Technological Change and Deforestation: a Theoretical Overview

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1. Introduction[1]

This book seeks to answer the question: 'Does technological progress in tropical agriculture boost or limit deforestation?' Theory alone provides few unambiguous answers. But it can sort out the main arguments, structure the discussion and provide testable hypotheses. This chapter sets out basic economic theories relevant to the book's central question.

The first step in any scientific discussion is to define the key terms. In our case, the terms 'technological change', 'technological progress' and 'intensification' and the terms used to describe various technologies lend themselves to a certain degree of confusion. Thus, before going into the theories themselves, section 2 provides basic definitions and classifies technologies based on factor intensities. Factor intensities are critical to determining how new technologies affect forest clearing when farmers are labour- and/or capital-constrained, as is often the case.

Section 3 explores how farm households make decisions about clearing forest and how technological change affects those decisions. This constitutes the microeconomic part of our story and our discussion draws from the rich literature on agricultural household models. This literature suggests that whether or not technological progress reduces deforestation will depend on the constraints farmers face, the market conditions and the type of technology involved.

The next step is to look at the aggregate effects of all farmers' decisions, sometimes referred to as the general equilibrium effects. This provides the macroeconomic part of the story, which we present in section 4. We take into account that technological change might alter prices and wages and induce migration. In other words, certain variables that are fixed at the household level are endogenous when we consider the agricultural sector as a whole and the interaction between this and other sectors.

Other chapters in this book deepen and extend our discussion of the relevant theories. Reardon and Barrett, Shively and Martinez, and Yanggen and Reardon use models similar to those presented in this chapter. Holden, Roebeling and Ruben, and Vosti *et al.* use farm programming models to test empirically some of the hypotheses we derive. Cattaneo and Jayasuriya extensively discuss general equilibrium effects. Coxhead *et al.* deal with the issue of risk, which this chapter does not deal with much. Kaimowitz and Smith discuss another issue that we ignore here, namely the economics of scale.

2. Defining Technological Change[2]

One can approach technological change or technological progress in agriculture from different angles. Economic theory normally defines technological progress as an increase in total factor productivity (TFP). This implies that farmers produce more physical output with the same amount of physical inputs or, conversely, the same output with fewer inputs. Others define technological progress as any change in the production process that increases net profit. This definition partly overlaps with the previous one. As long as prices remain constant, an increase in TFP will increase profits.

New technologies take various forms. They may be embodied in inputs and capital goods, as in the case of improved seeds and fertilizers, or they can be disembodied, which means that they rely entirely on new management practices or information. Analysts often describe the impact of new technologies, embodied or otherwise, in terms of how intensely they use various inputs (mainly labour, capital and land). Thus, technologies may be labour-saving, capital-intensive, and so on. At times, the exact meaning of these terms appears convoluted, so we shall explain how we use them in this text.

The most intuitive approach is to start with a situation where farmers must use a fixed proportion of inputs to produce their output. They cannot substitute labour for land, capital for labour, or any other factor for another factor. Economists refer to such situations by saying that farmers have Leontief-type technologies. Equation (1) gives the amount of output, Y, they can produce using the inputs labour (L), land (H) and capital (K):[3]

$$Y = \min[L, H, K] \tag{1}$$

This functional form rules out substitution between inputs. One can think about a Leontief situation as a recipe. To produce a cake, you need a fixed amount of eggs, flour, milk and appliances. Two ovens cannot make up for a lack of milk, you cannot substitute flour for eggs, etc. The Leontief production function undoubtedly oversimplifies the situation. In real life, farmers can, to a certain extent, substitute between inputs. For example, they can apply herbicides or do the weeding by hand. Even so, the insights and definitions from the simple Leontief case apply to more general formulations.

One can define factor (input) intensities in relation to output or other factors of production. Most chapters in this book use definitions that refer to the amount of labour or capital per unit of land (H). Hence, y, l and k denote output, labour and capital per hectare, respectively, and by dividing by H we can write equation (1) as:

$$y = \min[l, k] \tag{2}$$

Table 2.1 classifies technologies based on the change in physical yield and factor intensities. A labour-intensive technology increases labour input per hectare, whereas a labour-saving technology has the opposite effect. Similarly, a capital-intensive technology increases capital inputs per hectare and a capital-saving technology reduces them. A labour-saving technology may increase or decrease yield, but farmers will only adopt it if it increases their profits (recall the definition of TFP). Falling labour costs should more than compensate for any possible fall in output or revenues. New technologies can be both labour- and capital-intensive. One such example would be a fertilizer technology that increases both the use of the capital input (fertilizer) and the need for weeding (labour). Pure yield-increasing technologies raise yields without altering the labour and capital requirements per hectare. Economists also call these labour- and capital-neutral technologies, also referred to as Hicks neutral technologies.

Some analysts use the term land-saving to describe technologies. But, once we measure inputs per unit of land, the concept becomes meaningless. The term yield-increasing technologies captures much of what these analysts are referring to. Unlike pure yield-increasing technologies, simply calling something a yield-increasing technology may or may not imply higher input use.[4]

The most widely used alternative to measuring factor intensities in terms of units of land is to measure them in terms of output.[5] Dividing through by Y in equation (1), we get:

Table 2.1. Classification of technologies based on change in yield and factor intensities.

Type of technology	Yield (y)	Labour per ha (l)	Capital per ha (k)
Labour-intensive	+	+	?
Labour-saving	?	–	?
Capital-intensive	+	?	+
Capital-saving	?	?	–
Pure yield-increasing (Hicks neutral)	+	0	0
Yield-increasing and input-intensive ('land-saving')	+	+	+

$$1 = \min[l^Y, h^Y, k^Y] \quad (3)$$

The coefficients inside the brackets refer to the minimum amount of each input needed to produce one unit of the output. The term 'land-saving technology' now makes perfect sense. It is a technology that reduces h^Y. Similarly, the new meaning of labour and capital intensity becomes l^Y and k^Y. The term yield-increasing technological progress loses its meaning. In the remainder of this chapter, we define labour and capital intensities in terms of input per hectare (we use equation (2) rather than equation (3)).

Capital-intensive technological change can take various forms. For our purposes, it is critical to distinguish between two categories of capital-intensive technological change, those that save labour, such as tools and draught animals, and those that save land, such as fertilizers. By definition, the former reduce the amount of labour demanded per hectare. The latter often have the opposite effect. Thus, how higher capital input use affects the demand for labour depends on which type of capital farmers adopt. Below we show that this greatly influences how technological change will affect deforestation.

Many people associate the concept of technological change with that of agricultural intensification, which they understand to mean higher input use (or output) per hectare.[6] Intensification therefore relates to the terms yield-increasing and land-saving technological change. None the less, technological change and agricultural intensification are not synonymous. Change in technologies may or may not imply intensification. Intensification can occur without any change in the underlying technology (in economic jargon: without any change in the production function).

Where do new technologies originate? In some cases, outside development or extension agencies generate and introduce new technologies. In other cases, the technologies arise 'spontaneously' within the rural communities themselves. Such 'spontaneous' technological changes often respond to changes in the context. For example, changes in population density may trigger the search for land-saving technologies, as initially hypothesized by Boserup (1965). Similarly, changes in relative prices may induce technological change, as farmers find ways to switch from expensive inputs to cheaper ones or to introduce more valuable crops.

So far, the discussion may seem to suggest that farmers produce only a single output. In reality, farmers often produce multiple outputs, including annual crops, tree crops, livestock products and processed goods, and they use more than one production or land-use system to produce these outputs. This has implications for our definition of technological progress. When we define technological progress and TFP at the farm level, this will include: (i) technological progress for a particular crop and/or production system; (ii) the introduction of a new crop and/or production system (technology) with higher TFP; and (iii) a shift in farm inputs towards crops/systems with higher TFP. In all three cases TFP at the farm level increases, and therefore they qualify as technological progress.

3. Farm-level Effects

Farmers respond to economic opportunities. They allocate their scarce resources (land, labour and capital) to meet their objectives. These objectives include things like ensuring family survival, maximizing income or minimizing risk. Available technology, assets, market conditions, land tenure and other factors constrain the choices farmers have available. Technological change may modify these constraints and provide incentives that encourage farmers to allocate their resources in a different manner. Two key concepts to understand farmers' response to technological change are therefore constraints and economic incentives.

To analyse how farmers may change their land use in response to technological changes, we start with the analytically simplest case, where farmers are integrated into perfect output and input markets.[7] Even though this is rather unrealistic at the forest margin, it is a useful starting-point. After analysing this simple case, we then introduce market imperfections, labour and capital constraints, farms with multiple outputs and dynamic wealth and investment effects that affect the capital constraint.

3.1. The perfect market case

Consider a farm household that produces one commodity with a fixed-input (Leontief) technology. Labour, capital and output per hectare are all fixed. Land is abundant (i.e. its price equals zero) and agricultural expansion takes place in 'empty' forest. When farmers move inputs and outputs between a village and the field, they incur transport costs. Thus, land rent diminishes as you move further from the village centre.

Given these assumptions, we can use a von Thünen approach to determine how far the agricultural frontier advances. The frontier will expand until the net profit or land rent is zero.

$$r = py - wl - qk - vd = 0 \tag{4}$$

Equation (4) shows the variables that influence land rent and hence the limits of the agricultural frontier. Output price (p), yield (y), wage rates (w), per-hectare labour requirements (l), the price of capital (q), per-hectare capital requirements (k), transport costs per km (v) and distance in km (d) determine the land rent per hectare (r). The outer limit of agriculture is the distance d^*, where the land rent is zero. This agricultural frontier determines the total amount of land in production. Figure 2.1 presents land rent as a function of distance (the rent gradient).

This simple model can represent several types of technological change (see Table 2.1). As long as markets are perfect, the type of technological change will not affect the qualitative results. All types of technological progress increase the rent at any given distance (the rent gradient shifts upward) and

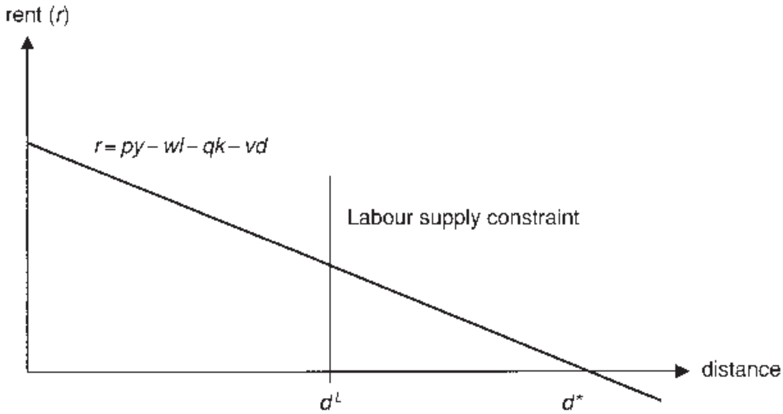

Fig. 2.1. The agricultural frontier.

promote the expansion of the agricultural frontier. Thus, with perfect markets, technological progress unambiguously stimulates deforestation.

The perfect-market model provides an important insight. Technological progress in frontier agriculture makes it more profitable and therefore leads farmers to expand into forests. Although this conclusion is based on stylized and unrealistic assumptions, one should not simply discount it, since, to one degree or another, it also applies to the more realistic models presented below. Several of the cases discussed in this book demonstrate that, even though the real world is much more complex, this simple prediction is often borne out in real life. When technological change makes agriculture at the frontier more profitable, deforestation increases.

3.2. The constrained farm household

In the previous subsection, we assumed that no transaction costs keep farmers from trading freely in any market. In practice, transaction costs may be so high that farmers decide it is not worth their while to participate in certain markets (Sadoulet and de Janvry, 1995). This means that, de facto, those markets do not exist for some households. Peasant households may also not face a complete set of markets for other reasons, such as the inability to share risks.

The absence of certain markets has important consequences for how households are likely to respond to technological changes. One commonly missing market is the labour market. Family labour often has few alternative uses outside the farm and many households cannot afford to hire labour. Thus, they must rely entirely on family labour. In such circumstances, the amount of labour the family has available will limit how much land it can use. Assuming that the maximum labour input the family has access to is L^S, we get:

$$L^D = L(d;l) \leq L^S \qquad (5)$$

L^D is the demand for labour on the farm. The greater the distance (i.e. the larger the total cultivated area) and the higher the labour intensity (l), the more labour the farmer will demand. If the labour constraint is binding, equation (5) will determine the boundaries of the agricultural frontier, not equation (4). The vertical line in Fig. 2.1 illustrates this case. Under these circumstances, the forest frontier will be at d^L, instead of d^*.

Capital constraints can also affect the relation between technological change and deforestation. The availability of capital (K^S) can constrain the expansion of the agricultural frontier, and can be modelled as follows:

$$K^D = K(d;k) \leq K^S \qquad (6)$$

When farmers' limited access to labour and/or capital constrains their ability to expand their area, the type of technological change will influence how technological change affects deforestation. For example, when households have a limited amount of capital (K^S) at their disposal, the only way they can adopt a new capital-intensive technology is if they reduce their cultivated area. More generally, technological changes that allow farmers to use less of their scarce factor will boost deforestation. Innovations that are intensive in the scarce factor will reduce deforestation.

Adding more realistic features to the model may modify these results. For example, we have assumed that farmers cannot substitute between different inputs. However, in reality, farmers may find ways to relax their capital constraint by substituting labour for capital. If they do, the new technology will not necessarily reduce deforestation. The new capital-intensive technology may also help the farmers become eligible for credit or persuade them to request more credit, thus removing their capital constraint and allowing them to expand their area.

Equally important is the fact that the profits farmers obtain in previous periods largely determine their access to capital in the current period. We would expect any technological progress that improves farmers' profits to relax their future cash constraints. Technological changes may provide the funds farmers need to expand. Hence, thanks to technological change, farmers who initially behaved as if they were credit-constrained may accumulate capital over time and start behaving more like unconstrained profit-maximizers (Holden, 1998).

The utility-maximizing household

Households' well-being does not only depend on how much food and other goods they consume. People also need leisure. Households choose the number of hours they work based on the returns to labour and the pleasure they derive from pursuing other activities. Therefore, labour supply is not fixed, although the total amount of available time is. In mathematical terms, the household's time constraint is:

$$L^D = L(d;l) \leq L^S = L^T - c^L \qquad (7)$$

where L^T is the total amount of time the household has available and c^L is the time it dedicates to non-production activities. In such settings, the situation portrayed in Fig. 2.1 is no longer straightforward. Consider the case of pure yield-increasing technological change. If y goes up, it will have (contradictory) effects on the amount of time farmers spend working in their fields. On the one hand, technological progress increases the returns to labour. This encourages households to work more and take less leisure. In other words, if the rent function in Fig. 2.1 shifts outwards, the household has an incentive to supply more labour, thus shifting d^L to the right. This is the so-called substitution effect. On the other hand, technological progress makes our household richer. We can expect it to use some of its additional income to take more leisure time. As long as the household cannot hire labour, to consume more leisure it must work fewer hours. Technological progress may thus decrease the labour supply, shifting d^L to the left. This is the income effect. Depending on which of the two effects dominates, technological progress may increase or decrease deforestation.

The opposite of the perfect-market model is the subsistence (or full-belly) model, based on what we called the subsistence hypothesis in Chapter 1. Here the crucial assumption is that people seek a predefined fixed level of material well-being and have little interest in going beyond that level. As soon as a household achieves this level, the household will turn to leisure or other non-production activities. Any yield-increasing technological progress will then unambiguously benefit forest conservation. As the rent function in Fig. 2.1 shifts upward, the household will be able to achieve the same amount of income using less labour, capital and land. Thus, the supply of labour simply decreases in response to technological progress. In this case, there is no conflict between the welfare and conservation objectives. Although the subsistence model may accurately describe the individual farmer's response to technological change in certain circumstances, there is little evidence to suggest that the model applies at the aggregate level (Holden *et al*., 1998; Angelsen, 1999a).

In summary, if farmers face a set of perfect markets, technological change will spur deforestation. When farmers are labour (capital)-constrained, as is often the case at the forest margin, labour (capital)-saving technological progress will probably lead to more deforestation. Labour- and/or capital-intensive technological progress will lead to less deforestation, unless the constraints are 'soft' and/or there is a large 'investment' effect (i.e. higher profits relax future capital constraints). Technological change affects household income and this may affect the amount of labour they supply.

3.3. Intensive and extensive production systems at the household level

In this section, we extend our discussion to situations where farms maintain two production systems: one intensive and one extensive. The former has higher yield and labour and capital intensities than the latter. This allows us to capture how shifts between intensive and extensive systems provoked by technological change determine the overall demand for agricultural land. Farmers choose to engage in more than one production system for several reasons. These include: risk spreading, distributing seasonal labour requirements, the gender division of labour, the desire for self-sufficiency, the presence of multiple soil types, production systems that correspond to various stages in a land-use cycle and distinct transport costs, depending on the location of the crop or pasture. Below we use the transport-cost argument to explain the coexistence of intensive and extensive farming systems, although we could have used some of the other factors.

Figure 2.2 illustrates the land rents of the two production systems, again inspired by von Thünen. Our farmer will locate the intensive system closer to the centre (village) and the extensive system between the intensive system and the forest.[8]

We can now distinguish between the intensive (d^i) and extensive (d^e) frontiers. To those interested in conserving natural forests, the extensive frontier is the most relevant. It is worth emphasizing, though, that in real life many extensive systems are based on tree crops and provide some of the same environmental services as natural forests.

As long as we have perfect markets, technological change in the intensive sector will not affect the extensive frontier. Farmers treat the two systems as separate activities and make their decisions about how to maximize their profits in each system without taking into account the other system. Perfect markets imply that the two systems do not compete with each other for inputs. Farmers use each input up to the point where marginal revenues equal marginal cost. In the case of the extensive sector, the results from section 3.1 directly apply. Technological change will promote deforestation.

More interesting results emerge when farmers face constraints and have to allocate a fixed amount of labour and/or capital between the two systems. Consider first technological change within the extensive production system.

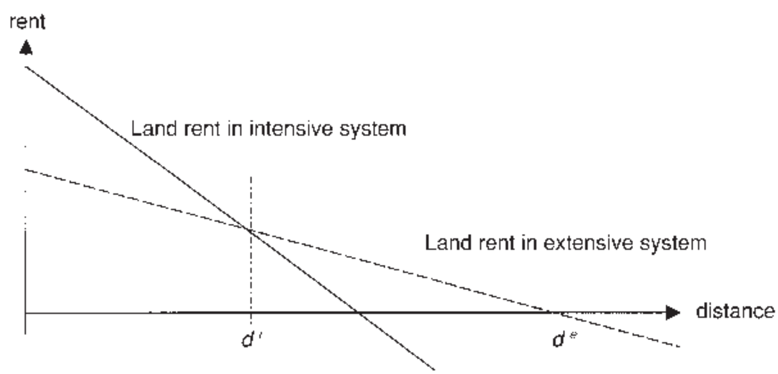

Fig. 2.2. Intensive and extensive frontiers.

Capital- and labour-saving technological change will still increase demand for land, thus spurring deforestation. But the effect will be even stronger because farmers can shift labour and capital from intensive to extensive cultivation. The fact that farmers can shift resources between the intensive and extensive systems implies that labour- or capital-neutral technological progress will also encourage deforestation. Capital- and/or labour-intensive technological changes have ambiguous effect, but – unlike in the case of one production system – they may lead to more deforestation. The net effect depends on the initial size of the two sectors, the difference in capital and/or labour requirements and the increase in capital and/or labour requirements following the technological change.

As long as farmers are resource-constrained, labour (or capital)-intensive or neutral technological progress in the intensive system will contract the extensive frontier. Farmers will divert their scarce labour and capital away from the extensive system and into the intensive system. Labour (or capital)-saving technological progress has two contradictory effects on the extensive frontier. It will shift resources to the intensive sector, but it also frees labour. In one analytical model, assessed by Angelsen (1999b), the first effect always dominates. Labour-saving technological progress in the intensive sector reduces the overall demand for land. To what extent one can generalize these results, however, remains uncertain.

If one takes into account the dynamic interactions between the two sectors, one can obtain rather different results. Technological progress in the intensive sector can serve as a source of capital that farmers use to expand the extensive sector. In other words, increased profits in intensive agriculture can relax the capital constraint and allow farmers to invest more in activities involving forest clearing (see Ruf, Chapter 16, this volume).

Including these dynamic interactions also leads to ambiguous results with regard to the impact of off-farm income opportunities. In the unconstrained world, off-farm opportunities increase the opportunity cost of labour. That makes land expansion more expensive and causes the agricultural frontier to contract. But farmers can also use increased wage earnings to invest more in hiring labour to clear forest, purchasing more cattle and similar activities (see Vosti *et al.*, Chapter 7, this volume).

At least four important lessons emerge from this brief discussion. First, the effect of technological progress on deforestation greatly depends on which agricultural subsector the technological progress occurs in. Secondly, if farmers can switch between different systems, technological change will affect overall land demand much more than in situations with only one production system. Thirdly, in multiple production-system contexts, even labour- and/or capital-intensive technological progress in the extensive system may lead to more deforestation, because of the opportunity to shift resources to the frontier. Fourthly, dynamic investment effects resulting from higher farm income due to technological change in any system (or due to off-farm income increases) can increase the pressure on forests.

4. Macroanalysis: General Equilibrium Effects

The previous section focused on the individual household's response to changes in technological parameters and prices. However, technological progress is unlikely to involve only one household. And, if a large number of households adopt the new technologies, this will have economic repercussions beyond those envisioned in section 3. These macroeconomic effects can either diminish or enlarge the microeconomic impact discussed in section 3. We can identify two major types of macroeconomic effects. The first operates through changes in the number of households living in the forest area – i.e. through migration to or from the extensive margin. The second works via changes in prices.

4.1. Migration

The impact of technological progress on deforestation depends on the number of agricultural households at the extensive margin, since that will determine to what extent aggregate labour supply constrains agricultural expansion. Typically, people compare the level of well-being that they can expect in different regions and choose to live where they will do best. To analyse this type of decision, we assume there are two regions, uplands and lowlands, and that the expected per capita income in each region declines as the number of people in the region rises.[9] People will migrate from one region to another until each region has the same level of per capita income, as illustrated by point L_1 in Fig. 2.3. The length of the box is total population.[10]

Technologies influence the location of the curves. Consider first a technology that only functions in so-called traditional lowland agricultural

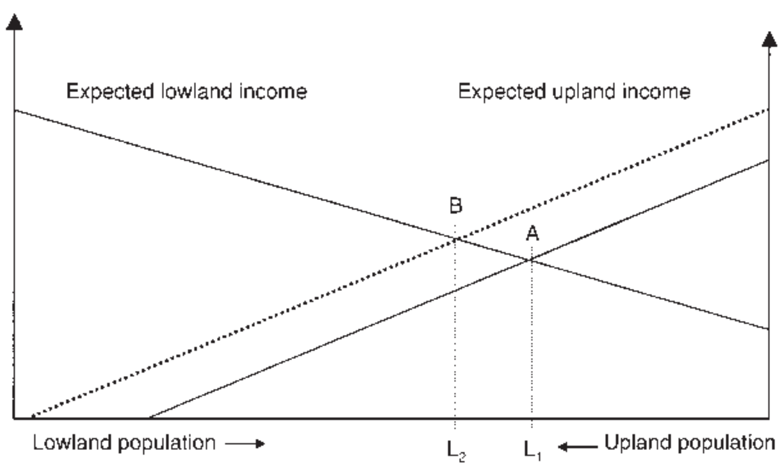

Fig. 2.3. Migration between lowland and upland.

areas, and not at the extensive margin in the uplands, where the forests are. The technology may only apply to the lowlands because it can only be used in certain types of soils or requires good access to markets or other institutions, or for some similar reason. Introducing a technology like this shifts the lowland income curve upward, thus reducing upland population and deforestation. Creating attractive economic opportunities outside the uplands, either in agriculture or elsewhere, is therefore an important tool for securing forest conservation.

Now consider a technological change that applies to upland regions, but not elsewhere. The dotted line in Fig. 2.3, where L_2 is the new equilibrium, reflects this. Since the technological change makes upland agriculture more attractive, compared with activities in the lowlands, people migrate to the uplands (from L_1 to L_2). Possible reasons why the change may occur only in the uplands are that the cultivation of the crop enjoys a forest rent or that the region has specialized in certain crops due to its comparative advantage.

To determine the aggregate effect of technological change on deforestation, we can multiply the per-household effect (section 3) by the number of households living at the margin. Once one takes into account the potential of technological change to attract additional households to the forest margins, the risk that technological changes can increase deforestation generally increases substantially.

The shape of the two curves in Fig. 2.3 strongly influences the magnitude of the impact of technological change. The level of lowland incomes directly determines upland labour supply, so the lowland income curve and the upland labour supply curve are the same thing. If the curve is flat (i.e. upland labour supply is elastic), new upland technologies will have large effects and many potential migrants will move to the forest in response to the new economic opportunities. Similarly, we can consider the upland income curve to be the labour demand curve. A flat curve implies that the uplands can absorb a lot of migrants without exhausting the economic opportunities – in part, perhaps, because forests are abundant. Thus, when both curves are flat (migration keeps labour constraints from emerging and forests abound), the conditions are ideal for technological change in the uplands to provoke massive forest clearing. The commodity booms discussed in this book by Wunder (Chapter 10) and Ruf (Chapter 16) provide good examples of such situations.

4.2. Endogenous prices

The second main macroeconomic feedback mechanism operates via price changes. These include both output and input prices (including wages, although the previous section indirectly dealt with wage changes). If innovations substantially increase the supply of agricultural output (and possibly greatly increase the demand for labour), output prices may go down while wages and other input prices may rise.

We can decompose the price effect into two elements: (i) how sensitive market prices are to changes in supply (the demand elasticity); and (ii) how much supply increases in relation to the size of the market. The relative increase in production in the region affected by the technological change and the region's market share determine the latter.

Based on this, we can distinguish between agricultural outputs destined mostly for domestic markets, such as subsistence food crops, e.g. maize and cassava, and products sold in international markets, such as banana, rubber, coffee and cocoa. With respect to the latter, in many cases, no matter how much technological change increases yields in a country, the aggregate effect will not be large enough to influence world prices. Although there are exceptions, most individual countries face a horizontal demand curve for export crops. Hence, the assumption of fixed prices for agricultural crops, underlying the micromodels in section 3, still largely holds when it comes to export crops. However, substantial increases in the supply of crops produced for the domestic market will exert strong downward pressure on prices, since the demand curve in these cases can be quite steep (in other words, demand is inelastic).

Depending on whether the increase in agricultural productivity outweighs the price decline induced by the rise in aggregate supply, revenues may go up or down in the individual households. If technological progress affects crops whose price is not very sensitive to changes in supply (as is the case for most export crops), the increase in productivity will generally exceed the price decrease, so agricultural activities will expand at the expense of forests. On the other hand, if agricultural prices are quite sensitive to changes in supply, the price decrease may outweigh the productivity increase. The literature refers to this latter situation as a treadmill. The more farmers produce, the less they earn, and hence the less incentive they have to clear additional forest (at least as long as the income effect is not dominant (see section 3.2)).

Technological progress may be region-specific, benefiting some producers but not others. If agricultural productivity rises outside the forest region and farmers both in and out of the forest region produce the same crop and sell it in the same market, which has downward-sloping demand, deforestation should decrease. Frontier farmers will receive lower prices, even though they did not benefit from the innovation, which makes them worse off. This will induce households to move away from the frontier and, as long as they face perfect markets, households will produce less than they otherwise would. Households in imperfect market situations may produce more or less, depending on the magnitude of the income and substitution effects.

Thus far, we have ignored the role of factor prices. Given that developing-country agriculture tends to be rather labour-intensive, wages may play an important role. As long as the labour supply is not perfectly elastic (for example, because the labour force is fixed), increasing the demand for labour will bid up wages. Thus, if technological progress generates additional employment, wages will go up and this may discourage forest clearing. In alternative specifications, land and labour can be substitutes. If the price of labour increases, farmers may use more land instead of labour, which implies greater deforestation.

5. Conclusions

In this chapter, we have discussed how economic theory predicts that technological change will affect deforestation. We conclude that the impact will depend on: (i) the type of technical change; (ii) the presence of market imperfections; (iii) the extent to which farmers can substitute between factors; (iv) the way households balance work against leisure; (v) whether the technology affects the intensive or extensive production systems; (vi) how much people migrate in response to regional income differentials; and (vii) how steep the demand and supply curves for outputs and inputs are. Dynamic wealth effects may play a role if innovations allow farmers to accumulate resources that they then use to finance investments in activities associated with forest conversion.

Taking all this into account, we would like to stress two central results and mention one caveat.

First, if both the input and output markets are well developed and ‘perfect’, we can expect technological progress to promote deforestation. However, high transaction costs at the forest frontier may limit farmers’ access to certain markets. Without well-functioning labour and capital markets, technological change will have ambiguous effects, depending on whether it relaxes binding constraints or makes them bind even tighter. If farmers have several production systems and can divert inputs from one to another as their relative profitability changes, this may magnify the micro-level effects.

Secondly, if technological change affects the production possibilities of many farmers, general equilibrium effects arise. In general, the price effects tend to ‘dampen’ the micro-level effects. For example, if supply increases as a result of new technologies, this may depress prices and effectively counteract the initial incentive to deforest. For the migration effects, however, it matters a great deal whether the innovations perform better on the forest frontier or in traditional agricultural areas, since a greater impact in one of the two areas may trigger migration to or from the frontier.

Finally, it is worth pointing out that all of the previous discussion largely ignored the complex relation between technological change, land degradation and deforestation. Households at the extensive margin often deplete their soils and then move on and deforest a new parcel. Technologies that reduce land degradation reduce the incentive to ‘cut, crop and run’, thereby lessening the pressure on natural forests. On the other hand, sedentary agriculture generally retains fewer characteristics of natural ecosystems than fallow systems or extensive agricultural land uses. In addition, for all the reasons discussed in section 3, any technology that increases profits can potentially result in greater land clearing. This further illustrates the complexity of the relation between technological progress in agriculture and forest conservation, and the difficulty of reaching unambiguous general conclusions.

Notes

1 This chapter is based on two papers presented at the Costa Rica workshop: Angelsen, A., Kaimowitz, D., Holden, S., Smith, J. and Vosti, S., Technological change in agriculture and tropical deforestation: definitions, theories and hypotheses; and Bulte, E., van Soest, D. and van Kooten, G.C., Opening Pandora's box? Technological change and tropical deforestation. We would like to thank our co-authors for their inputs in the process of writing the present chapter.

2 Initially, we made a distinction between the concepts of 'technological progress' and 'technological change', the latter being broader. Since these terms are used more or less interchangeably in the debate, we have not maintained the distinction in this book, except that technological change also includes technological progress in reverse (technological regress). The same goes for the terms 'technological' and 'technical', although we prefer the former.

3 Note that we have defined the inputs L, H and K such that exactly one unit is required to produce an output Y.

4 Some people use the term 'land-intensive' interchangeably with 'land-saving' or 'yield-increasing'. It is, however, by no means self-evident whether land-intensive means that farmers use a lot of land per unit of labour and capital (also referred to in the literature as extensive land use) or the opposite.

5 One could argue that agricultural intensification should be defined in terms of output per unit of the scarce factor. Since labour is often the scarce factor at the forest frontier, a third option would be to divide through by labour in equation (1), and focus on labour productivity (output per worker) and the land and capital requirements per worker.

6 To measure input intensity with more than one input, we need a common yardstick, normally a monetary unit. This raises several issues. Should we use farm-gate or social prices? What prices should we use to value non-market output and inputs? Are the relevant prices those that existed before the technological change or after?

7 A 'perfect' market implies that farmers can take prices as given, can buy or sell as much as they want at that price and have perfect information, and that the input or output involved is homogeneous, e.g. family and hired labour are perfect substitutes.

8 This model and the corresponding results are taken from Angelsen (1999b). See also Randall and Castle (1985) for a more general treatment of the von Thünen model with two production systems.

9 The latter assumption may be realistic for agriculture, but is unlikely to hold for urban areas, because most industrial activities exhibit increasing returns to scale (see Murphy *et al.*, 1989).

10 This analysis makes a few simplifying assumptions. There are no migration costs. Marginal income equals average income. No one is unemployed, nor do they prefer to live in a particular region for non-monetary reasons. The figure is a simplified version of the Harris–Todaro migration model (e.g. Stark, 1991).

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