only into account the complementarity effect described above. Here are these results, simplified by the assumption that $\sigma \leq 1$, the most plausible hypothesis *a priori* (cf Section 4). First, labor-augmenting technical change decreases agricultural labor in a closed economy, and decreases agricultural labor in an open economy provided the elasticity of substitution between land and labor is lower than the land income share. Second, land-augmenting technical change decreases agricultural labor in a closed economy provided the economy is close enough to a state of subsistence, and increases agricultural labor in an open economy.

3 Derivation of the elasticities of agricultural labor in a simplified model

As a preliminary to the model calibration, the elasticities of agricultural labor with respect to land-augmenting and labor-augmenting technical change are derived from a simplified version of the model presented in Section 1. Given the central importance of the elasticity of substitution in agriculture, a natural simplification of this model is the case of a constant elasticity of substitution (CES) production function in agriculture. To facilitate understanding of the results, the functional forms of production technologies are now made explicit:

$$\begin{aligned} &Y^M = M L^M, \\ &Y^A = A\left[\beta (A_L L^A)^{\frac{\sigma-1}{\sigma}} + (1-\beta)(A_S S)^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}}, \qquad \beta \in (0,1),\ \sigma > 0. \end{aligned} \tag{13}$$

The modern sector has constant returns to scale for simplicity. Note that constant returns to scale in the modern sector imply constant returns to scale for the economy as a whole, meaning that L^A, S can be interpreted as per capita inputs, Y^A, Y^M as per capita outputs and λ as the per capita subsistence level. This is the interpretation that I choose from now on. This interpretation allows me to dispense from considerations relative to the size of the labor force[6].

Functional forms (13), along with preferences and market clearing as defined in Section 2 (equations (3) and (8)), provide explicit shapes for the relationship of L^A with respect to A_L and A_S. Properties and graphs of these shapes are given in the Online Appendix A. As expected from Proposition 1, L^A is a decreasing function of A_L and A_S in a neighborhood of their minimum values. The additional insight of (13) is that when the subsistence level is positive, $L^A(A_L)$ has *exactly* one turning point while $L^A(A_S)$ has *at most* one turning point.

In this section, instead of studying the shapes of $L^A(A_L)$ and $L^A(A_S)$ in detail, it is more informative to derive the elasticities of L^A with respect to A_L, A_S and A and to compare them for different values of an underlying parameter. This is especially useful to assess the relative effectiveness of different types of technical change. Replacing (1) with (13) in the model of Section 2 and computing the derivative of L^A with respect to $\hat{S}$ yields:

$$\frac{\partial L^A}{\partial \hat{S}} = \frac{(A_L)^{-1}\left(\dfrac{Y^A-\lambda}{Y^A}-\sigma\right)}{\dfrac{Y^A-\lambda}{Y^A}\dfrac{\hat{S}}{\hat{L^A}}+\gamma\left(\dfrac{\hat{S}}{\hat{L^A}}\right)^{\frac{1}{\sigma}}}, \tag{14}$$

$$with \quad \gamma = \frac{\sigma}{\nu^M}\frac{\beta}{(1-\beta)}.$$

Now, turning equation (14) into an elasticity of labor with respect to augmented land (i.e. $\epsilon_{L^A,\hat{S}} = \frac{\hat{S}}{L^A}\frac{\partial L^A}{\partial \hat{S}}$):

$$\epsilon_{L^A,\hat{S}} = \epsilon_{L^A,A_S} = \epsilon_{L^A,S} = \frac{\dfrac{Y^A-\lambda}{Y^A}-\sigma}{\dfrac{Y^A-\lambda}{Y^A}+\dfrac{\sigma}{\nu^M}\dfrac{1-s_S}{s_S}}, \tag{15}$$

[6]In Section 2, where the modern sector possibly has decreasing returns to scale, one cannot dispense with such considerations without losing in generality.

where s_S is as before the competitive income share of land in agricultural output. If ϵ_{L^A,A_S} is negative, A_S drives labor out of agriculture; if it is positive, A_S attracts labor in agriculture. The same computation can be done for labor-augmenting technical change and Hicks-neutral technical change:

$$\epsilon_{L^A,A_L} = \frac{\dfrac{\sigma - s_S}{s_S}\left(\dfrac{Y^A - \lambda}{Y^A} - \dfrac{\sigma(1-s_S)}{\sigma - s_S}\right)}{\dfrac{Y^A-\lambda}{Y^A} + \dfrac{\sigma}{\nu^M}\dfrac{1-s_S}{s_S}}, \tag{16}$$

$$\epsilon_{L^A,A} = \frac{-\dfrac{\lambda}{Y^A}\dfrac{\sigma}{s_S}}{\dfrac{Y^A-\lambda}{Y^A} + \dfrac{\sigma}{\nu^M}\dfrac{1-s_S}{s_S}}. \tag{17}$$

Additionally, there is a natural relationship between the three elasticities presented above:

$$\epsilon_{L^A,A} = \epsilon_{L^A,A_L} + \epsilon_{L^A,A_S}. \tag{18}$$

The effect of Hicks-neutral technical change on agricultural labor is the sum of labor-augmenting and land-augmenting technical changes. Equations (15), (16) and (17) show that the elasticity of agricultural labor to technical changes of different types can be calibrated using just four economic indicators: the elasticity of substitution σ, the proximity to subsistence $\frac{Y^A-\lambda}{Y^A}$, the income share of land s_S, and the Cobb-Douglas parameter ν^M, which can be interpreted as the long-run share of spending devoted to non-food items.

Equations (15), (16) and (17) are striking by their simplicity but could be somewhat misleading to the reader in inducing to believe that σ affects the elasticities in a simple way. Indeed, one should keep in mind that σ not only enters directly in the equation, but also indirectly through Y^A and s_S. As a result, the total derivatives of ϵ_{L^A,A_L}, ϵ_{L^A,A_S} and $\epsilon_{L^A,A}$ with respect to σ are extremely tedious, and do not provide clear results. However, their partial derivatives with respect to σ, that is, *holding agricultural output and the income share of land constant*, are easily computed and provide key insights into the role of σ. The spirit of studying the partial effect of σ is to be able to compare the effectiveness of different sources of structural change in settings where nothing changes (i.e. the level of development, the relative scarcity of factors) except for the underlying elasticity of substitution. By the same spirit, it is possible to evaluate the partial effect of an increase in agricultural output Y^A, while holding constant the income share of land s_S. This allows the comparison of economies with the same relative factor scarcities but at different levels of development. The purpose of Proposition 2 below is to summarize the key insights of the analysis of partial effects.

Proposition 2 *Consider* ϵ_{L^A,A_S}, ϵ_{L^A,A_L} *and* $\epsilon_{L^A,A}$ *as computed in equations* (15), (16) *and* (17), *with* $\lambda > 0$.

(a) When evaluating the partial effect of a change in σ *(i.e. holding* Y^A *and* s_S *constants):*
ϵ_{L^A,A_L} *is increasing concave,*
ϵ_{L^A,A_S} *and* $\epsilon_{L^A,A}$ *are decreasing convex.*

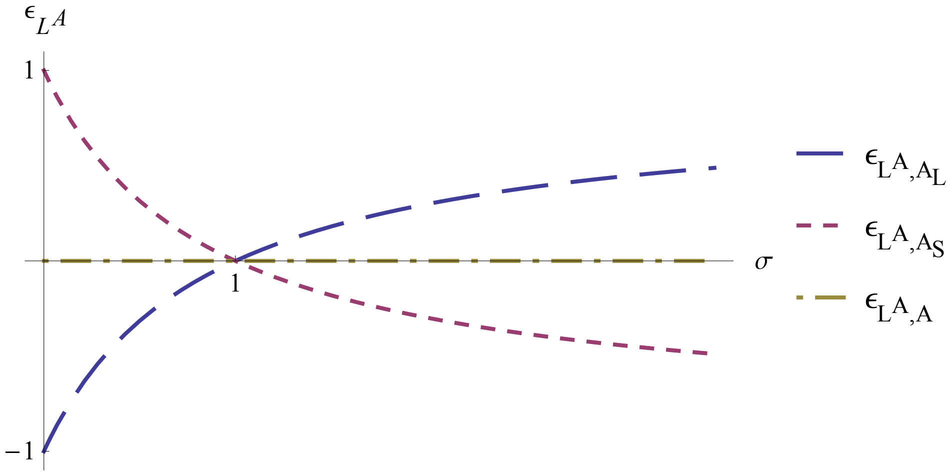
(b) When evaluating the partial effect of a change in Y^A *(i.e. holding* s_S *constant):*
ϵ_{L^A,A_L} *is increasing concave if* $\sigma > s_S v^A$ *and decreasing convex otherwise,*
ϵ_{L^A,A_S} *and* $\epsilon_{L^A,A}$ *are increasing concave.*

Proposition 2 states that as the elasticity of substitution rises, labor-augmenting technical change loses effectiveness in structural transformation due to a rising elasticity, while Hicks-neutral and land-augmenting technical changes become more effective due to falling elasticities. To illustrate Proposition 2, Figure 1 plots elasticities (15) to (17) as a function of the partial effect of σ. A baseline case is Figure 1 panel (a) where λ has been set to zero to set aside the role of Engel's law. In this case, ϵ_{L^A,A_L} and ϵ_{L^A,A_S} sum to zero and $\epsilon_{L^A,A}$ is therefore merged with the horizontal axis. At $\sigma = 0$, ϵ_{L^A,A_L} is equal to -1 and ϵ_{L^A,A_S} is equal to 1. This is only natural since in this situation the CES production function becomes a Leontief production function and so augmented land $\hat{S}$ is proportional to augmented labor $\hat{L^A}$. To the left of $\sigma = 1$, land-augmenting technical change attracts labor in agriculture while labor-augmenting technical change drives labor out agriculture. At $\sigma = 1$, both elasticities are zero and to the right of $\sigma = 1$, the roles are reversed; land-augmenting technical change now drives labor out of agriculture while labor-augmenting technical change attracts labor in agriculture. This clearly shows the importance of differentiating between sources of technical change in understanding structural change.

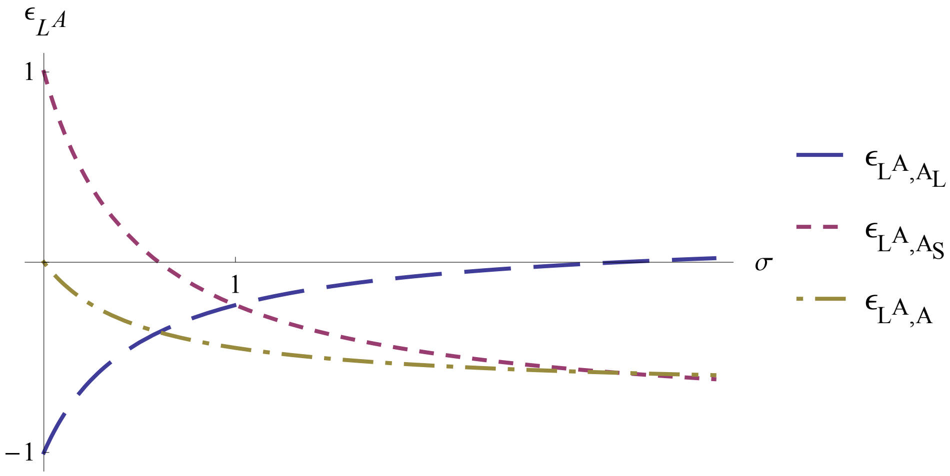
Figure 1 panels (b) and (c) show that a positive subsistence level has the effect of pushing all the curves downward, so that $\epsilon_{L^A,A}$ enters into negative territory. Panel (b) is an example of elasticities behavior when the economy is relatively far away from a state of subsistence. Which type of technical change drives labor out of agriculture still clearly depends on whether σ is higher or lower than one. However panel (c) is an example of what happens when the economy is relatively close to a state of subsistence. With the exception of a small interval close to zero, both elasticities are largely negative. This illustrates the fact that close to subsistence the choice between different types of productivity improvements does not matter.

Figure 2 plots elasticities (15) to (17) as a function of agricultural output, setting the income share of land equal to 0.5 (this assumption ensures that ϵ_{L^A,A_L} and ϵ_{L^A,A_S} start at the same initial value and makes comparability easier) and assuming $\sigma > s_S \nu^A$. Figure 2 panels (a), (b) and (c) essentially carry the same message than Figure 1 but using a different perspective. All elasticities rise with agricultural output, but the regime of substitution affects the type of technical change that become ineffective (i.e. attracts labor in agriculture) over the course of development. The inelastic case (panel a) corresponds to land-augmenting technical change becoming ineffective, while in the elastic case (panel c) labor-augmenting technical change is concerned. Finally, the Cobb-Douglas case of panel (b) is a situation were both types of technical change stay effective with a rise in agricultural output.

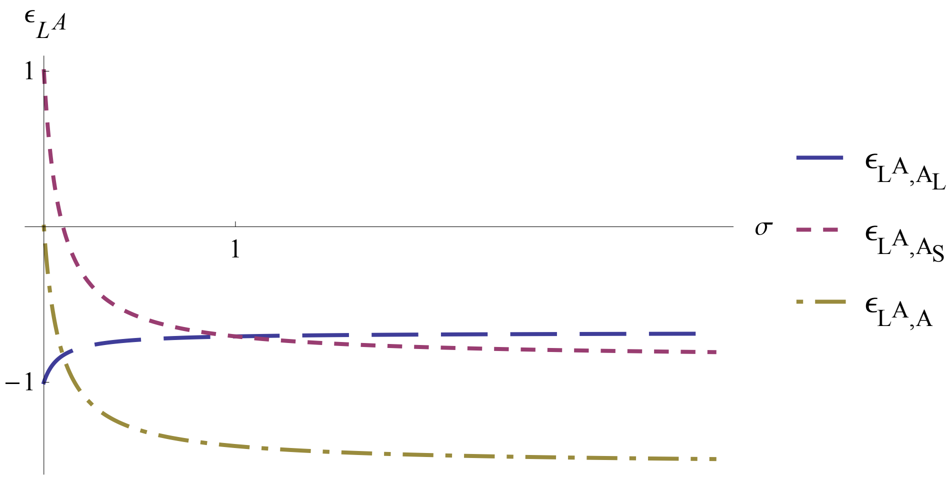
These observations, along with the hypothesis that $\sigma < 1$, are consistent with the historical patterns of technical change in agriculture described by Hayami and Ruttan (1985), Ruttan (1977, 2002) and Alston (2014). Ruttan (2002, page 166) observes that : "During the later stages of development, as the price of labor begins to rise relative to the price of land, the growth path [of land and labor productivity] tends to shift in a labor saving direction." The present conclusion that labor-augmenting technical change is more effective in the structural transformation of advanced countries is consistent with the observed behavior of developed countries putting more effort into labor-saving technologies.



(a) $\lambda = 0$

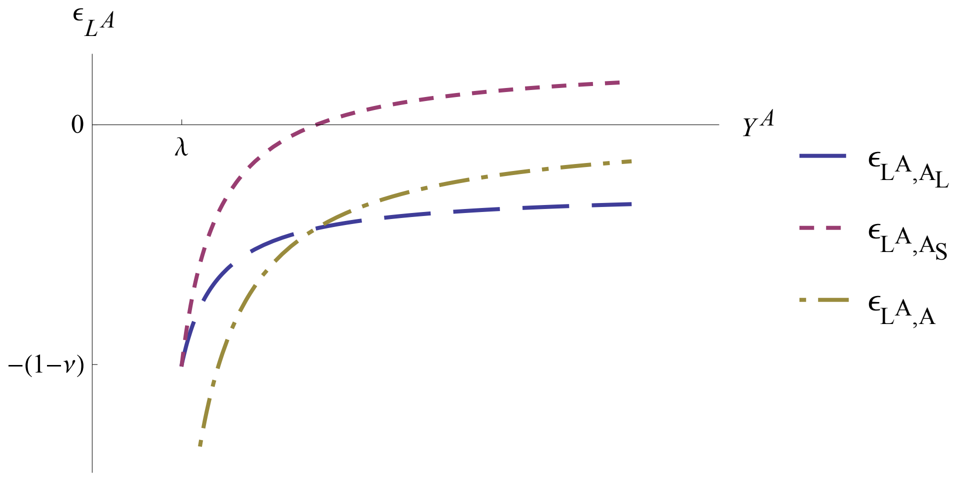


(b) $\lambda > 0$, *far from the subsistence level*

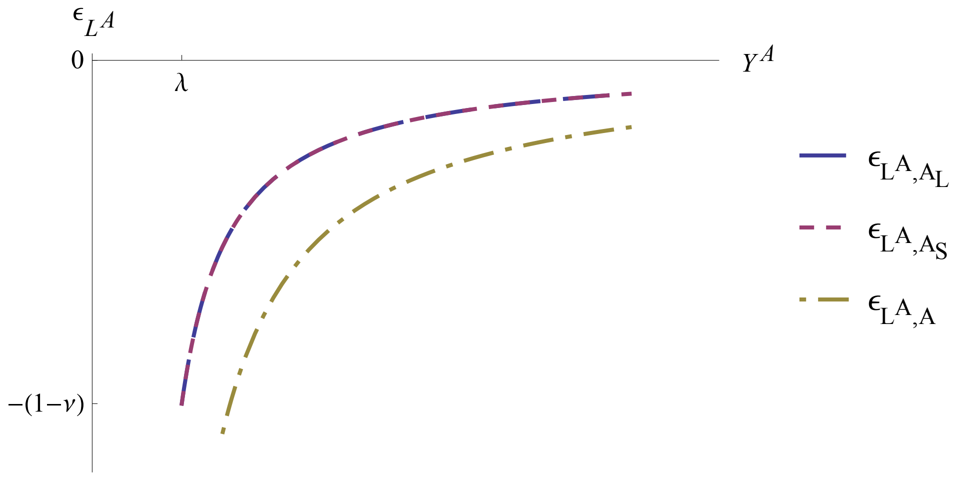


(c) $\lambda > 0$, *close to the subsistence level*

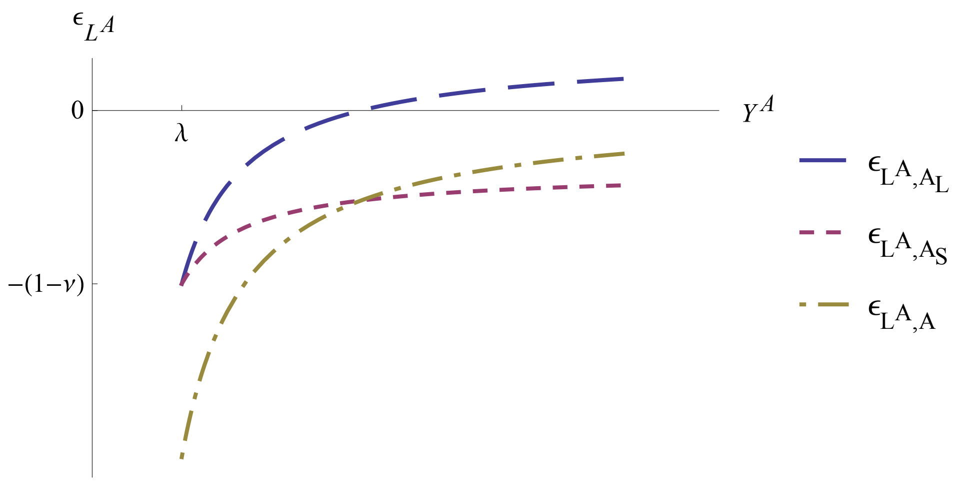
Figure 1: *Various elasticities as a function of the partial effect of sigma*



(a) $\sigma < 1$



(b) $\sigma = 1$



(c) $\sigma > 1$

Figure 2: *Various elasticities as a function of the partial effect of agricultural output, income share of land=0.5*

4 Calibration of the elasticities of agricultural labor

In this section I calibrate the elasticities of agricultural labor derived in Section 3 (equations (15), (16) and (17)) to investigate the effect of different types of technical change on structural transformation. The calibration is made at a country and regional level for a total of 166 countries and 8 broad regions of the world for the period 2011-2012. Data sources and methodological choices are discussed first, then the results are summarized.

Before getting into the calibration details, a note of caution is in order. The model describes a closed economy, and the calibration should be interpreted as such. The question of whether an economic unit is approximately described as closed or open is practically a question of size: small or insular countries usually have a much higher degree of openness than large countries or world regions. Along these lines, the calibration results of a country such as Vietnam (with exports and imports averaging 100 of its GDP in 2017 according to the World Bank) cannot be taken as seriously as the calibration results of a regional ensemble such as East Asia & Pacific. But there is more to it than the question of size. Working on the case of Ghana, Caselli, Chen and Gollin (2012) have shown that high transportation costs in rural areas of the developing world can prevent large fraction of the population to access international markets. This means that the closed economy might be a good approximation of the situation faced by rural farmers in Sub-Saharan Africa and parts of Asia.

4.1 Data and methods

Table 1 presents the data sources used to calibrate ϵ_{L^A,A_L}, ϵ_{L^A,A_S} and $\epsilon_{L^A,A}$. Under the heading ”Weights for regional aggregation” is a description of the data used to aggregate country results into regional results.

Clearly the key parameter lacking data support in existing literature is the elasticity of substitution σ. First, estimates of σ in the literature are limited to roughly twenty countries, each study having its own estimation method carried over different time periods. Without sufficient localized information on σ, even for broad regions of the world, I have chosen to assign to all countries the same value of σ. Second, in the model of this paper the elasticity of substitution applies to augmented land and augmented labor, which are broad categories encompassing all the inputs useful for agricultural production. In the literature, elasticities of substitution apply to just land and labor and other inputs are assigned a different elasticity of substitution estimated separately. Despite these limitations, available evidence (Table (2)) suggests an elasticity of substitution within a range of 0.2 to 1.2, inclined on average toward the inelastic case. To assess the sensitivity of the results to the elasticity of substitution, three values of σ are used for calibration: 0.2, 0.5 and 1.2. The meta-analysis of Klaus Salhofer (2000) (Table (2)) on European countries suggests that 0.5 is the most reasonable guess.

Facing a similar limitation on data availability, all countries have been assigned the same Cobb-Douglas parameter ν^M. Since ν^M is inherently a long run variable and since the calibration focuses on developing countries that did not fully achieve structural change, it is indeed difficult to guess ν^M at a country level. In this study, I have computed ν^M as the share of final consumption devoted to non-food items among OECD countries. Having achieved their structural transformation out of agriculture, these countries are deemed to provide a good approximation of the long run situation. The resulting value of ν^M is roughly 0.89.

Data on the income share of land is based on Fuglie (2015) using the most recent estimates of 2011-2012. Fuglie draws on 19 studies at a country level to assign income shares to 17 broad regions of the world, assuming small economies behave similarly to large economies like Brazil or India for which estimates are available. The income shares as computed by Fuglie include six classes of agricultural inputs: labor, land, livestock capital, machinery capital, crop materials (e.g. fertilizers) and livestock materials (e.g. feed). As documented in Table 1, the income share of labor is assumed to be the sum of the income shares of labor and fixed capital while the income share of land sums up the remaining inputs.

Finally, a few words on the empirical counterparts of λ and Y^A. λ is based on FAO estimates of the Minimum Dietary Energy Requirement (MDER) at a country level. The MDER is expressed in kilocalories and reflects a person's energy needs consistent with preserving good health in the long run (Naiken 2003, Wanner *et alii* 2014). It is first computed by sex and age groups on the basis of the reference body weight and physical activity, and then each group energy requirement is weighted by the proportion of that group in the total population. Happily, the MDER -though not estimated primarily for the purpose of economic analysis- fits closely the idea of the subsistence level of a representative household[7]. To obtain the indicator of proximity to subsistence $\frac{Y^A-\lambda}{Y^A}$, I compare the MDER with actual food supply per capita as estimated by the FAO. Both measurements are comparable and are expressed in kilocalories per capita per day.

[7] This conceptual proximity, however, does not necessarily mean that the MDER coincides with the mathematical definition of λ in (3), which implies that when $C^A = \lambda$ the household income is entirely spent on food.

Table 1: *Data sources for the calibration of* ϵ_{L^A,A_L}, ϵ_{L^A,A_S} *and* $\epsilon_{L^A,B}$

Concept	Data item	Data source	Available at country level
Agricultural output per capita: Y^A	Food supply in kilocalories per capita per day, 2011-2012 average	Food and Agriculture Organization (FAO)	Yes
Subsistence level: λ	Minimum Dietary Energy Requirement (MDER) in kilocalories per capita per day, 2011-2012 average	FAO	Yes
Income share of land in agriculture: s_S	Sum of income shares: land, livestock capital, crop materials, livestock materials. 2011-2012 estimates	Fuglie (2015)	Yes
Cobb-Douglas preference parameter: ν^M	Weighted average of the share of final household consumption devoted to non-food expenditures among OECD countries[2], 2016	OECD	No
Elasticity of substitution: σ	Set to 0.2, 0.5 and 1.2	Table 2	No
Weights for regional aggregation			
Agricultural labor	Employment in agriculture (paid + self employment), 2011-2012 average	International Labor Organization	Yes
Agricultural output	Net production value of agriculture in constant 2004-2006 international dollars, 2011-2012 average	FAO	Yes

Table 2: *Estimates of the elasticity of substitution between labor and land*

Author	Year	Country	Period	Additional Specifications	Estimate
Bilkis Raihana	2012	Bangladesh	1973-1995	non-homothetic structure with technical change	(-0.0615)
K. Melfou *et alii*	2008	Greece	1990-1996		0.256
			1969-1996		0.409
D.D. Tewari and Shashi Kant	2005	South Africa	1965-1997		15.63
Klaus Salhofer	2000	Europe	Meta-analysis of 32 studies		0.5
				corrected for outliers	0.5
				corr. for outliers & weighted	0.3
Subhash C. Sharma	1991	South Korea	1949-1971		1,1982-1,3073
			1918-1938 and 1949-1971		1,0811-1,1326
Subhash C. Ray	1982	United States	1939-1977	Hicks-neutral technical change	0.7482
			1977		0.6196
Wayne Thirsk	1974	Colombia	1968	Rice	0.36-1.18
				Cotton	0.02-0.64
				Corn	0.28-0.8
				Sesame, Soybeans and Sorghum	0.12-0.89
				Wheat and Barley	(-0,83)-0,87
Hans P. Binswanger	1974	United States	1949, 1954, 1959, 1964		0.204

Table 3: *Results for broad regions*

Region	Proximity to subsistence	Income share of land	Elasticity of substitution	Elasticity of agricultural labor with respect to		
				Labor-aug. TC	Land-aug. TC	Hicks-neutral TC
Central Asia	0.43	0.47	0.2	-0.70	0.28	-0.42
			0.5	-0.53	-0.11	-0.64
			1.2	-0.40	-0.42	-0.81
East Asia & Pacific	0.37	0.44	0.2	-0.70	0.23	-0.47
			0.5	-0.56	-0.14	-0.70
			1.2	-0.45	-0.41	-0.86
Europe	0.42	0.54	0.2	-0.71	0.33	-0.38
			0.5	-0.52	-0.11	-0.63
			1.2	-0.36	-0.48	-0.84
L. America & Carib.	0.38	0.40	0.2	-0.69	0.20	-0.49
			0.5	-0.56	-0.13	-0.69
			1.2	-0.47	-0.36	-0.83
M. East & N. Africa	0.43	0.41	0.2	-0.68	0.29	-0.39
			0.5	-0.52	-0.07	-0.59
			1.2	-0.39	-0.34	-0.73
North America	0.46	0.68	0.2	-0.74	0.45	-0.29
			0.5	-0.49	-0.06	-0.55
			1.2	-0.20	-0.67	-0.87
South Asia	0.27	0.38	0.2	-0.71	0.11	-0.61
			0.5	-0.62	-0.19	-0.81
			1.2	-0.56	-0.38	-0.93
Sub-Saharan Africa	0.30	0.43	0.2	-0.73	0.08	-0.65
			0.5	-0.63	-0.25	-0.87
			1.2	-0.56	-0.45	-1.01
World	0.37	0.46	0.2	-0.71	0.16	-0.55
			0.5	-0.59	-0.17	-0.76
			1.2	-0.50	-0.40	-0.91

4.2 Results

Country results of the elasticities of agricultural labor, the proximity to subsistence and the income share of land are available in the Online Appendix B. In Section 4, Table (3) gives the elasticities of agricultural labor at a regional level, where country results are weighted by the share of agricultural labor in regional agricultural labor[8][9]. I focus the following discussion on ϵ_{L^A,A_S} and ϵ_{L^A,A_L} , as $\epsilon_{L^A,A}$ is just a sum of these two components.

Table (3) shows that when σ is equal to 1.2, labor and land-augmenting technical changes have relatively similar values around (-0.5) and (-0.4) except for North America. In this situation, both types of technical change are expected to be roughly equally effective for structural transformation out of agriculture. In North America however, land-augmenting technical change (-0.67) is considerably more effective than labor-augmenting technical change (-0.2). When σ decreases to 0.5, labor-augmenting technical change is roughly equal to (-0.5) and is three to eight times more effective than land-augmenting technical change everywhere in the world. Regions where land-augmenting technical change remains substantially effective are Sub-Saharan Africa (-0.25) and South Asia (-0.19). Finally, when σ reaches 0.2, land-augmenting technical change yields positive elasticities in every region, close to 0.1 in Sub-Saharan Africa and South Asia, but frequently closer to 0.3. Labor-augmenting technical change reaches (-0.7) and drives structural transformation entirely, while land-augmenting technical change (or land use) slows it down.

In every scenario labor-augmenting technical change is consistently negative, leading to the conclusion that it is everywhere an effective means of structural transformation. As for land-augmenting technical change, it seems reasonable to believe that it contributes to structural transformation in Sub-Saharan Africa

[8]This weighting rule assumes that each country faces the same relative increase in technical change. More generally, if $y = \sum_I y_i$, $x = \sum_I x_i$ and $\frac{dx_i}{x_i} = \frac{dx_j}{x_j}$ $\forall i, j \in I$, then $\epsilon_{y,x} = \frac{1}{y} \sum_I y_i \, \epsilon_{y_i,x_i}$.

[9]At a regional level, the proximity to subsistence and the income share of land are computed using the share of agricultural output in regional agricultural output.

and South Asia, given that it keeps consistently low values in these regions, even for low sigmas. However, one can raise doubts as to its effectiveness in other regions of the developing world, that is, in other parts of Asia and the Pacific, in Latin America and in the Middle-East and North Africa (MENA) region.

5 Calibration of the rates of technical change

Figuring out the positive or negative sign of elasticities in Section 4 is useful to ascertain which type of technical change is likely to be effective in structural transformation. But when two elasticities have the same sign, the relative importance of different types of technical change also depends on their relative pace. If the pace of land-augmenting technical change is several times faster than the pace of labor-augmenting technical change, then this will compensate for its relatively low elasticity observed in the data. This section therefore estimates the rates of land- and labor-augmenting technical changes at a regional level over 2005-2015. Once this is done, the rates of technical changes are combined with the elasticities of Section 4 to decompose the growth of agricultural labor per capita in terms of different types of technical change.

In this section, I reduce the set of possible outcomes by assuming $\sigma = 0.5$. This means that in every region land-saving technologies contribute to structural transformation, albeit with a low effectiveness compared with labor-saving technologies. The growth rate of land per capita, another driver of structural transformation, is estimated as well. Data and methodological choices are discussed first, then the results are summarized.

5.1 Data and methods

The model of Section 3 can be described abstractly as:

$$F(L^A, A_L, A_S, S, \lambda) = 0 \tag{19}$$

where L^A, S and λ are per capita variables, and I have assumed no Hicks-neutral technical change without loss of generality. Differentiating with respect to time and rearranging yields:

$$\frac{\dot{L^A}}{L^A} = \epsilon_{L^A,A_L}\frac{\dot{A_L}}{A_L} + \epsilon_{L^A,A_S}\frac{\dot{A_S}}{A_S} + \epsilon_{L^A,S}\frac{\dot{S}}{S} + \epsilon_{L^A,\lambda}\frac{\dot{\lambda}}{\lambda} \tag{20}$$

I assume λ to be a constant[10] and since $\epsilon_{L^A,A_S} = \epsilon_{L^A,S}$ this yields:

$$\frac{\dot{L^A}}{L^A} = \epsilon_{L^A,A_L}\frac{\dot{A_L}}{A_L} + \epsilon_{L^A,A_S}\left(\frac{\dot{A_S}}{A_S} + \frac{\dot{S}}{S}\right) \tag{21}$$

Equation (21) is the growth decomposition presented in this section. The main difficulty of calibrating (21) is that most of the existing literature on agricultural productivity rely on the assumption of unbiased technical change. Therefore in the usual case only estimates of Hicks-neutral technical change are available. Nevertheless, my model has a large interpretation of land and labor-augmenting technical changes, an interpretation that includes what most agricultural models would refer to as input growth. This makes it possible to discriminate to some extent between types of technical change. To see this, consider the following agricultural model:

$$Y^A = A\,G(K, L^A, Z, S), \tag{22}$$

where G has constant returns to scale, K is machinery capital, Z is fertilizer and the other variables keep the same interpretation. This model of unbiased technical change is the starting point of most studies on agricultural productivity. Now, I assume that this model can be rewritten as

$$Y^A = A\,G[F_1(K, L^A), F_2(Z, S)], \tag{23}$$

where F_1 and F_2 have constant returns to scale. Yet another way to write model (23) is

$$Y^A = G[Af_1(k)L^A, Af_2(z)S], \tag{24}$$

[10]There is good reasons why λ can in fact change over time. For example, the MDER as estimated by FAO can diminish as a result of the population getting younger. In practice however, the growth rate of the MDER is too small for this to be significant.

where $k = \frac{K}{L^A}$, $z = \frac{Z}{S}$ and f_1 and f_2 are the intensive forms of F_1 and F_2. Interpreting equation (24) from the perspective of the model of Section 3, $A_L = Af_1(k)$ and $A_S = Af_2(z)$. Thus A_L and A_S have a specific component despite the assumption of Hicks-neutral technical change in the baseline model (22). Naturally, only part of the underlying bias in technical change is revealed, while the ideal situation would be to assume biased technical change directly in (22).

I assume further that F_1 and F_2 are Cobb-Douglas production functions, and I extend the factors affecting land productivity to include animal feed and livestock. This yields

$$\begin{aligned} A_L &= A k^{\alpha}, \\ A_S &= A z^{\gamma} x^{\delta} y^{\eta}, \end{aligned} \tag{25}$$

where x is animal feed per unit of land and y is livestock per unit of land.

The two equations in (25) are used to calibrate the average growth rates of A_L and A_S over the period 2005-2015. To calibrate α, γ, δ and η, I use the same income shares that were used to calibrate ϵ_{L^A,A_S} and ϵ_{L^A,A_L}. For example, α is set equal to the share of machinery capital divided by the sum of the share of machinery capital and the share of agricultural labor. To calibrate A, k, z, x and y, I use the dataset of agricultural inputs and TFP levels provided by the United States Department of Agriculture (USDA)[11] based on the methodological work of Fuglie (2012,2015)[12]. Lastly, to calibrate the growth rate of L^A and S in (21), agricultural labor and land data are provided by USDA while population data is from FAO.

Since the estimates of total factor productivity provided by USDA rely on a specific regional grouping, I follow this grouping in my computations. This results in a loss of precision for the Asian continent, which is treated as a single

[11] https://www.ers.usda.gov/data-products/international-agricultural-productivity.aspx. Database last updated in October 15, 2018.

[12] For the period 2011-2015, USDA uses the same income shares in their TFP estimates as the ones I use for calibration. For the period 2005-2010, they only slightly differ. This ensures consistency between the computations of total factor productivity and the computations of elasticities.

region. To compensate for this loss, I provide subregional results as well. USDA's grouping of countries by regions and subregions is detailed in Table 8.

5.2 Results

Tables 4 and 5 present the growth rates of various agricultural outcomes at a regional and subregional level over 2005-2015[13]. Data on agricultural output is not used in the calibration and is for informative purpose only.

Table 6 gives four sets of results: columns (1) to (3) show the average growth rates of A_L, A_S and S over 2005-2015. Columns (4) and (5) show the values of ϵ_{L^A,A_L} and ϵ_{L^A,A_S} as estimated in Section 4 and assuming $\sigma = 0.5$[14]. Columns (6) to (8) show the product of columns (1) to (3) with columns (4) and (5). They give a growth decomposition of L^A in terms of A_L, A_S and S. Finally, column (9) indicates the average growth rate of L^A over 2005-2015 and column (10) is the residual, that is, column (9) minus columns (6), (7) and (8). Table 7 is analogous to Table 6 but the results are detailed at a subregional level.

The first striking result of Tables 6 and 7 is that in developed regions, the contribution of labor-augmenting technical change to structural transformation is much higher than the contribution of land-augmenting technical change (columns (6) and (7)). Labor-saving technologies contribute eight to ten times more than land-saving technologies in Europe, North America and the Baltic countries. This factor however reduces to three to four in Oceania (Australia and New Zealand) and the subregion Developed Asia. Other regions where the contribution of labor technologies is markedly higher include South Africa and the regional ensemble Middle East & North Africa. In all these regions, the growth rate of land-augmenting technical change tends to be lower than what it is for labor (columns (1) and (2)), which accentuates the effect of the already low

[13]The average growth rates are computed assuming continuous compounding

[14]As before, country level elasticities have been aggregated into regional elasticities using agricultural employment, but the geographical areas have been adjusted to match USDA's grouping.

elasticity for land changes (column (5)).

Standing at an intermediate level are the regions of Asia, Former USSR and Latin America & Caribbean where the contribution of land technologies is substantial at around -1% per year, and the contribution of labor technologies is between -2% to -4%. These regions have low elasticities for land changes but a high growth rate of land-augmenting technical change. Especially striking is the 8.4% growth rate of land-augmenting technical change in Former USSR, which is due to the 10% growth rate of fertilizer over the period (Table 4).

Finally, Sub-Saharan Africa stands out and deserves special attention. First, the contribution of labor-saving technologies to structural transformation is very small compared to the world average. This is because the growth of machinery capital did not catch up with the growth of agricultural labor (Table 4). Second, the contribution of land-saving technologies is slightly higher, but the effect of land-saving technologies is entirely offset by a decrease in land per capita. This results in a low overall effect of technical change. To the exception of its Southern subregion, all the subregions of Sub-Saharan Africa face a similar situation.

Equally substantially affected by a decrease in land per capita, Oceania has a contribution of land per capita of nearly 1% and South Africa has a contribution of 0.5% . But the burden in these regions is more limited, since Oceania (Australia and New Zealand) has already done much of its structural transformation, and South Africa has a high contribution of labor-saving technologies.

Another noticeable result of Tables 6 and 7 is the relatively high residual (column (10)) of developed regions (e.g. Europe, North America, Developed Asia). This might suggest that nonagricultural factors are important in later stages of structural transformation. Another likely explanation is that decreases in agricultural labor per capita substantially lag behind increases in agricultural productivity. The growth rate of agricultural labor would then be the results of accumulated increases in agricultural productivity over current and previous decades.

Table 4: *Average growth rate in percentage, 2005-2015*

Region	Agricultural output	TFP	Machinery capital	Agricultural labor	Livestock	Feed	Fertilizer	Land	Population
Asia (except Middle East)	6.0	4.8	9.8	-2.0	1.9	8.1	4.0	1.4	2.0
Europe (except USSR)	0.7	3.2	-0.5	-7.3	-0.7	-0.5	-0.9	-0.8	0.5
Former USSR	5.7	4.3	-3.4	-3.5	2.0	4.7	10.6	0.2	0.5
L. America & Caribbean	5.6	3.5	3.1	-1.5	0.8	5.2	6.4	1.8	2.4
M. East & N. Africa	3.5	3.3	2.7	-0.5	2.3	5.5	-2.1	-0.4	3.9
North America	2.2	3.1	-1.2	-4.2	-0.9	-4.0	3.1	-1.2	1.7
Oceania	2.2	3.3	1.0	0.4	-1.6	0.3	2.2	-2.3	3.1
South Africa	3.3	1.9	6.3	-4.8	0.2	2.1	1.5	-0.7	2.5
Sub-S. Africa (except S.A.)	5.4	0.6	4.5	4.8	5.3	5.3	11.7	3.2	5.6
World	4.6	3.2	4.8	-0.8	1.8	3.3	3.6	0.8	2.4

Source: author's computations on the database of the USDA, Economic Research Service. Available at https://www.ers.usda.gov/data-products/international-agricultural-productivity.aspx

Table 5: *Average growth rate in percentage, 2005-2015*

Region	Subregion	Agri-cultural output	TFP	Machinery capital	Agri-cultural labor	Livestock	Feed	Fertilizer	Land	Population
Asia	Developed	-0.3	3.9	-6.5	-10.5	1.2	2.5	-5.1	-1.1	0.3
Asia	Northeast Asia	6.1	6.7	13.1	-8.4	0.8	9.9	2.9	2.0	1.1
Asia	Pacific	3.3	1.2	6.0	3.6	1.8	1.7	-10.6	2.0	3.8
Asia	South Asia	6.6	3.8	13.0	2.0	2.0	6.2	4.9	0.7	2.8
Asia	Southeast Asia	6.0	3.4	8.0	0.8	4.7	6.9	7.6	2.0	2.4
Europe	Transition	0.3	2.3	4.6	-7.6	-2.1	-1.8	3.0	-1.2	-0.5
Europe	Northwest	1.3	3.7	-2.9	-6.5	-0.4	-0.4	-1.9	0.0	1.0
Europe	Southern	0.0	4.1	-2.9	-7.3	-0.1	0.3	-3.4	-1.3	0.5
Former USSR	Baltic	6.2	7.7	-2.1	-6.8	-1.3	-3.5	9.4	2.3	-2.2
Former USSR	Central Asia	6.7	3.1	2.6	1.5	6.9	5.9	4.6	0.0	2.6
Former USSR	East Europe	5.4	5.5	-5.8	-7.6	0.0	4.8	12.1	0.2	0.0
L. America & Caribbean	Caribbean	4.0	3.9	-1.1	-0.1	1.8	1.8	2.0	-1.4	1.5
L. America & Caribbean	Central America	4.4	3.4	1.1	-1.1	1.9	2.6	3.7	-0.5	3.1
L. America & Caribbean	S. America. Andean	5.1	2.7	-0.8	0.7	-0.2	7.4	6.3	1.2	2.7
L. America & Caribbean	S. America. Northeast	6.8	5.0	5.8	-5.0	1.1	6.2	8.1	2.3	1.9
L. America & Caribbean	S. America. Southern Cone	4.6	3.4	0.4	-0.1	-0.2	5.6	1.9	3.5	2.0
M. East & North Africa	Middle East	2.2	2.6	2.7	-0.7	2.5	3.6	-3.4	-1.1	4.2
M. East & North Africa	North Africa	5.9	4.6	2.5	-0.3	2.1	9.0	0.5	1.0	3.5
North America	North America	2.2	3.1	-1.2	-4.2	-0.9	-4.0	3.1	-1.2	1.7
Oceania	Oceania	2.2	3.3	1.0	0.4	-1.6	0.3	2.2	-2.3	3.1
South Africa	South Africa	3.3	1.9	6.3	-4.8	0.2	2.1	1.5	-0.7	2.5
Sub-S. Africa	Central	5.7	1.5	2.3	2.8	2.9	8.5	12.5	4.5	6.1
Sub-S. Africa	Eastern	6.2	-0.5	5.1	5.1	9.5	4.1	9.2	5.5	6.1
Sub-S. Africa	Horn	4.0	0.5	7.9	5.2	4.1	3.3	11.7	-0.4	5.2
Sub-S. Africa	Nigeria	3.7	-0.5	4.4	4.5	5.0	1.2	8.9	2.9	5.3
Sub-S. Africa	Sahel	6.9	1.0	7.5	5.8	5.5	6.3	11.2	5.2	6.4
Sub-S. Africa	Southern	6.8	3.0	3.1	5.0	2.7	15.5	14.0	0.3	5.6
Sub-S. Africa	Western	6.8	0.4	2.8	3.5	7.9	8.7	15.5	5.5	5.0
World		4.6	3.2	4.8	-0.8	1.8	3.3	3.6	0.8	2.4

Source: author's computations on the database of the USDA, Economic Research Service. Available at https://www.ers.usda.gov/data-products/international-agricultural-productivity.aspx

Table 6: *Average growth rate in percentage, 2005-2015*

	Growth in exogenous parameters			Elasticities of agri. labor with respect to		Sources of growth in agricultural labor per capita				
Region	**Labor-aug. TC (1)**	**Land-aug. TC (2)**	**Land per capita (3)**	**Labor-aug. TC (4)**	**Land-aug. TC (5)**	**Labor-aug. TC (6)**	**Land-aug. TC (7)**	**Land per capita (8)**	**Agri. labor per capita (9)**	**Residual (10)**
Asia	6.5	6.0	-0.6	-0.59	-0.17	-3.8	-1.0	0.1	-4.0	0.6
Europe (except USSR)	5.4	3.3	-1.3	-0.52	-0.10	-2.8	-0.3	0.1	-7.8	-4.8
Former USSR	4.3	8.4	-0.3	-0.55	-0.15	-2.4	-1.2	0.0	-4.1	-0.5
L. America & Caribbean	5.2	5.8	-0.5	-0.56	-0.13	-2.9	-0.8	0.1	-3.9	-0.3
M. East & N. Africa	4.2	3.6	-4.4	-0.50	-0.06	-2.1	-0.2	0.2	-4.5	-2.4
North America	4.2	4.1	-2.9	-0.49	-0.06	-2.1	-0.2	0.2	-5.8	-3.7
Oceania	3.6	4.2	-5.4	-0.52	-0.16	-1.9	-0.7	0.9	-2.7	-1.0
South Africa	8.6	3.7	-3.2	-0.53	-0.16	-4.6	-0.6	0.5	-7.3	-2.7
Sub-S. Africa (except S.A.)	0.5	2.2	-2.4	-0.63	-0.25	-0.3	-0.5	0.6	-0.8	-0.6
World	4.4	4.5	-1.7	-0.59	-0.17	-2.6	-0.8	0.3	-3.2	-0.1

Table 7: *Average growth rate in percentage, 2005-2015*

		Growth in exogenous parameters			Elasticities of agri. labor with respect to		Sources of growth in agricultural labor per capita				
Region	Subregion	Labor-aug. TC	Land-aug. TC	Land per capita	Labor-aug. TC	Land-aug. TC	Labor-aug. TC	Land-aug. TC	Land per capita	Ag. labor p. capita	Residual
Asia	Developed	5.5	4.0	-1.4	-0.55	-0.18	-3.0	-0.7	0.3	-10.8	-7.4
Asia	Northeast Asia	10.6	6.8	0.9	-0.55	-0.12	-5.8	-0.8	-0.1	-9.5	-2.8
Asia	Pacific	1.3	0.1	-1.8	-0.56	-0.17	-0.7	0.0	0.3	-0.2	0.3
Asia	South Asia	5.1	5.3	-2.1	-0.62	-0.19	-3.1	-1.0	0.4	-0.9	2.9
Asia	Southeast Asia	3.7	5.2	-0.5	-0.57	-0.19	-2.1	-1.0	0.1	-1.7	1.3
Europe	Transition	6.2	2.3	-0.8	-0.52	-0.11	-3.3	-0.3	0.1	-7.2	-3.7
Europe	Northwest	5.2	2.8	-1.0	-0.50	-0.09	-2.6	-0.2	0.1	-7.4	-4.7
Europe	Southern	5.0	4.2	-1.8	-0.51	-0.06	-2.6	-0.3	0.1	-0.6	2.1
Former USSR	Baltic	9.2	5.5	4.4	-0.51	-0.09	-4.7	-0.5	-0.4	-4.6	1.0
Former USSR	Central Asia	3.5	7.4	-2.6	-0.59	-0.21	-2.1	-1.6	0.6	-1.1	2.0
Former USSR	East Europe	5.9	9.4	0.2	-0.52	-0.10	-3.0	-1.0	0.0	-7.6	-3.6
L. America & Caribbean	Caribbean	3.2	5.9	-2.9	-0.65	-0.21	-2.1	-1.3	0.6	-1.7	1.0
L. America & Caribbean	Central America	4.9	5.2	-3.5	-0.56	-0.11	-2.7	-0.6	0.4	-4.1	-1.2
L. America & Caribbean	Andes	2.3	6.4	-1.5	-0.59	-0.18	-1.3	-1.2	0.3	-2.0	0.3
L. America & Caribbean	Northeast	8.2	8.6	0.4	-0.51	-0.07	-4.2	-0.6	0.0	-7.0	-2.1
L. America & Caribbean	Southern Cone	3.6	2.4	1.5	-0.57	-0.15	-2.0	-0.4	-0.2	-2.1	0.5
M. East & N. Africa	Middle East	3.6	2.5	-5.3	-0.52	-0.08	-1.9	-0.2	0.4	-4.9	-3.2
M. East & N. Africa	North Africa	5.4	5.7	-2.5	-0.49	-0.03	-2.6	-0.2	0.1	-3.8	-1.0
North America	North America	4.2	4.1	-2.9	-0.49	-0.06	-2.1	-0.2	0.2	-5.8	-3.7
Oceania	Oceania	3.6	4.2	-5.4	-0.52	-0.16	-1.9	-0.7	0.9	-2.7	-1.0
South Africa	South Africa	8.6	3.7	-3.2	-0.53	-0.16	-4.6	-0.6	0.5	-7.3	-2.7
Sub-S. Africa	Central	1.5	1.7	-1.6	-0.61	-0.21	-0.9	-0.3	0.3	-3.3	-2.4
Sub-S. Africa	Eastern	-0.5	1.4	-0.6	-0.65	-0.28	0.3	-0.4	0.2	-1.0	-1.1
Sub-S. Africa	Horn	0.8	3.6	-5.6	-0.68	-0.32	-0.5	-1.2	1.8	0.0	-0.1
Sub-S. Africa	Nigeria	-0.5	0.7	-2.4	-0.55	-0.13	0.3	-0.1	0.3	-0.8	-1.3
Sub-S. Africa	Sahel	1.1	1.6	-1.2	-0.59	-0.18	-0.7	-0.3	0.2	-0.6	0.2
Sub-S. Africa	Southern	2.9	6.1	-5.3	-0.65	-0.28	-1.9	-1.7	1.5	-0.6	1.5
Sub-S. Africa	Western	0.3	2.4	0.6	-0.56	-0.15	-0.2	-0.3	-0.1	-1.5	-0.9
World		4.4	4.5	-1.7	-0.59	-0.17	-2.6	-0.8	0.3	-3.2	-0.1

Table 8: *Regional groupings*

Sub-Saharan Africa (except South Africa)						
Central	**Eastern**	**Horn**	**Sahel**	**Southern**	**Western**	**Nigeria**
Cameroon	Burundi*	Djibouti	Burkina Faso	Angola	Benin	
Central African Republic	Kenya	Ethiopia	Cape Verde	Botswana	Côte d'Ivoire	
Congo Republic	Rwanda	Somalia*	Chad	Comoros*	Ghana	
Congo, DR*	Seychelles*	Sudan	Gambia	Lesotho	Guinea	
Equatorial Guinea*	Tanzania	South Sudan	Mali	Madagascar	Guinea-Bissau	
Gabon	Uganda		Mauritania	Malawi	Liberia	
Sao Tome & Principe			Niger	Mauritius	Sierra Leone	
			Senegal	Mozambique	Togo	
				Namibia		
				Réunion*		
				Swaziland		
				Zambia		
				Zimbabwe		
Asia (except Middle East)					**Middle East & North Africa**	
Developed	**Northeast Asia**	**South Asia**	**Southeast Asia**	**Pacific**	**Middle East**	**North Africa**
Japan	China	Afghanistan	Brunei	Fiji	Bahrain*	Algeria
Korea Republic	Korea, DPR	Bangladesh	Cambodia	Micronesia[a]	Iran	Egypt
Taiwan (China)	Mongolia	Bhutan*	Indonesia	New Caledonia	Iraq	Libya*
Singapore*		India	Laos	Papua New Guinea*	Israel	Morocco
		Nepal	Malaysia	Polynesia[b]	Jordan	Tunisia
		Pakistan	Myanmar	Solomon Islands	Kuwait	
		Sri Lanka	Philippines	Vanuatu	Lebanon	
			Thailand		Oman	
			Timor-Leste*		Qatar*	
			Viet Nam		Saudi Arabia	
					Syria*	
					Turkey	
					UAE	
					Yemen	

Source: https://www.ers.usda.gov/data-products/international-agricultural-productivity/documentation-and-methods/

* Countries marked with an asterisk are included in the estimates of total factor productivity but are not included in the estimates of elasticities of agricultural labor.

[a] Micronesia: estimates for the elasticities of agricultural labor are available for Kiribati only.

[b] Polynesia: estimates for the elasticities of agricultural labor are available for French Polynesia and Samoa only.

Table 8: *Regional groupings (continued)*

Latin America & Caribbean					**North America**	**South Africa**
Northeast	**Andes**	**Southern Cone**	**Central America**	**Caribbean**		
Brazil	Bolivia	Argentina	Belize	Bahamas	Canada	South Africa
French Guiana*	Colombia	Chile	Costa Rica	Cuba	United States	
Guyana	Ecuador	Paraguay	El Salvador	Dominican Republic		
Suriname	Peru	Uruguay	Guatemala	Haiti		
	Venezuela		Honduras	Jamaica		
			Mexico	Lesser Antilles[c]		
			Nicaragua	Puerto Rico*		
			Panama	Trinidad & Tobago		
Europe (except USSR)			**Former USSR**			**Oceania**
Northwest	**Southern**	**Transition**	**Baltic**	**East Europe**	**Central Asia**	
Austria	Cyprus	Albania	Estonia	Belarus	Armenia	Australia
Belgium	Greece	Bosnia	Latvia	Kazakhstan	Azerbaijan	New Zealand
Denmark	Italy	Bulgaria	Lithuania	Moldova	Georgia	
Finland	Malta	Croatia		Russian Federation	Kyrgyzstan	
France	Portugal	Czechia		Ukraine	Tajikistan	
Germany	Spain	Hungary			Turkmenistan	
Iceland		Macedonia			Uzbekistan	
Ireland		Montenegro				
Luxembourg		Poland				
Netherlands		Romania				
Norway		Serbia				
Sweden		Slovakia				
Switzerland		Slovenia				
United Kingdom						

Source: https://www.ers.usda.gov/data-products/international-agricultural-productivity/documentation-and-methods/

* Countries marked with an asterisk are included in the estimates of total factor productivity but are not included in the estimates of elasticities of agricultural labor.

[c] Lesser Antilles: estimates for the elasticities of agricultural labor are available for Barbados, Saint Lucia and Saint Vincent and the Grenadines only.

6 Conclusion

The purpose of this study is to understand under which circumstances different sources of technical change contribute to industrialization. With Cobb-Douglas preferences and a general framework of production, I showed that when the economy is close to a state of subsistence, both labor- and land-augmenting technical changes contribute to structural transformation. However, when the economy moves away from a state of subsistence, taking into account the elasticity of substitution between land and labor is critical. If the elasticity of substitution is low, land-saving technologies or land expansion can slow industrialization due to their strong complementarity with labor. If the elasticity of substitution is high, labor-saving technologies can slow industrialization by the same mechanism.

I then calibrated a simplified model to investigate which type of technical change is effective in practice. A low scenario of substitution between land and labor would suggest that only labor-saving technologies drive structural transformation. But the most plausible scenario suggests that land-saving technologies can play a role in structural transformation, provided the rate of land-augmenting technical change is not too low. In Asia, Latin America and the former USSR, the rate of land-augmenting technical change is high enough that land-saving technologies contribute one third to one fifth of the structural transformation over 2005-2015. In Europe and North America, the contribution of land-saving technologies is much smaller and is roughly one tenth. This is in line with empirical evidence that developed countries tend to move in a labor-saving direction. In Sub-Saharan Africa, the overall rate of technical change is low, and the decreasing land per capita slows structural transformation substantially.

More localized, country-level information on the elasticity of substitution between land and labor and the bias of technical change would be required to reduce the set of possible outcomes and strengthen this empirical conclusion. Also, an econometric analysis of the relative importance of labor- versus land-saving technologies in structural transformation would be a stimulating exercise to test the theoretical predictions of the model.

A Proofs

A.1 Proof of Proposition 1

Proof of the uniqueness of L^A

Given that the market equilibrium decentralizes the optimal solution, one might as well write L^A as the solution to:

$$\begin{aligned} \max_{L^A} \quad & U(Y^A(L^A), Y^M(L^A)) \\ s.t. \quad & 0 \le L^A \le 1. \end{aligned} \tag{26}$$

Since the constraint set for this problem is compact and $U(L^A)$ is continuous as a composition and product of continuous functions, a solution exists by the Weierstrass theorem. Additionally, the constraint set for this problem is convex, so the solution is unique if $U(L^A)$ is strictly concave. Using the utility function (3) and the set of assumptions (2), it can be easily shown that

$$\frac{\partial^2 U}{\partial {L^A}^2} < 0, \tag{27}$$

proving that L^A must be unique.

Proof of L^A response to exogenous changes

Let us rewrite equation (11) using a new notation:

$$f(L^A, \nu^A) = \frac{1}{A_L} g(\hat{S}, \hat{L^A}, \hat{\lambda}), \tag{28}$$

with

$$f(L^A, \nu^A) = \frac{\nu^A}{\nu^M} \frac{F(L^M)}{F'(L^M)}, \tag{29}$$

$$g(\hat{S}, \hat{L^A}, \hat{\lambda}) = \frac{G(\hat{L^A}, \hat{S}) - \hat{\lambda}}{G_{\hat{L^A}}(\hat{L^A}, \hat{S})}. \tag{30}$$

f and g have the following derivatives:

$$f_{L^A} = \frac{\nu^A}{\nu^M}\left(\frac{FF''}{(F')^2} - 1\right) < 0\,, \tag{31}$$

$$f_{\nu^A} = \frac{1}{(\nu^M)^2}\,\frac{F}{F'} > 0\,, \tag{32}$$

$$g_{\hat{L^A}} = 1 + \frac{(G-\hat{\lambda})(-G_{\hat{L^A}^2})}{(G_{\hat{L^A}})^2} > 0\,, \tag{33}$$

$$g_{\hat{S}} = \frac{G_{\hat{S}}G_{\hat{L^A}} - (G-\hat{\lambda})G_{\hat{S}\hat{L^A}}}{(G_{\hat{L^A}})^2} \geq 0 \;\text{ or }\; < 0\,, \tag{34}$$

$$g_{\hat{\lambda}} = -\frac{1}{G_{\hat{L^A}}} < 0\,, \tag{35}$$

where the signs are deduced from the set of assumptions (2).

By implicit differentiation of L^A:

$$\frac{\partial L^A}{\partial \nu^A} = -\frac{f_{\nu^A}}{f_{L^A} - g_{\hat{L^A}}} > 0, \tag{36}$$

$$\frac{\partial L^A}{\partial \hat{\lambda}} = \frac{\frac{1}{A_L}\,g_{\hat{\lambda}}}{f_{L^A} - g_{\hat{L^A}}} > 0, \tag{37}$$

$$\frac{\partial L^A}{\partial \hat{S}} = \frac{\frac{1}{A_L}\,g_{\hat{S}}}{f_{L^A} - g_{\hat{L^A}}}, \tag{38}$$

$$\frac{\partial L^A}{\partial A_L} = \frac{\frac{L^A}{A_L}\left(g_{\hat{L^A}} - \frac{g}{\hat{L^A}}\right)}{f_{L^A} - g_{\hat{L^A}}}. \tag{39}$$

To get the sign condition of $\frac{\partial L^A}{\partial \hat{S}}$, rearrange $g_{\hat{S}}$ in the following way:

$$g_{\hat{S}} = \frac{G\,G_{\hat{S}\hat{L^A}}}{(G_{\hat{L^A}})^2}\left(\frac{G_{\hat{L^A}}G_{\hat{S}}}{G\,G_{\hat{S}\hat{L^A}}} - \frac{G-\hat{\lambda}}{G}\right), \tag{40}$$

where the cross marginal product of G is positive. Indeed, by homogeneity of degree one

$$G_{\hat{S}\hat{L^A}} = -\frac{\hat{L^A}}{\hat{S}}G_{\hat{L^A}^2} > 0, \tag{41}$$

since $G_{L^{A2}} < 0$ by (2). Hence the sign of $g_{\hat{S}}$ depends on the term in brackets. But the first term within the brackets is simply the elasticity of substitution for functions with constant returns to scale:

$$\frac{G_{\hat{L^A}} G_{\hat{S}}}{G\, G_{\hat{S}\hat{L^A}}} = \sigma\left(\frac{\hat{L^A}}{\hat{S}}\right), \tag{42}$$

where $\frac{\hat{L^A}}{\hat{S}}$ is an argument of σ. Dropping the argument of σ for convenience, this yields the following sign condition for g_I:

$$g_{\hat{S}} \gtreqless 0 \quad \Leftrightarrow \quad \frac{Y^A - \lambda}{Y^A} \lesseqgtr \sigma, \tag{43}$$

and finally:

$$\frac{\partial L^A}{\partial \hat{S}} \lesseqgtr 0 \quad \Leftrightarrow \quad \frac{Y^A - \lambda}{Y^A} \lesseqgtr \sigma. \tag{44}$$

The implications of different values of σ are easily deduced from (44).

To get the sign condition of $\frac{\partial L^A}{\partial A_L}$, rearrange $g_{\hat{L^A}} - \frac{g}{\hat{L^A}}$ in the following way:

$$g_{\hat{L^A}} - \frac{g}{\hat{L^A}} = 1 - \frac{G - \hat{\lambda}}{\hat{L^A} G_{\hat{L^A}}}\left(1 + \frac{\hat{L^A} G_{\hat{L^A}^2}}{G_{\hat{L^A}}}\right). \tag{45}$$

Using homogeneity of degree one, it can be shown that

$$\frac{\hat{L^A} G_{\hat{L^A}^2}}{G_{\hat{L^A}}} = -\frac{s_S}{\sigma}. \tag{46}$$

Now using (46) and the fact that $s_{L^A} = \frac{\hat{L^A} G_{\hat{L^A}}}{G}$:

$$g_{\hat{L^A}} - \frac{g}{\hat{L^A}} = 1 - \frac{G - \hat{\lambda}}{G}\frac{1 - \frac{s_S}{\sigma}}{s_{L^A}}, \tag{47}$$

slightly rearranging and using the fact that $s_{L^A} = 1 - s_S$:

$$g_{\hat{L^A}} - \frac{g}{\hat{L^A}} = 1 - \frac{G - \hat{\lambda}}{G}\frac{\sigma - s_S}{\sigma(1 - s_S)}, \tag{48}$$

this gives the sign condition for $g_{\hat{L^A}} - \frac{g}{\hat{L^A}}$:

$$g_{\hat{L^A}} - \frac{g}{\hat{L^A}} \gtreqless 0 \quad \Leftrightarrow \quad \frac{Y^A - \lambda}{Y^A}\frac{\sigma - s_S}{1 - s_S} \lesseqgtr \sigma, \tag{49}$$

and finally:

$$\frac{\partial L^A}{\partial A_L} \lesseqgtr 0 \quad \Leftrightarrow \quad \frac{Y^A - \lambda}{Y^A}\frac{\sigma - s_S}{1 - s_S} \lesseqgtr \sigma. \tag{50}$$

Once again, the implications of different values of σ are easily deduced. In particular, one can see clearly the consequences of $\sigma \leq 1$ using the equivalent inequality:

$$\frac{Y^A - \lambda}{Y^A}\frac{1 - \frac{s_S}{\sigma}}{1 - s_S} \lesseqgtr 1.$$

A.2 Proof of Proposition 2

Proposition 2 involves straightforward first and second derivatives computations. They are given below.

Derivatives with respect to σ

$$X_1 = \frac{\frac{Y^A - \lambda}{Y^A}\frac{1}{s_S}}{\left(\frac{Y^A - \lambda}{Y^A} + \frac{\sigma}{\nu^M}\frac{1 - s_S}{s_S}\right)^2} > 0, \tag{51}$$

$$\frac{\partial \epsilon_{L^A,A_L}}{\partial \sigma} = X_1 \left(\frac{1 - s_S\nu^A}{\nu^M} - \frac{\lambda}{Y^A}\right) > 0, \tag{52}$$

$$\frac{\partial \epsilon_{L^A,A_S}}{\partial \sigma} = -X_1 \, \frac{1 - s_S\nu^A}{\nu^M} < 0, \tag{53}$$

$$\frac{\partial \epsilon_{L^A,A}}{\partial \sigma} = -X_1 \, \frac{\lambda}{Y^A} < 0, \tag{54}$$

$$\frac{\partial X_1}{\partial \sigma} = -2X_1 \, \frac{\frac{1 - s_S}{\nu^M s_S}}{\frac{Y^A - \lambda}{Y^A} + \frac{\sigma}{\nu^M}\frac{1 - s_S}{s_S}} < 0. \tag{55}$$

Given (55), first and second derivatives are opposite in sign.

Derivatives with respect to Y^A

$$X_2 = \frac{\frac{\lambda}{Y^{A2}}\frac{\sigma}{s_S}}{\left(\frac{Y^A - \lambda}{Y^A} + \frac{\sigma}{\nu^M}\frac{1 - s_S}{s_S}\right)^2} > 0, \tag{56}$$

$$\frac{\partial \epsilon_{L^A,A_L}}{\partial Y^A} = X_2 \, \frac{1 - s_S}{s_S} \, \frac{\sigma - s_S\nu^A}{\nu^M} \gtreqless 0 \quad \Leftrightarrow \quad \sigma \gtreqless s_S\nu^A, \tag{57}$$

$$\frac{\partial \epsilon_{L^A,A_S}}{\partial Y^A} = X_2 \, \frac{1 - s_S\nu^A}{\nu^M} > 0, \tag{58}$$

$$\frac{\partial \epsilon_{L^A,A}}{\partial Y^A} = X_2 \left(1 + \frac{\sigma}{\nu^M}\frac{1 - s_S}{s_S}\right) > 0, \tag{59}$$

$$\frac{\partial X_2}{\partial Y^A} = -2\,\frac{X_2}{Y^A}\,\frac{1 + \dfrac{\sigma}{\nu^M}\dfrac{1-s_S}{s_S}}{\dfrac{Y^A-\lambda}{Y^A} + \dfrac{\sigma}{\nu^M}\dfrac{1-s_S}{s_S}} < 0. \tag{60}$$

Given (60), first and second derivatives are opposite in sign.

B Main results under CES preferences

Let us assume that preferences take the following CES form:

$$U(C^A, C^M) = \left[\nu^A (C^A - \lambda)^{\frac{\epsilon-1}{\epsilon}} + \nu^M (C^M)^{\frac{\epsilon-1}{\epsilon}}\right]^{\frac{\epsilon}{\epsilon-1}}, \qquad \nu^A + \nu^M = 1,\ \epsilon > 0, \tag{61}$$

then the following proposition is the equivalent of Proposition 1.

Proposition 3 *Consider a competitive market economy whose technology is characterized by* (1) *and* (2)*, whose representative consumer has preferences* (61) *and with market clearing* (8)*. Then, at an interior solution, the equilibrium allocation of labor* L^A *reacts to exogenous parameters as follows:*

$$\frac{\partial L^A}{\partial \nu^A} > 0 \qquad \frac{\partial L^A}{\partial \lambda} > 0,$$

$$\frac{\partial L^A}{\partial A} \lesseqgtr 0 \Leftrightarrow \frac{\epsilon-1}{\epsilon}\, Y^A \lesseqgtr \lambda \qquad \frac{\partial L^A}{\partial M} \lesseqgtr 0 \Leftrightarrow \epsilon \gtreqless 1,$$

$$\frac{\partial L^A}{\partial A_L} \lesseqgtr 0 \Leftrightarrow \frac{Y^A-\lambda}{Y^A}\,\frac{\sigma - s_S}{1-s_S} \lesseqgtr \frac{\sigma}{\epsilon},$$

$$\frac{\partial L^A}{\partial A_S} \lesseqgtr 0 \Leftrightarrow \frac{Y^A-\lambda}{Y^A} \lesseqgtr \frac{\sigma}{\epsilon},$$

furthermore, $\dfrac{\partial L^A}{\partial S}$ *has the same sign as* $\dfrac{\partial L^A}{\partial A_S}$.

By examining the sign conditions of $\frac{\partial L^A}{\partial A_L}$ and $\frac{\partial L^A}{\partial A_S}$, it is apparent that CES preferences extend the initial results in a straightforward manner: the threshold σ under Cobb-Douglas preferences is now replaced by the threshold $\frac{\sigma}{\epsilon}$. It is possible as in Proposition 1 to draw the consequences of different values of σ and ϵ by choosing for them a value less, equal or greater than one (with now nine different cases). A low ϵ increases the threshold of effectiveness for A_L and A_S; intuitively, low substitution possibilities between goods means that technical change is effective *further away* from the state of subsistence. Another consequence of CES preferences is that Hicks-neutral technical change (both in agriculture and manufacturing) is now subject to conditions on ϵ. When $\epsilon < 1$, A drives labor out of agriculture while M drives labor in agriculture. When $\epsilon > 1$, A drives labor out of agriculture provided agricultural output Y^A is lower than a fraction $\frac{\epsilon}{\epsilon-1}$ of the subsistence level λ, and M drives labor out of agriculture. Thus, the idea of proximity to subsistence is now extended to Hicks-neutral technical change.

Proof of Proposition 3

This proof is analogous to the proof of Proposition 1 in Section A.1. I give the derivatives of the functions f and g, which are defined as in Section A.1.

$$f(L^A,\nu^A,M) = \frac{\nu^A}{\nu^M}\frac{[MF(L^M)]^{\frac{1}{\epsilon}}}{MF'(L^M)}, \tag{62}$$

$$g(\hat{S},\hat{L^A},\lambda,A) = \frac{[AG(\hat{L^A},\hat{S})-\lambda]^{\frac{1}{\epsilon}}}{AG_{\hat{L^A}}(\hat{L^A},\hat{S})}. \tag{63}$$

$$f_{L^A} = \frac{\nu^A}{\nu^M}[MF]^{\frac{1}{\epsilon}-1}\left(\frac{FF''}{(F')^2}-\frac{1}{\epsilon}\right) < 0, \tag{64}$$

$$f_M = \frac{\nu^A}{\nu^M}[MF]^{\frac{1}{\epsilon}-1}\,\frac{\frac{1-\epsilon}{\epsilon}F}{MF'}, \tag{65}$$

$$f_{\nu^A} = \frac{1}{(\nu^M)^2}\,\frac{[MF]^{\frac{1}{\epsilon}}}{MF'} > 0, \tag{66}$$

$$g_{\hat{L^A}} = [AG-\lambda]^{\frac{1}{\epsilon}-1}\left(\frac{1}{\epsilon}+\frac{(G-\frac{\lambda}{A})(-G_{\hat{L^A}}{}^2)}{(G_{\hat{L^A}})^2}\right) > 0, \tag{67}$$

$$g_{\hat{S}} = [AG-\lambda]^{\frac{1}{\epsilon}-1}\,\frac{\frac{1}{\epsilon}G_{\hat{S}}G_{\hat{L^A}}-(G-\frac{\lambda}{A})G_{\hat{S}\hat{L^A}}}{(G_{\hat{L^A}})^2} \geq 0 \text{ or } < 0, \tag{68}$$

$$g_A = [AG-\lambda]^{\frac{1}{\epsilon}-1}\,\frac{\frac{1-\epsilon}{\epsilon}G+\frac{\lambda}{A}}{AG_{\hat{L^A}}} < 0, \tag{69}$$

$$g_{\hat{\lambda}} = -\frac{1}{\epsilon}\,\frac{[AG-\lambda]^{\frac{1}{\epsilon}-1}}{AG_{\hat{L^A}}} < 0. \tag{70}$$

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