Relative agricultural productivity and tropical deforestation

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Version: June 18, 2012

Paper Prepared for Fifteenth Annual Conference on Global Economic Analysis

Abstract

Agriculture production is the primary driver of global deforestation, and technological change in agriculture has implications for agricultural land extensification decisions. Some have even suggested that agricultural productivity improvements could help address deforestation. Recent studies have pointed out the importance of considering total factor productivity (TFP) improvements. TFP has two components—technological convergence (or catching-up), as well as frontier shifts. Historically, each has exhibited significant variation across agricultural sectors and across global regions, with many regions experiencing net positive productivity growth due to improvements in the technology despite falling further from the frontier. This paper analyzes the potential implications of TFP growth, relative agricultural productivity growth, and convergence on deforestation, as well as overall land use and agricultural production. We find that total factor productivity increases, and technological convergence, can *increase* deforestation. In particular, deforestation and land-use are strongly influenced by relative agricultural productivity growth across regions and sectors. Overall, we find that agricultural productivity growth is more nuanced than generally discussed and TFP growth and convergence patterns are potentially very important to global agriculture and deforestation.

Introduction

Deforestation is a significant global source of greenhouse gas emissions and historical contributor to climate change. Reducing carbon emissions by avoiding deforestation has been estimated to have large greenhouse gas (GHG) abatement potential (e.g., Kinderman et al., 2008), and could be especially valuable as a near-term abatement strategy in

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managing the long-run costs of attaining climate change objectives (e.g., USEPA, 2010). Agriculture production is the primary driver of tropical deforestation, and technological change in agriculture has implications for land extensification decisions and therefore deforestation. Some have suggested that agricultural productivity improvements should be a part of the strategy for addressing deforestation. Previous land-use projections modeling of yield improvements support this perspective (e.g., Sands and Leimbach, 2003). Recent studies however have pointed out the importance of considering total factor productivity (TFP) improvements versus partial factor productivity (PFP), e.g., yield improvements (Nin et al.). There are estimates of historic patterns of agricultural TFP growth (Ludena et al., 2007; Fuglie, 2010) and some have projected potential agricultural TFP patterns (Ludena et al., 2007; Hertel et al., 2009).

Ludena et al. (2007) and Hertel et al. (2009) characterize technological change as having two facets—convergence (or catching up) to the technological frontier and shifts in the frontier. The combination determines total factor productivity growth, i.e., increases in output for a given set of inputs. The historically pattern of technological convergence and frontier shifts exhibits significant variation between agricultural sectors and across global regions, with many regions experiencing net positive productivity growth due to improvements in technology despite some regions falling further from the technological frontier. Thus, convergence towards or away from the frontier is likely a factor in agricultural production and land use, as is relative agricultural productivity growth across regions and sectors.

From a deforestation perspective, this body of literature begs a few questions. What are the deforestation implications of TFP growth? How important is the pattern of productivity growth to global agriculture? And what are the implications for deforestation? Can convergence, and total factor productivity, help reduce deforestation? Building future projections off of historical analysis, we extend a global dynamic computable general equilibrium model to consider alternative future global technological change patterns. With endogenous land allocation and management decisions of heterogeneous land types, and a revised endogenous total land endowment approach, we are able to explore global agricultural production and land extensification decisions. Overall, we consider the economic implications of technological change patterns for regional agricultural production, land-use, and deforestation.

Agriculture Total Factor Productivity

Estimated total factor productivity growth (TFP) for agriculture from 1961 to 1996 is shown in the left side of figure 1 (Hertel et al., 2009). There is significant variation across crops and livestock and between ruminants and non-ruminants, as well as across regions. For instance, all regions of the world experienced outward shifts in the agricultural productivity frontier. However, most regions also moved further from the frontier during this time; the exceptions being ruminants in China and crops in industrialized countries. On net, total factor productivity has increased in most regions and agricultural sectors, with non-ruminants experiencing the largest growth. Crop and ruminant total factor productivity has declined or been stagnant in a few regions—South and Southeast Asia and Middle East and North Africa (MENA).

It is important to distinguish TFP growth from partial factor productivity growth (PFP), such as crop yield improvements. The former refers to increased profitability of all production inputs, while the later refers only to the productivity of a single input, such as land in the case of crop yield improvements. PFP estimates (e.g., output per hectare, output per head) tend to overestimate productivity growth for crops and livestock, especially for developing countries, because they do not adjust for input substitution that has affected productivity, e.g., fertilizers or irrigation (Nin et al., 2003).

Hertel et al. (2009) projected TFP growth to 2025 using historical technological change and a logistic convergence assumption. The result was convergence in most regions (figure 1, right), which is somewhat of a departure from the historical pattern. Figure 1 represents one potential future pattern of productivity improvement. It reflects heterogeneity across regions, agricultural sectors, frontier shifts and convergence.

We explore the land-use and production implications of productivity patterns by considering alternative TFP patterns derived from the same data. Specifically, we consider the following scenarios: “global” uniform growth, “regional” uniform growth, “regional/sectoral” differentiated growth, and technological frontier shifts only (“no convergence”). See table 1 for the alternative TFP growth rate assumptions for the eleven regions of our economic model. The “regional/sectoral” pattern is the TFP growth pattern shown in figure 1 (right). For global uniform growth, we assume uniform weighted average TFP growth for all regions and agricultural sectors. For regional uniform growth, we assume uniform weighted average growth across agricultural sectors within each region but variation across regions. The weighted averages were derived by Hertel et al. (2009) using output share weights. Finally, for the frontier shift pattern, we evaluate the role of convergence by assuming no convergence/divergence (i.e., leaving out the 1997-2025 convergence bars in figure 1). Thus, each region maintains its distance from the technological frontier as the frontier shifts out over time. Below we briefly describe our economic modeling framework before discussing results.

Model

This uses a modified dynamic computable general equilibrium (CGE) model documented in Golub et al. (2009). The description here offers only a brief exposition of the model's features.

The model incorporates an econometrically estimated, international cross-section, AIDADS demand system. This demand system represents changes in the consumption bundle as incomes rise, which is particularly important in the fast-growing developing countries with changing food consumption preferences.

The supply side of the model is built from the standard GTAP model production functions. These are constant returns to scale, nested constant elasticity of substitution functions. In forestry, the substitution between land and other value added inputs is incorporated to reflect changes in output per unit of land with respect to changes in management intensity as estimated by the Global Timber Model of Sohngen and Mendelson (2006). In food processing, the substitution between farm-based products and marketing inputs is introduced. These intensification possibilities reduce pressure of the growing consumer demands on land.

Consumer demand is translated into the derived demands for land through sectoral production functions. Equilibrium land rents are determined by equating these demands to land supply. Land endowment in each region is disaggregated into Agro-Ecological Zones (AEZs), which represent heterogeneity in biophysical productivity of land with higher numbered AEZs more productive. Within each AEZ, the mobility of land across uses is modeled as a nested constant elasticity of transformation (CET) function. The elasticity of which captures the ease/cost of conversion.

Technological change in the agricultural sectors varies by scenario as described in the previous section. Technological change in forestry processing is based on the Global Timber Model. Unlike many CGE models, our land endowment is endogenous and can expand into inaccessible tropical forests. Thus, total managed land—cropland, pasture, and accessible forest—can expand or contract within each region and AEZ. Land endowment expansion within each AEZ is controlled by a land endowment elasticity parameter. Specifically, the elasticity is the percentage change in land endowment relative to the percentage change in land rents. This approach is different from that initially used in Golub et al. (2009). The elasticities were estimated with the Global Timber Model and alternative agricultural commodity demand scenarios. The endowment elasticities provide a measure of responsiveness on how readily inaccessible tropical forests are accessed for agricultural production when returns to agricultural land increase. The additional endowment can be utilized by any of the managed land use activities in the CGE model to produce crops, livestock, or timber.

Results

Because of our interest in deforestation, we begin our results discussion with tropical land-use. We then broaden our discussion to consider relative productivity and convergence implications globally for agricultural production and land-use, including temperate deforestation.

Tropical land-use

First, we evaluate the implications of the productivity patterns on managed land extent—land endowment expansion into inaccessible forests in Southeast Asia, Latin America, and Sub-Saharan Africa. We then look within the land endowment at managed land use changes to evaluate the cause of land endowment changes.

In figure 3, we see that SE Asia is more responsive to the alternative TFP patterns, while Latin America is less so and Sub-Saharan Africa is almost unresponsive. In the figure, we also plot crop TFP growth (figure 3 triangles), and find that they are likely a part of the explanation for the endowment expansion variation in SE Asia across productivity scenarios, and possibly Latin America. Higher regional crop TFP growth appears to be consistent with land endowment expansion. However, there is more to it as we can it is not a linear relationship. Also, the relationship is not unique within region (e.g., an 18% endowment expansion in SE Asia corresponds with different TFP growth rates of 1.43% and 0.35%). Finally, there are different crop TFP-endowment expansion relationships across regions. Overall, we only find a strong positive correlation in SE Asia (correlation coefficient 0.81), and weak negative correlations in the other two tropical regions. Thus, TFP growth can drive deforestation, but other factors are also relevant.

Another possible factor is relative regional crop TFP growth (figure 3 dots). In SE Asia and Latin America, we find correlations of 0.93 and 0.94 respectively. For SSA, there is a positive, but weak correlation of 0.26. Thus, we find that increased deforestation at the inaccessible frontier corresponds to increased agricultural productivity in SE Asia, and increased relative agricultural productivity in both SE Asia and Latin America. Given this evidence, we explore relative productivity growth more thoroughly further below. Before that however, we look within the land endowment at managed land-use changes.

The land-use change drivers of tropical endowment expansion differ by region (figure 4). In SE Asia and Sub-Saharan Africa, we find increases in both accessible forest and agricultural land. In Latin America, only agricultural land is increasing, and accessible forests decreasing. Note that the Figure 4 results are revenue share weighted changes in land-use. This is a useful metric for capturing land-use changes with commercial production implications. In all three regions, across productivity scenarios, we see trade-offs between agriculture and accessible forest land. For instance, in SE Asia, the global uniform pattern produces higher agricultural land expansion than the other patterns and lower accessible forest expansion. While in Latin America, the global uniform pattern produces lower agricultural land expansion and less accessible forest loss. Thus, agricultural land expansion results in accessible and inaccessible forest loss, in the form of reduced forest expansion or increased forest loss. Across scenarios, cropland changes are the key driver of net agricultural land-use change; however, pasture is also changing.

Finally, we see that the regional endowment expansion pattern across agricultural productivity assumptions (figure 3) matches that observed in regional agricultural land expansion (figure 4). Thus, the different response across regions corresponds to TFP growth and relative regional crop productivity growth.

Relative Productivity

The land change outcomes are the result of many drivers, including population, income, regional differences in endowments and markets, and technological improvements in general. To isolate the effects of relative agricultural productivity we want to control for the effects of other drivers. We can accomplish this by normalizing to the global uniform TFP growth results. In the global uniform scenario there are no differences in relative productivity growth. Thus, the results represent the implications of all drivers but relative agricultural productivity. Normalized results will allow us to focus on the responsiveness of regions and sectors to changes in the agricultural productivity patterns in the form of deviations from the global uniform TFP growth results. How might relative productivity affect the future? We discuss the implications for 2025 outcomes. Also, because we are interested in responsiveness to relative productivity changes, the implications are presented in percentage terms.

With the regional productivity pattern deviations there are decreases in agricultural TFP in 2025 for all but three regions (Table 2). China experiences a large increase in TFP, while increases in Latin America and EIT are modest. Regions with higher TFP also have better relative TFP growth—China in particular has over twice world average growth. In the table, we find that higher TFP and relative TFP growth leads to increased agricultural output and decreased forestry output. Behind the agricultural production responses are increases in returns to agricultural land and increases in agricultural land area that converts both accessible and inaccessible forests. In all three regions we find increasing cropland, but in China it is at the expense of pasture, while in Latin America and EIT, pasture acreage is also increasing. For regions with lower TFP and relative TFP growth, we find reductions in output, endowment expansion, and cropland (with increasing accessible forest and pasture).

Finally, in understanding the role of crop TFP, it is helpful to note the relative preference for crop production. Despite identical TFP across crops and ruminants, crop land rents and output increase more than they do for ruminants (e.g., China, EIT) as crops are viewed as a higher value land use for food and livestock feed.

Table 3 presents the 2025 deviations associated with regional and sectoral heterogeneity in TFP. There is also significant relative TFP growth heterogeneity within and across sectors. Land-use and output now respond to three forces: TFP growth itself, relative TFP growth across regions, and relative TFP growth across sectors. In SE Asia, we find lower crop and ruminant TFP and relative TFP growth, which together result in lower output, land endowment expansion, and agricultural land area. In Latin America, there is also lower crop and ruminant TFP, but relative ruminant TFP growth is strong and results in increased ruminant output and increased agricultural acreage and land endowment.

The role of relative TFP growth across sectors (vs. regions) is evident in China where relative TFP growth is strong in both crops and ruminants. However, growth is significantly stronger in ruminants and, as a result, so is the increase in ruminant output. North America is another example, stronger relative crop TFP growth translates into increased crop production despite declining TFP. In both China and North America we find deforestation of accessible forests with pasture and cropland expansion respectively.

Plotting all the deviations across scenarios and regions within each scenario (including no convergence deviations), we find strong positive correlations between output and relative TFP growth for both crop and ruminant production (figure 5), with the relationship for crop production a bit stronger. A similar type of figure for revenue share weighted accessible forest area change and relative regional crop TFP reveals a robust negative correlation (figure 6). Thus, while increased TFP can increase deforestation of accessible and inaccessible forest, increased relative TFP has an even stronger relationship with increased deforestation. Figure 6 shows that the slope of the relationship varies by AEZ, but the negative correlation is robust across AEZs.

Productivity Convergence

Finally, we explicitly assess the role of convergence in agricultural productivity. Convergence is especially important to developing and transitional economies, but, as we see, also to developed regions because of the relative effects. Convergence is a large fraction of the projected TFP growth from Hertel et al. (2009). In the tropics, in figure 1 (right), SE Asia is diverging and losing ground as the technological frontier shifts out for crops and ruminants. Latin America is as well for crops, but to a lesser extent, and is converging for ruminants. Sub-Saharan Africa is converging for both crops and ruminants. The convergence assumptions are less important for the developed countries, but are a significant part of China and S Asia's net agricultural TFP growth.

Convergence processes are not well understood, and other future patterns are certainly feasible (e.g., figure 1 left). We therefore want to explore the importance of convergence. We do this by simply removing the convergence/divergence assumptions. In other words, we limit productivity growth to the figure 1 1997-2025 frontier shifts and regions maintain their relative position to the frontier.

However, unlike our previous discussions, we are only interested in the convergence effects. Therefore, we look at frontier shift only deviations from the regional/sectoral TFP pattern results. The effects of convergence on land in the tropics are noteworthy (not shown). We see 5% increases in endowment expansion in SE Asia and Latin America, as well as increased accessible forest loss. Thus, the productivity divergence assumptions in the regional/sectoral TFP scenario were *reducing* deforestation. Put another way, productivity convergence in these two regions results in increased deforestation. The results for Sub-Saharan Africa are consistent, with reductions in crop and ruminant productivity convergence resulting in reduced inaccessible and accessible forest loss. The land use shifts towards agriculture in SE Asia and Latin America are associated with higher land rents and large increases in production (49% and 29% respectively).

Convergence is also having a prominent effect on China and S Asia. Removing the convergence assumptions results in significant reductions in agricultural output (26% and 17% in crops and 23% and 19% in ruminants), with surprisingly little affect on land use change. Thus, these regions are reducing output but increasing the land and non-land inputs per unit of output. We also find an overall convergence impact on GDP. For instance, removing the catching up component of agricultural TFP growth in China and South Asia, results in 9% reductions in each region's 2025 GDP, primarily due to reduced consumption. This result generalizes to one of increased TFP growth, lower prices, and increased consumption.

Conclusions

Agriculture is a primary driver of global deforestation, and agricultural productivity is a critical factor that some suggest could be stimulated to diminish land competition, and reduce deforestation in particular. Total factor productivity (TFP) improvements have been an important part of historic agricultural productivity gains. Agricultural TFP growth can vary by region and agricultural commodity, as well as in the composition of growth between convergence and shifts in the technological frontier. This paper analyzes the potential implications of TFP growth, relative agricultural productivity growth, and convergence on deforestation, as well as overall land use and production.

We find that agricultural TFP growth patterns are potentially very important to global agriculture and deforestation. However, we also find that technological convergence (or catching-up), and total factor productivity increases, can increase deforestation. Agricultural total factor productivity improvements, especially for crops, can imply increased returns to agricultural lands and increased deforestation of inaccessible and accessible forests. However, that is not inevitable, as relative productivity growth across regions and commodity sectors significantly influences land-use decisions. The importance of relative TFP growth is evident in the changes in global land rents and agricultural output, and ultimately agricultural land expansion. Overall, we found strong positive correlations between agricultural TFP growth and output and deforestation, especially with crops.

Finally, given potential policy interest in targeted productivity growth in specific regions and sectors as a potential strategy for reducing deforestation, we ran supplemental scenarios with increased TFP growth in individual tropical regions and agricultural sectors off of the regional/sectoral TFP scenario (Latin America/SE Asia, crops/ruminants). We found that improvements in Latin America or SE Asian crop TFP, ceteris paribus, led to increased inaccessible and accessible forest loss and pasture land conversion to cropland. However, improvements in Latin America or SE Asian ruminant TFP, ceteris paribus, produced virtually no change in land endowment, but did result in modest managed land reallocation towards pasture. Neither of these results suggests that regional sector specific TFP improvements are promising means for reducing deforestation.

Note that this paper was not intended to promote or validate particular productivity growth assumptions. Instead, we illustrate the potential importance of relative productivity improvements and convergence processes, as well as technology diffusion that affects both production opportunities via frontier shifts and realized improvements associated with keeping up or converging towards the shifting frontier. We also highlight the importance of TFP, and of understanding what kind of agricultural productivity growth is implied by different technological improvements. We hope this study motivates further dialogue on productivity projections assumptions, as well as research into better understanding of historic agricultural productivity and improvement mechanisms for regional convergence and technological frontier shifts.

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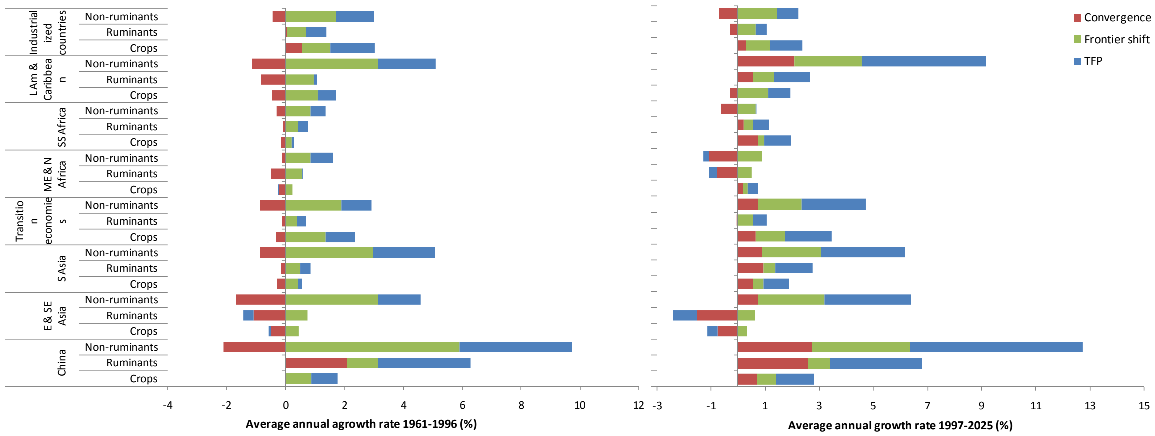

Figure 1. Agricultural productivity growth 1961-1996 (left) and 1997-2025 (right)

Table 1. Average Annual Total Factor Productivity Growth Patterns

	ANZ	China	HY Asia	SE Asia	S Asia	N Am	L Am	W EU	EIT	MENA	SSA
Global uniform											
Crops	1.43%	1.43%	1.43%	1.43%	1.43%	1.43%	1.43%	1.43%	1.43%	1.43%	1.43%
Ruminants	1.43%	1.43%	1.43%	1.43%	1.43%	1.43%	1.43%	1.43%	1.43%	1.43%	1.43%
Non-ruminants	1.43%	1.43%	1.43%	1.43%	1.43%	1.43%	1.43%	1.43%	1.43%	1.43%	1.43%
Regional uniform											
Crops	0.86%	3.07%	0.86%	0.11%	1.13%	0.86%	1.53%	0.86%	1.48%	0.17%	0.86%
Ruminants	0.86%	3.07%	0.86%	0.11%	1.13%	0.86%	1.53%	0.86%	1.48%	0.17%	0.86%
Non-ruminants	0.86%	3.07%	0.86%	0.11%	1.13%	0.86%	1.53%	0.86%	1.48%	0.17%	0.86%
Regional/sectoral											
Crops	1.21%	1.41%	-0.39%	-0.39%	0.95%	1.21%	0.83%	1.21%	1.75%	0.38%	0.99%
Ruminants	0.39%	3.42%	0.39%	-0.90%	1.40%	0.39%	1.35%	0.39%	0.51%	-0.29%	0.58%
Non-ruminants	0.75%	6.47%	0.75%	3.23%	3.13%	0.75%	4.66%	0.75%	2.41%	-0.22%	0.03%
Frontier shift only (no convergence)											
Crops	0.89%	0.70%	0.35%	0.35%	0.37%	0.89%	1.12%	0.89%	1.08%	0.20%	0.25%
Ruminants	0.67%	0.82%	0.67%	0.62%	0.44%	0.67%	0.76%	0.67%	0.56%	0.50%	0.35%
Non-ruminants	1.46%	3.62%	1.46%	2.45%	2.21%	1.46%	2.51%	1.46%	1.62%	0.89%	0.66%

Table note: ANZ = Australia/New Zealand, HY Asia = high income Asia, SE Asia = Southeast Asia, S Asia = South Asia, N Am = North America, L Am = Latin America, W EU = Western EU, EIT = Economies in transition, MENA = Middle East/North Africa, SSA = Sub-Saharan Africa

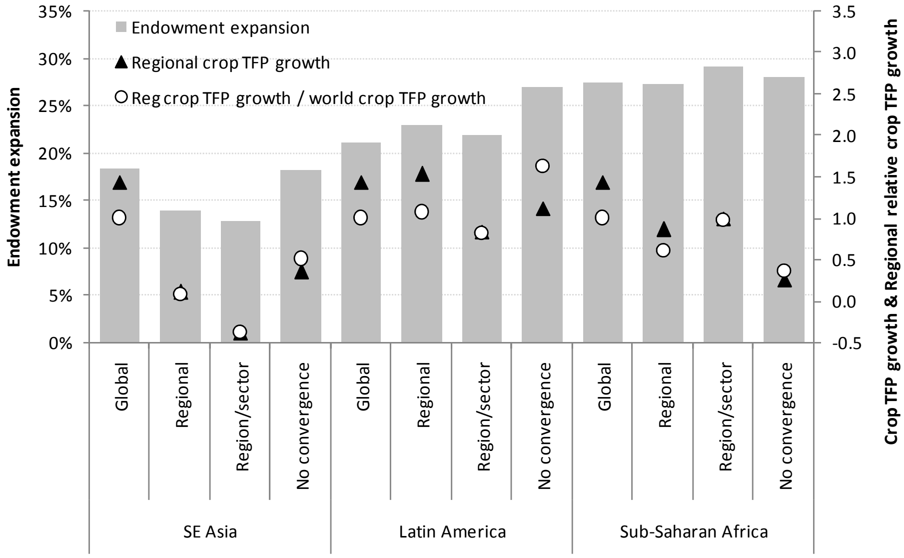

Figure 3. Tropical land endowment expansion, regional crop TFP growth, and relative regional crop TFP growth by 2025

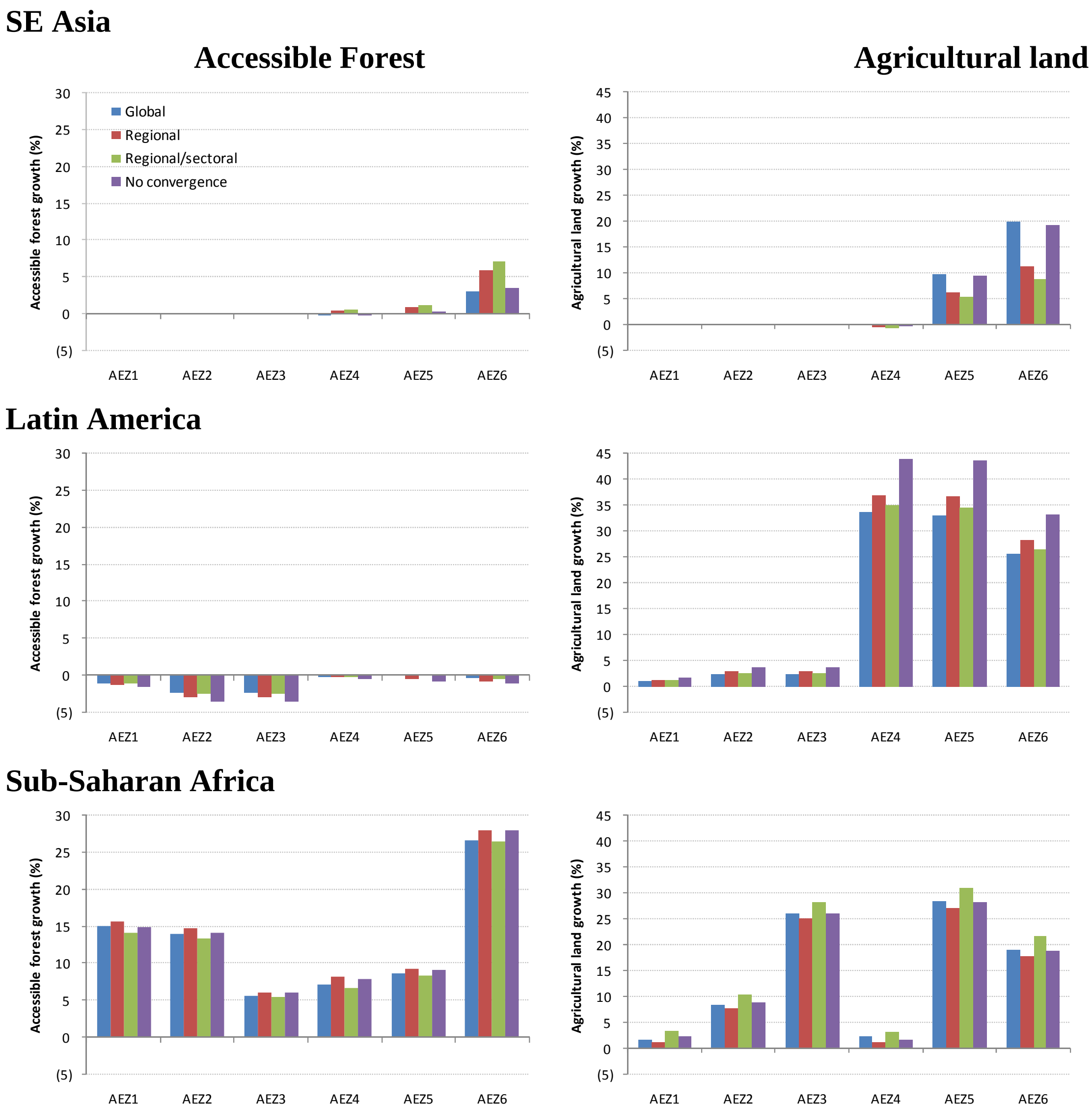

Figure 4. Tropical land-use changes by 2025 across TFP patterns (rev share weighted)

Table 2. Regional TFP 2025 Deviations from Global Uniform TFP Levels (%)

[redacted]

Table 3. Regional/sectoral TFP 2025 Deviations from Global Uniform TFP Levels (%)

	ANZ	China	HY Asia	SE Asia	S Asia	N Am	L Am	W EU	EIT	MENA	SSA
Agricultural TFP											
Crops	(6)	(1)	(40)	(40)	(12)	(6)	(15)	(6)	9	(25)	(11)
Ruminants	(25)	72	(25)	(48)	(1)	(25)	(2)	(25)	(23)	(38)	(21)
Non-ruminants	(17)	289	(17)	64	59	(17)	141	(17)	31	(37)	(32)
Relative agricultural TFP growth											
Crops	1.19	1.38	(0.38)	(0.38)	0.93	1.19	0.81	1.19	1.72	0.37	0.97
Ruminants	0.32	2.80	0.32	(0.74)	1.15	0.32	1.11	0.32	0.42	(0.24)	0.48
Non-ruminants	0.24	2.06	0.24	1.03	1.00	0.24	1.48	0.24	0.77	(0.07)	0.01
Output											
Crops	8	8	(56)	(53)	(11)	6	(17)	7	24	(37)	(9)
Ruminants	(26)	29	(24)	(39)	(2)	(31)	15	(18)	0	(32)	(16)
Non-ruminants	(93)	294	(59)	(0)	5	(93)	431	(93)	(29)	(97)	(75)
Forestry	74	435	65	37	(40)	77	15	(1)	12	(22)	(27)
Land endowment expansion											
				(5)			1				2
Accessible forest area											
AEZ1	0	0	0	0	(0)	(0)	(0)	0	(2)	2	(1)
AEZ2	0	(0)	0	0	(0)	(0)	(0)	(3)	(3)	1	(1)
AEZ3	(0)	(0)	10	0	(0)	(1)	(0)	(3)	(3)	3	(0)
AEZ4	(0)	(0)	7	1	(0)	(0)	(0)	(1)	(3)	3	(0)
AEZ5	(2)	(1)	4	1	(1)	(1)	(0)	(1)	(3)	2	(0)
AEZ6	(3)	(2)	8	4	(1)	(2)	(0)	(1)	(4)	0	(0)
Agricultural land area											
AEZ1	0	0	0	0	0	0	0	(0)	2	(2)	2
AEZ2	0	0	0	0	0	0	0	3	3	(2)	2
AEZ3	0	0	(9)	0	0	1	0	3	3	(3)	2
AEZ4	0	0	(7)	(1)	0	0	1	1	3	(3)	1
AEZ5	2	1	(4)	(4)	1	1	1	1	3	(2)	2
AEZ6	3	2	(7)	(9)	1	2	1	1	4	0	2
Land rents											
Crops	30	12	(36)	(22)	4	28	3	21	19	(15)	6
Ruminants	25	(1)	(26)	(11)	4	21	10	20	23	(6)	8
Forestry	15	4	(17)	(7)	1	20	3	11	8	(6)	5

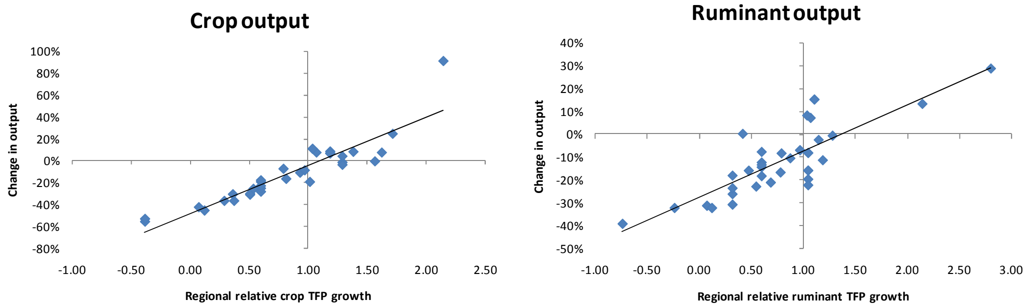

Figure 5. 2025 deviations in agricultural output with respect to relative regional TFP growth

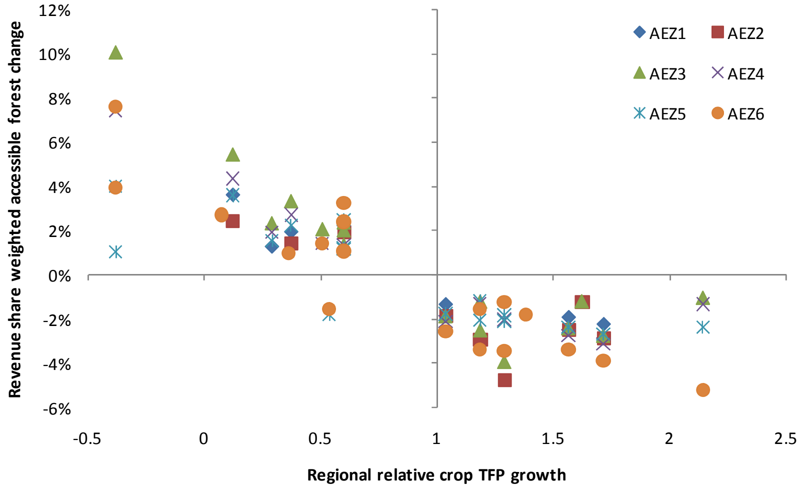

Figure 6. 2025 deviations in revenue share weighted accessible forest with respect to relative regional TFP growth