Economic Models of Tropical Deforestation A Review

David Kaimowitz and Arild Angelsen

CIFOR
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Cover: Deforestation in Bungo Tebo district, Jambi, Sumatra
(photo: Carmen Garcia)

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Section One

Introduction

1.1 A Boom in Deforestation Modelling

Policy makers, scientists and the public are increasingly concerned about tropical deforestation and its negative consequences such as climate change, biodiversity loss, reduced timber supply, flooding, siltation, and soil degradation. This has led economists to greatly expand their efforts to model the questions of why, where, when and how much forest is converted to other land uses. This is reflected in the fact that over 90 per cent of the economic deforestation models currently available have been produced since 1990.

The quantitative models that have emerged provide insights that can improve policy formulation, but they have strong assumptions and data limitations. This paper synthesises the results of some 150 deforestation models. It describes their assumptions, methodologies, data and main results, and assesses their strengths and weaknesses. It also identifies promising areas for future research.

The models that concern us use mathematical equations to represent key social processes associated with deforestation. We focus mainly on models that describe how landholders behave and why, and the linkages between their decisions and the rest of the economy. To keep the paper's scope within manageable bounds, we largely ignore normative models concerned with how much forest clearing is socially optimal.[1] We also exclude models with no explicit economic or social underpinnings, such as Markov chain and logistic function models. As social scientists, we are sceptical of such 'fatalistic' models, which allow little room for individual choice.

Our focus on deforestation also implies that we do not discuss forestry models designed to analyse optimal rotation length and management intensity. Hence issues related to sustainable forest management beyond the question of forest cover change are only dealt with superficially. Further, we are not reviewing models concerned with the factors that promote reforestation or secondary forest regrowth.[2]

Like all social science models, the models we discuss simplify complex multidimensional processes, and highlight only a few of the many variables and causal relations involved in land-use change. Nevertheless, they help us explore possible effects of policy or other exogenous changes on land use, allow us to think about deforestation more systematically, and clarify the implications of different assumptions, which may not be obvious, about how the economy operates. Some models also give information about the magnitude and location of the processes involved in deforestation and policies' quantitative effects.

As Lambin (1997) has recently noted, no one research approach can hope to elucidate the full range of social processes affecting land use. The methodologies used in each instance must be tailored to the research questions of interest. To obtain a more comprehensive view of deforestation processes, there will always be 'a need for a synthesis of the results gathered from a variety of investigation methods' (Lambin 1997: 1).

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[1] The socially optimal level of deforestation is hard to determine due to the difficulties in estimating the benefits of forests to different groups (Pearce 1994). Moreover, models that seek to determine the social optimum often have limited practical relevance to explain *why* deforestation occurs as they assume that decision makers' objectives are to maximise social welfare, a strong assumption indeed. In spite of this, many authors use social optimisation models for explanatory purposes, a practice of which we are critical.

Models that seek to determine socially optimal forest stocks or deforestation rates include Hassan and Hertzler (1988), Ehui and Hertel (1989), Ehui *et al*. (1990), Rodriguez (1991), Barbier and Rauscher (1994), Strand (1996), Bulte and van Soest (1996a), Lensink and van Soest (1996), van Soest and Jepma (1996), Barbier and Burgess (1997) and van Soest (1998).

Ruben (personal communication, 1997) notes that optimal control models could be useful to explore the conflicts in objectives between farmers, loggers and the state.

[2] Hyde and Newman (1991) reviews traditional forestry models focusing on permanent logging operations.

This guide's exclusive emphasis on quantitative models in no way implies we believe such models to be more useful or accurate than qualitative analyses or studies based solely on descriptive statistics. In Section 7, we argue that all three types of studies are needed and can complement each other. This also implies that this review fails to incorporate many relevant insights from the quantitative literature that have yet to be formally modelled.

Lambin (1994, 1997) and Brown and Pearce (1994) have previously reviewed deforestation models, but do not cover the same ground as this study. Lambin devotes much attention to qualitative models and models that lack explicit economic foundations, while Brown and Pearce look only at regression models, and is more of a collection than a synthesis. Other works that have useful reviews of subsets of the literature include Dore *et al.* (1996), Vosti *et al.* (1996), Xie *et al.* (1996) and van Soest (1998).

1.2 'Deforestation'

In most instances, we use the term deforestation to describe situations of complete long-term removal of tree cover. In a few cases, we also address issues related to biomass loss, shortened fallow length and other types of forest degradation. The models we review vary with regards to the precise definition of forest used, if indeed they provide any definition at all. In particular, most do not explicitly state whether they consider long fallows/secondary forest to be 'forest'.

Unlike many studies on tropical deforestation, we do not assume that selective logging, as typically practised in the tropics, directly deforests large areas. Nevertheless, it does require a limited amount of forest to be cleared for logging roads and installations, and often facilitates subsequent conversion of forest to agricultural land by farmers.

Even though the models we review were largely created in response to public apprehension over excessive deforestation, we ourselves do not believe all tropical deforestation to be inappropriate in the sense that the social costs are higher than the benefits. This will in particular be true when considering local and national-level benefits and costs of deforestation. Many significant costs are, however, at the global level, related to carbon release and biodiversity loss. Including these would probably make most deforestation undesirable but, without any mechanisms for compensating tropical forest countries, issues of global income distribution arise in addition to the question of economic efficiency.

We do believe that current policies often lead to inappropriate deforestation, since the people who clear forest do not have to pay for the negative externalities associated with their actions, even at the local or national levels. We also feel that, regardless of the decisions they ultimately make, policy makers should at least be aware of the potential impact of their policies on forest cover.

1.3 Outline of the Review

This review first offers a framework for analysing deforestation and a set of typologies of economic deforestation models relevant for different levels of aggregation (Section 2). Section 3 looks at household or firm-level analytical and empirical models. Section 4 discusses regional models, which are either spatial or non-spatial, and either regression or simulation models. Section 5 reviews national and macro-level models, including general equilibrium, global regression and trade and commodity models. For each type of model discussed in Sections 3, 4 and 5, we analyse its variables, hypotheses, assumptions, data, methodology, results, strengths and limitations. Section 6 summarises our major conclusions about the different factors driving deforestation. The final section gives recommendations for future research.

We hope policy analysts who use models to inform their decisions, as well as model makers, will find this guide useful. Policy analysts will probably be most interested in Section 2, which provides a conceptual framework for analysing deforestation, and the synthesis of the models' conclusions (Section 6); those sections can be read as stand-alone pieces. These readers may also find it useful, however, to skim through the rest of the text, to get a feeling for the main assumptions and limitations of currently available models. They may also want to look at a paper that summarises the main conclusions of this review.[3]

Global literature reviews, such as this one, inevitably emphasise the similarities between different countries and regions, rather than their differences. Readers should be aware, however, that the factors affecting deforestation, the interactions between them, and the magnitude of their effects all vary significantly from one location to another. Models based on data from distinct locations can reach conflicting conclusions not only because they use different definitions, variables or methodologies but also because the processes they seek to explain are themselves fundamentally different.

In this context, it is worth noting that a large proportion of the (non-global) models currently available focus on only a handful of countries: Brazil, Cameroon, Costa Rica, Indonesia, Mexico, Thailand and, to a lesser extent, Ecuador, the Philippines and Tanzania. Most of these are medium or large, politically fairly stable, countries that have large areas of tropical rainforest. Since much less modelling work has been conducted in drier countries, forest-

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[3] Arild Angelsen and David Kaimowitz. 1997. What can we learn from economic models of deforestation? Seminar paper, Center for International Forestry Research, Bogor.

poor countries, and countries involved in military conflicts, one must use great caution when extrapolating the results presented here to those locations. Appendix 2 provides a list of the models we have identified currently available for each country.

1.4 Some Major Conclusions

The review concludes that deforestation tends to be greater when: forested lands are more accessible; agricultural and timber prices are higher; rural wages are lower; and there are more opportunities for long distance trade. Population and migration both affect deforestation rates, but in a complex fashion that cannot simply be reduced to saying population growth promotes deforestation. Major doubts remain regarding the relationships between deforestation and productivity growth, input prices, land markets, land and forest tenure security, and household income (poverty) that can only be resolved through future research.

Generally, it is hard to find any clear-cut relationship between macroeconomic variables and policies and deforestation. A significant finding of this review is, however, that a number of the policy reforms included in current economic liberalisation and adjustment efforts may increase pressure on forests.

The paper recommends some major shifts in future research. That research will probably be more productive if it concentrates on household and regional-level studies, instead of national and global studies. The review criticises multi-country regression models, which we believe are of limited value due to the very poor forest data quality they use, among other things. National studies such as general equilibrium models are useful when they take into account regional diversity, distinguish between subsectors of agriculture, and modify conventional perfect competition assumptions. More attention should be paid to institutional issues and modelling of large-scale farmers/ranchers and logging companies.

Section Two

Types of Economic Deforestation Models

This paper covers analytical and empirical models and simulations. Analytical models are abstract, theoretical constructs. They include no empirical data, but they present theories in a rigorous framework, which allows researchers to determine the logical implications of their assumptions. They use formal mathematical equations, but these equations have only algebraic expressions, and no numbers. Empirical models quantify the relationships between variables, using empirical data and statistical methods, while simulation models use parameters based on stylised facts drawn from various sources to assess scenarios and the impact of policy changes (Lambin 1994).

Models vary with regard to their temporal nature, i.e., they can be more or less static or dynamic, and can have different time horizons. Most models reviewed here are essentially static. The analytical models generally include multi-period income and expense streams, but are not path dependent and assume that all variables adjust instantaneously. The empirical models use mostly cross-sectional or panel data, which are treated as if time did not matter. Simulation models, however, tend to be more dynamic; and there is growing interest among economists in building dynamic recursive simulation models that use the values of the endogenous variables in each period (and some exogenous trends such as population growth) as inputs into the model in the following period.

Models also have different objectives. Some seek mostly to explain the causes of past deforestation. Others have been designed to predict where, when, or how much deforestation will occur in the future. Another common objective is to assess, *a priori*, how policy interventions will influence deforestation. To a certain extent, these objectives overlap, but distinct methods and variables are more effective at achieving particular objectives (Lambin 1997).

2.1 Conceptual Framework

We have found the following conceptual framework useful both to understand the processes of deforestation and to classify modelling approaches. The variables in economic deforestation models can be divided into five types:

- *Magnitude and location of deforestation:* This is the main dependent variable.
- *Agents of deforestation:* This refers to the individuals or companies involved in land-use change and their characteristics. Some deforestation models consider the number of agents to be endogenous (migration) but almost all assume their characteristics are exogenous.
- *Choice variables:* These are activities about which the agents make decisions. By definition, they are endogenous. For any particular agent or group of agents, decisions with respect to choice variables determine the amount of forest cleared.
- *Agents' decision parameters:* These variables directly influence agents' decisions with respect to the choice variables, but are external to individual agents. Most models regard these variables as exogenous, except for general equilibrium models, which treat prices as endogenous macro-level variables and explicitly model the markets that determine them.
- *Macro-level variables and policy instruments:* These variables affect forest clearing through their influence on decision parameters, but do not affect agents' decisions directly. In most models they are exogenous.

Box 1 lists the main categories of variables that fall under each of these five types, while Appendix 1 includes a full list of the different variables that have been used in these models, organised by category and type.

Box 1: Variables Analysed in Deforestation Models

Magnitude and Location of Deforestation

Characteristics of deforestation agents

- Initial population
- Objectives and preferences
- Initial resource endowments and knowledge
- Cultural attributes

Choice variables

- Land allocation
- Labour allocation and migration
- Capital allocation
- Consumption
- Other technological and management decisions

Agents' decision parameters

- Output prices
- Labour costs
- Other factor (input) prices
- Accessibility
- Available technology and information
- Risk
- Property regimes
- Government restrictions
- Other constraints on factor use
- Environmental factors (physical)

Macro-level variables and policy instruments

- Demographics
- Government policies
- World market prices
- Asset distribution
- Macroeconomic trends
- Technology

Figure 1 illustrates the relationships between the main types of variables, and provides a simple logical approach to analysing deforestation. The starting point of that approach is to identify the agents of deforestation (small farmers, ranchers, plantations, loggers, etc.) and their relative importance in forest clearing. These agents' actions are the *direct sources* of deforestation. Theoretically at least, the magnitude of their effects can be directly measured – although it may be difficult to do so (see, for example, Sunderlin and Resosudarmo 1996) – and no economic analysis, *per se*, is required.[4]

The combination of variables at the second and third level illustrates the agents' decision problem. Agents make decisions about choice variables based on their own characteristics and exogenous decision parameters. Together these determine the set of permissible choices and constitute the *immediate causes* of deforestation.

Finally, broader economic, political, cultural, demographic, and technological forces determine the agents' characteristics and decision parameters. These factors can be thought of as the *underlying causes* of deforestation.[5]

In other words, we distinguish between explanations of deforestation at three different levels: sources, immediate causes and underlying causes. In contrast, most existing literature – when it makes any distinction at all – normally only distinguishes between two levels. Typically, it refers to 'sources' of deforestation as first-level, direct or proximate causes, and merges the 'immediate' and 'underlying' causes, labelling them second-level, indirect, ultimate or underlying causes or driving forces of deforestation.

We consider a distinction between immediate and underlying causes useful and necessary for several reasons. First, it helps to single out the parameters that are directly relevant to decision-makers. Secondly, methodologically, micro-level models handle the immediate causes better, whereas macro-level models focus more on underlying causes. Thirdly, since the underlying causes determine the decision parameters, mixing these two levels flaws the cause-effect relationship, and creates serious problems in regression models. Finally, one obtains much more conclusive results for the immediate causes than the underlying causes.

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[4] As a practical matter, the interaction between different types of agents frequently makes it difficult to separate their impacts and determine their relative importance. Often, ranchers and loggers facilitate small farmers' entrance into forested areas, farmers engage in logging to finance agricultural expansion, and ranchers follow small farmers into agricultural frontier areas.

[5] For the sake of simplicity, Figure 1 and our discussion imply the causal relations go in only one direction. However, important feedback effects in the opposite direction also exist.

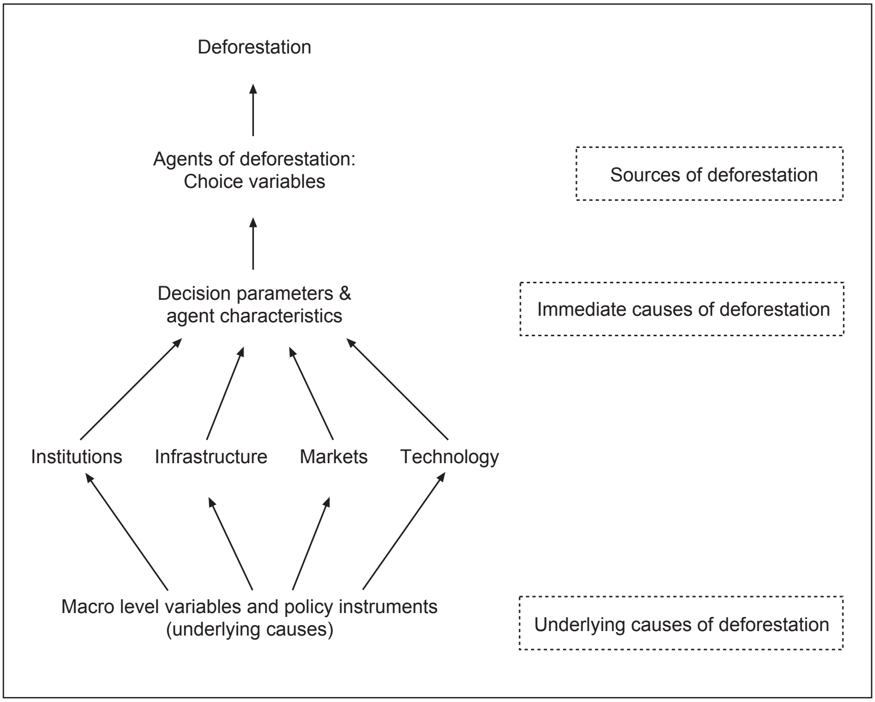

Figure 1. A framework of different types of variables affecting deforestation

2.2 Scale

The above framework and typology of variables are closely linked to the issue of scale, or the size of the unit of analysis under study. Analysis at different scales allows us to answer distinct questions. To obtain a full picture requires an approach that employs a nested set of scales (Vosti *et al.* 1996). ‘At broad scales, the high level of aggregation of data obscures the variability of situations and relationships, and produces meaningless averages’ (Lambin 1994: 15). However, at lower scales it may be impossible to fully capture processes occurring at higher levels of aggregation, which are greater than the sum of their parts. Common scales used in the models include individual households, farms or firms, small land areas (less than one square kilometre), regions, countries and the world.

Depending on the scale, different variables are likely to be considered endogenous or exogenous. At the level of the individual producer, agents generally choose how to allocate their resources in the context of exogenously determined prices, initial resources and preferences, policies, institutions and technological alternatives. The first group of models reviewed in this paper, that is, household and firm-level models (Section 3), focuses on this level and emphasise how agents' characteristics and decision parameters determine decisions regarding choice variables.

The only models at the individual producer level that do not assume all prices to be exogenous are the Chayanovian and subsistence models. These models view farm households as making trade-offs between consumption and leisure, and/or as uninterested in consuming more than a predetermined quantity of goods. This leads them to make decisions based on their own subjective (and endogenously determined) shadow prices, which are at least partially determined by their preferences, rather than market prices.

Most models at the small-area level emphasise variables for which georeferenced data are available, such as climate, topography, soil quality, natural vegetation, access to roads and markets, land ownership, restrictions on land use, and population. Many recognise that population, roads and market locations are partially endogenous, and seek to control for that. Spatial regression models are the most common type of empirical model at this scale, although linear programming and simulation models have been used.

The next relevant scale is the region or '*terroir*'. This is an area which has a distinct characteristic ecology, agrarian structure, political history, local institutions, established trade networks, pattern of settlement, infrastructure and land use (Lambin 1994: 16). At this level, some prices, institutions, demographic trends, and technological changes are endogenous, others not. Macroeconomic variables, national policies and international prices are largely exogenous. Due to data limitations, most regional empirical models use counties, provinces or states as proxies for regions. Few analytical models focus on this scale, and empirical models tend to use regression analysis, although there are a few regional Computable General Equilibrium (CGE) models, and interest in building such models is increasing rapidly.

Section 4 of this paper, 'regional-level models', covers both the small area and regional scales and concentrates on how variations in meso-level decision parameters (markets, infrastructure, institutions, technology) influence deforestation rates. Most models that explicitly incorporate the *spatial* dimension of deforestation are discussed in that section.

Models at the national and global scales (covered in Section 5) emphasise the relationships between underlying variables, decision parameters and deforestation. National and global regression models establish statistical correlations between deforestation and (exogenous) population variables, national policies, macroeconomic trends, prices, institutions and technology. Computable General Equilibrium (CGE) models and international trade models, on the other hand, make certain prices endogenous and show how macroeconomic policy changes affect prices and ultimately deforestation agents' behaviour. As shown in Figure 1, the links between underlying variables, decision parameters, and choice variables work through markets, institutions, infrastructure and technology, but CGE and international trade models confine themselves to market linkages.

2.3 Modelling Categories

Based on the above discussion, we have classified the models and organised the review based on two criteria: (i) *scale*: household/firm, regional (subnational), national; and (ii) *methodology:* analytical, simulation (including programming), and regression models. Table 1 gives the distribution of the models analysed based on these criteria.

Table 1: Number of economic models of deforestation in different categories.

	Analytical	**Simulation (including programming)**	**Regression**	**Total**
Household and firm level (micro)	15	9	9	33
Regional level (meso)	0	3	30	33
National level (macro)	19*	23	38	80
Total	34	35	77	146

* This figure includes an impressive 14 papers by the same authors (Jones and O'Neill), most of which have a similar methodological framework, but each has its own distinct features and addresses different issues.

The table also gives an indication of where the research efforts have focused so far. Models at the national level dominate, and regression analysis is by far the most common methodological approach. These figures should, however, be treated with some caution. First, in one way it would be more correct to say that we have reviewed some 150 papers (articles, reports and books) containing economic models rather than 150 models, as some papers have more than one model, and some models have more than one paper! We have tried to avoid double counting when making the table, but there is a problem in defining 'how different should a model be to be counted as a separate model'. Secondly, the research efforts behind the models vary greatly, for example, behind some of the empirical household models may be several years of fieldwork.

Section Three

Household and Firm-level Models

3.1 Analytical Open Economy Models

Small, open economy models assume all relevant prices are exogenous. The term indicates that deforestation agents behave as if their actions have no impact on prices (they are small economies in that sense) and that external market prices fully determine how they value their resources and outputs (as implied by ‘openness’). These assumptions may be unrealistic, but they greatly simplify the analysis and allow model makers to focus on some key aspects of behaviour associated with forest clearing.

Variables and assumptions

These models apply the conventional – and powerful – tool of constrained maximisation. Households and firms maximise an objective function – usually (discounted) profit – subject to constraints given by exogenous prices, institutions, infrastructure and technology.

Assuming all relevant prices are exogenous is analytically convenient, but carries strong implications, including the existence of a perfect labour market where individuals can always find employment at an exogenously determined wage rate. This, in turn, implies the level of population is endogenous, since labour must be allowed to move freely between the farm and off-farm sectors (migrate) to ensure labour supply and demand converge at the predetermined wage rate.

Once one assumes households maximise utility and markets are perfect, production decisions can be separated from consumption decisions (but not vice versa). This allows decisions about production, including land use, to be analysed as profit maximisation problems, even though the overall household goal is to maximise utility (Singh *et al.* 1986).

Profits come from production and, in some cases, land rents, and may include only current financial profits or may also take into account risk, time preferences and multiple period income and expenditure streams. Climatic and market fluctuations, weeds, pests, and diseases, land tenure insecurity, encroachment of logging concessions by farmers, political instability and violence can all cause risk.

Depending on the model, endogenous choice variables may include:

- cultivated area (Angelsen 1996);
- product mix (Bluffstone 1995; DeShazo and DeShazo 1995);
- fallow and cropping length (Angelsen 1994);
- location and timing of logging (Mæstad 1995);
- investment in land titles (Mendelsohn 1994);
- the decision whether to sustainably manage logged-over forests and exclude farmers (Walker 1987; Walker and Smith 1993);
- migration (Angelsen 1996);
- labour allocation to various activities (Southgate 1990);
- intensity of input use (DeShazo and DeShazo 1995);
- propensity to save (Mateo 1997); and
- the decision whether to collect fuelwood or purchase alternative fuel products (Bluffstone 1995).

Costs can include land, family and hired labour, transportation costs (both to markets and to farmers' fields), fixed and variable capital, and taxes. When transportation costs or land quality variations are incorporated, the models become spatial and their results depend on location.

The models present the cost of land in different ways, including land purchase prices or rental rates, land titling costs, the value of labour required to clear additional land or guard against encroachment, and the opportunity costs of keeping land fallow. They may also assume farmers have initial land endowments whose only costs are opportunity costs (Deininger and Minten 1996).[6]

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[6] In Mendelsohn (1994) the amount of land a producer can obtain by investing in land titles is also a function of how many other producers compete for the same land. This partially contradicts the small country assumption and implies land prices are endogenous. Nevertheless, we include this model in this section since it shares most characteristics of the other models discussed.

Land clearing can provide more-secure property rights, as well as current usufruct rights, giving occupants the claim to future land rents (Anderson and Hill 1990; Angelsen 1996). Since land must be cleared to obtain secure property rights, potential landholders have no way to obtain property rights over standing forests, so their decisions do not take into account any possible benefits from the future exploitation of forest products (Southgate 1990).

Methodology

These models apply standard mathematical techniques of optimisation, either classical optimisation (no constraints), Lagrange optimisation (equality constraints) or programming techniques such as Kuhn Tucker programming (inequality constraints). These methods allow model makers to derive the first-order conditions for a maximum, and then apply Cramer's rule to determine how shifts in exogenous parameters affect the endogenous variables. Model makers typically assume there are no economies of scale, objective functions are concave and twice differentiable, production factors have diminishing marginal returns, and interior solutions exist.

The functional forms of the production functions may be Cobb-Douglas (Deininger and Minten 1996), any monotonic function of labour (Southgate 1990; Angelsen 1996), labour and inputs (DeShazo and DeShazo 1995), labour and fallow period (Angelsen 1994), or completely unspecified (Anderson and Hill 1990; Mendelsohn 1994).

Only Walker and Smith (1993), Bulte and van Soest (1996b) and Mateo (1997) have produced dynamic models using methods such as optimal control or dynamic programming. Angelsen (1994) makes assumptions that allow him to make a dynamic model using static methods, while Mæstad (1995) uses a two-period model which captures certain dynamic aspects of logging companies' behaviour.

Bulte and van Soest (1996b) extend standard mining models to determine loggers' optimal depletion time for primary and logged-over forests. The dynamic element of their model comes from the interaction between rising marginal costs of logging (which keep loggers from removing the entire forest in one period) and the growth of timber in logged-over forests. Timber prices and growth rates, and the probability of encroachment in logged-over forests, all influence depletion time.

Walker and Smith (1993) have an optimal stopping model that analyses when logging concessions will decide to breach concession contracts requiring sustainable management and measures that avoid encroachment by farmers, and instead harvest all valuable timber and leave (liquidation harvesting). The authors use the backward induction principle from dynamic programming and a stationary Markov model with a transition matrix to prove this problem has a unique solution, and solve for it. World timber prices, arbitrary government cancellations of concession contracts, and detection of concession contract violations are stochastic, but concession owners know their probability distributions.

Mateo's (1997) optimal control model analyses how ranchers modify their decisions to clear land for pasture over time as their assets accumulate, time preferences change, and erosion degrades their pastures. In each period, ranchers' decisions depend on decisions taken previously.

Model results

The exogenous price assumption, implying a perfect labour market and free migration, makes the relative profitability of frontier farming and logging the main determinant of deforestation in these models. Forest clearing will increase when agricultural prices rise, see Table 2. It will decrease when the cost of land or transportation rises (Southgate 1990; DeShazo and DeShazo 1995; Angelsen 1996). If labour and land, or capital and land, are complements, increases in wage rates or capital costs reduce deforestation.[7] Improved off-farm employment opportunities should have the same result, since they raise the opportunity cost of labour (Angelsen 1996). Technological changes that make agricultural land more valuable as a result of disembodied yield increases, or capital- or labour- saving technologies promote forest clearing (Southgate 1990; DeShazo and DeShazo 1995; Angelsen 1996).

Initial population levels do not affect deforestation in these models since people migrate in response to regional income differences and population size becomes endogenous (Angelsen 1996).

The existence of risk, combined with risk aversion and high discount or interest rates, reduces investment. How this affects forest clearing depends on whether the model assumes land clearing or forest management to be the relevant investment. If the decision is whether to invest in clearing forest to produce crops or livestock over multiple periods, a landowner will invest less (clear less forest) when risk, discount rates or interest rates are high (Angelsen 1996; Southgate 1990).[8] But he/she will also invest less in managing forests (Mendelsohn 1994). It therefore becomes critical to distinguish between the issue of land *management* in areas where forest cover does not

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[7] As there is some confusion about the terminology used, when we refer to two factors as complements or substitutes, we mean that their cross derivative in the production function is positive or negative, respectively.

[8] Following a similar logic, they will also make fewer investments in logging operations. Bulte and van Soest (1996b), for example, show that if farmer encroachment in logged-over areas of forest concessions increases loggers' perceived risks, this will lower the area logged.

Table 2: The effect of selected exogenous variables on deforestation in the analytical open economy household models.

Variable	Effect on deforestation	Comments
Higher agricultural prices	Increases	The effect of a timber price increase depends on tenure security
Lower transport costs	Increases	
Higher input prices	Reduces	If inputs are complements to land
Higher wages	Reduces	If labour is a complement to land
Higher agricultural productivity	Increases	Hicks neutral technical change has the same effect as higher output prices
Higher land prices	Reduces	If no land market exists, the relevant price is the cost of bringing new land into cultivation
Higher discount and/or interest rates	Reduces	Forest clearing is a kind of investment
Higher risk	Reduces	For example, less-secure tenure
Open access to land	Increases	Forest clearing establishes land rights

change from the issue of land *expansion* (forest clearing). Lower discount rates may improve land management in already cleared areas but increase deforestation (Angelsen 1994).

Producers may *not* deforest more under 'pure' open access conditions than when property rights are secure. If forest clearing does not lead to an enforceable claim to land under the open access regime, and the *private* benefits of standing forests are negligible, forest will be cleared up to the same point under both open access and private property (Angelsen 1996).

If, on the other hand, land clearing provides property rights *and* land rents are expected to grow in the future, open access will lead to higher forest clearing than a system with secure property rights or where land is sold to the highest bidder (Anderson and Hill 1990; Angelsen 1996). Under these circumstances, farmers may clear land even though production is unprofitable in the short term if they believe profitability will increase in the future. Moreover, this tendency increases as land tenure security improves (i.e., the probability of losing the land declines) or farmers' discount rates decrease, implying that land titling programmes in agricultural frontier areas may actually promote deforestation (Angelsen 1996).

The length of time farmers leave land fallow decreases as one moves from a situation of full pre-existing private property rights to open access to where land clearing helps establish property rights (Angelsen 1994). Shorter fallows imply less secondary forest and total biomass.

Where producers have secure rights over forest resources, increasing the value of those resources through higher timber prices or improved forestry technologies have mixed effects on land clearing, as both the current and the future values of land increase. Where they do not have such rights, higher timber values only increase the net benefits of land clearing (presuming landholders sell the timber from cleared forest) and hence encourage deforestation (Southgate 1990; Deininger and Minten 1996).

If timber concessions are too large for concessionaires to exploit completely during the concession period, logging companies have no incentive to keep farmers from encroaching on logged-over forest. Such incentives only exist if they expect to log their entire concession and the discounted value of future timber harvests is greater than the cost of managing the forest and avoiding encroachment (Walker 1987). If sustainable forest management generates profits equal to or higher than the opportunity cost of capital, governments can use random inspections for contraction violations to make companies manage their concessions sustainably, as long as the probability of detecting a violation is sufficiently high. Under these circumstances concession duration and the likelihood of sustainable forest management are not related in any simple fashion (Walker and Smith 1993).

Timber trade restrictions and lower timber prices may reduce deforestation by loggers by making logging less profitable (Mæstad 1995). If total logging area over the concession period is fixed, lower prices will shift timber production towards later periods. Thus, at any given moment, the area of unlogged forest will be larger.

Strengths and limitations

These models make explicit the logical implications of different behavioural assumptions, and sometimes produce thought-provoking counter-intuitive results, as illustrated in the discussion about the relationship between tenure security, discount rates and deforestation. How realistic their conclusions are depends largely on the realism of their assumptions. The strongest assumption is that of perfect labour markets, where farmers can sell or purchase any amount of labour at an exogenously determined wage rate, and family labour is completely interchangeable with hired labour. This assumption is unlikely to be valid in most contexts, and even less so in the short run when there is no migration. Nevertheless, labour markets may be more perfect than sometimes believed, and it is useful to compare this extreme case with the opposite extreme, presented below, where labour markets are completely absent. Assuming output prices to be exogenous is more realistic when the products involved are exported or sold on national markets.

As noted previously, the assumption that households interact with perfect labour, capital, land, and product markets, implies that production and consumption decisions are separable.[9] While this simplifies analysis, it also make it impossible to fully discuss important issues such as how poverty and household composition affect resource use, since these aspects do so in part by influencing household preferences.

The models limit their analysis mainly to comparative statics. This points to the direction of effects, but not their magnitude. Furthermore, the models only consider equilibrium situations, implicitly assuming all variables adjust instantly. Finally, model makers can only consider very few (normally not more than two or three) endogenous variables and still produce unambiguous results.

3.2 Analytical Subsistence and Chayanovian Models

Subsistence and Chayanovian models move away from small, open economy models by relaxing the assumptions about perfect markets. In particular, the models have imperfect labour markets in which market wage rates no longer fully determine farm households' allocation of time between labour (consumption) and leisure. Instead, farmers allocate their time based on their subjective preferences, and model makers must take into account the consumption side when analysing household decision making.

Variables and assumptions

In subsistence or 'fully belly' models, the household's objective is to reach a certain subsistence target of consumption with the least possible amount of labour; in Chayanovian models, households trade off consumption and leisure. In extreme versions of the models, no off-farm labour market exists, and population is exogenous. The key distinction between open economy models and subsistence or Chayanovian models is, however, whether or not

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[9] Separability also requires one to assume family and hired labour to be perfect substitutes in the production function (e.g., no supervision costs), and that on and off-farm work provide the same level of utility (e.g., people do not prefer to work on their own farm).

farmers are quantity constrained in the labour market, not the existence of an off-farm labour market, *per se* (Angelsen 1996).

Angelsen (1996) analyses subsistence and Chayanovian models where labour is the only input, technology is exogenous, and fields farther from producers' houses have higher production costs because of the extra time required to walk to them. Per hectare labour intensity can be either exogenous or endogenous.

Labour is also the only input in Dvorak's (1992) subsistence model, and technology is still exogenous, but producers must now decide how long to crop each field and how long to leave each fallow. The amount of time required to clear fields for planting increases at a decreasing rate as the fallow period becomes longer and declines after the first year of cropping. Output per cropped hectare rises with more intensive weeding and longer fallows, and falls when the same area is cropped for longer periods. Labour dedicated to weeding becomes more productive as fallow periods increase.

Deininger and Minten's (1996) model exhibits certain Chayanovian features because family and hired labour are not perfect substitutes, even though it assumes all relevant prices are exogenous. Households allocate their time between wage labour and on-farm activities, but cannot use hired labour on their farm. Whether the model becomes an open economy or a Chayanovian one depends on the initial solution. If the solution implies farmers are net sellers of labour, the not-hiring constraint is not binding, and the model is an open economy one. If the constraint is binding, the model will be Chayanovian.

Model results

For several variables, the results of the subsistence models differ substantially from the open economy models, cf. Table 3. In subsistence models, farmers expand the amount of land they farm until they can produce enough food to meet their subsistence target. If they become more productive or receive higher prices for their produce, they need less land to meet that target and hence clear less forest. If their subsistence requirement increases or farming becomes more risky, they have to clear more land to ensure they reach their subsistence level. With endogenous per hectare labour intensity, the effects are similar, but weaker. Since each producer clears the same amount, the total amount cleared is proportional to the population (Angelsen 1996).[10]

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[10] Strictly speaking, one would expect producers with individual household compositions to have distinctive subsistence requirements, and hence clear different amounts of forest. In relatively large populations, however, these inter-household variations should average out and not affect the size of the total area cleared.

Table 3: The effect of selected explanatory variables on deforestation in open economy, subsistence and Chayanovian models.

Variable	Subsistence model	Chayanovian model	Open economy model
Higher agricultural prices	Reduce	Indeterminate	Increase
Population growth	Increase	Increase	No effect
Lower transport costs	No effect or reduce	Increase	Increase
Higher agricultural productivity	Reduce	Indeterminate	Increase
Higher wages	NA (reduce)	NA (reduce)	Reduce

NA = Not applicable

In Chayanovian models, higher output prices or labour productivity have both an *income* effect (the farmer wants more leisure since his income is higher) and a *substitution* effect (the farmer wants to expand his area since he receives more output for each day worked); in principle, either can dominate. If the income effect is stronger, price increases or productivity improvements reduce forest clearing; if the substitution effect dominates, forest clearing expands as in open economy models.

Angelsen (1996) presents a Chayanovian model with an additive Stone-Geary type utility function with a subsistence level of consumption. Using this functional form implies the income effect is likely to dominate for poor farmers, with a large share of their income from agriculture, and/or with high risk aversion. For those farmers, higher prices or agricultural productivity reduce deforestation, as predicted by the subsistence models, because at the lowest levels of income farmers are willing to give up large amounts of leisure to survive, but quickly revert to more ‘normal’ levels of leisure once they become slightly better off.

Lower transportation costs lead to more cleared forest, since both the income and substitution effects work in the same direction. Population growth leads to a less-than-proportional rise in area cleared, because the opportunity costs of bringing additional land into production rises as farmers have to walk further from their homes to their fields.

In the Deininger and Minten (1996) model, agricultural productivity improvements that affect *only* already cleared land reduce additional deforestation by inducing farmers to devote more time to land already under cultivation.[11] This highlights the fact that the way technological change affects deforestation depends partly on the assumptions made regarding labour markets, and that it is often important to distinguish between technological changes on established agricultural land and at the agricultural frontier.

Strengths and limitations

The subsistence models' key assumption, that households only seek to meet a pre-established consumption target and lose all interest in working once they have reached that goal, seems quite unrealistic. Nevertheless, that assumption underlies many studies and policy recommendations regarding deforestation. These models have the virtue of allowing economists to make the implications of these assumptions explicit and compare the models' predictions with those from models based on other assumptions. Subsistence models may also be empirically relevant in those situations where producers are virtually isolated from markets or where local norms require any production beyond subsistence levels to be shared, which greatly reduces the incentives to produce more.

How model makers expect variables such as population growth and technological change to affect deforestation depends crucially on their assumptions about the labour market. In this respect, the Chayanovian framework presents an intermediate case between the perfect labour markets in the open economy models and the complete absence of labour markets in the subsistence models. This is particularly relevant for analysing short-run situations, where population can be taken to be exogenous, or contexts with thin labour markets. When one introduces off-farm labour markets in Chayanovian models, but farmers are still quantity constrained in that market, the models gradually become more similar to open economy models (Angelsen 1996).

3.3 Empirical and Simulation Models

This section covers farm-level regression, linear and non-linear programming, and other simulation models. There are relatively few of these models, because they require skilled surveyors and time-consuming data collection.

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[11] Similarly, Larson (1991) shows that if forest clearing competes for producers' labour with other output-enhancing activities on land already in production, higher output prices, lower factor prices and technological changes can lead to less forest clearing by inducing farmers to allocate more labour to these other activities.

This also explains why, to date, most models have been produced in the context of thesis or dissertation research (Holden 1991; Bluffstone 1993; DeShazo 1993; Pichón 1993; Monela 1995; Ozório de Almeida and Campari 1995).

Variables and assumptions

We obtained eight farm-level regression models for review in this study (Table 4). Five were from the South American Amazon region, and the others from Honduras, India and Zambia. Jones *et al.* (1995) and Ozório de Almeida and Campari (1995) use data from directed settlements in Brazil, while Pichón (1997) looks at similar settlements in Ecuador. Godoy (1996) and Godoy *et al.* (1996) report findings on indigenous people in Bolivia, while Godoy *et al.* (1997) use data from Honduras. Foster *et al*. (1997) and Holden *et al*. (1997) focus on farmers in India and Northern Zambia, respectively. We also report the findings of a ninth study by Muñoz (1992), about land use on Mexican farms, based on Barbier and Burgess' (1996) description of that study.[12]

The dependent variables in these models include the:

- amount of land deforested since farm establishment (Pichón *et al.* 1994; Jones *et al.* 1995; Ozório de Almeida and Campari 1995);
- amount of forest cleared in the survey year (Holden *et al*. 1997; Ozório de Almeida and Campari 1995);
- amount of *primary* forest cleared in the survey year (Godoy *et al.* 1996, 1997; Godoy 1997);
- average forest area cleared per year (Jones *et al.* 1995);
- change in average forest cover per household in the household's village over a ten year period (Foster *et al*. 1997); and
- percentage of farmland still in forest (Muñoz 1992; Pichón 1997).

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[12] DeShazo and DeShazo (1995) refer to three additional Amazonian regression models (Pérez-Garcia 1991, Ozório de Almeida 1992 and DeShazo 1993) that we were unable to obtain. They mention that the models' independent variables include household size, number of adult males, assets at time of settlement, place of origin and land tenure conditions. Another empirical household model we could not obtain was Hofstad (1996). According to a personal communication from Lykke Andersen (1997), that paper uses data from 250 periurban families near Dar Es Salaam, Tanzania, to analyse the relationship between determinants of charcoal demand and deforestation.

The main explanatory variables are output and input prices, agricultural productivity, transportation costs, farmer characteristics, access to credit, land tenure security and soil quality. In addition to household-level variables, Godoy *et al.* (1996), Foster *et al.* (1997) and Godoy (1997) also take into account village-level variables, such as village size and age, average incomes, agricultural productivity, household size and population density, and the presence of stores, ranchers, factories and logging companies. Table 4 summarises the explanatory variables included in each model.

Table 4: Countries and explanatory variables covered by household level empirical and substitution models.

Model	Country	Type	Main explanatory variables
Angelsen (1996)	Indonesia	Simulation	Output prices, productivity, transport costs, wage rates, land tenure, discount rates
Bluffstone (1993)	Nepal	Simulation	Wage rates, off-farm employment
Foster *et al*. (1997)	India	Regression	Wage rates, household income, productivity, household size, population density, rainfall, land prices
Godoy *et al*. (1997)	Honduras	Regression	Productivity, off-farm employment, farmer characteristics, access to credit, income and wealth
Godoy *et al*. (1996)	Bolivia	Regression	Off-farm employment, land tenure, farmer characteristics, access to credit and information, cattle, transport costs, size and age of village
Godoy (1997)	Bolivia	Regression	Farmer characteristics, discount rates, wealth, income inequality, land tenure
Holden (1991, 1993a,b, 1997)	Zambia	Linear programming	Input prices, productivity, transport costs, population
Holden *et al*. (1997)	Zambia	Regression	Farmer characteristics, distance to grain depots, off-farm income, pig population
Holden and Simanjuntak (1995)	Indonesia	Linear programming	Output and input prices, productivity, transport costs
Jones *et al*. (1995)	Brazil	Regression	Clearing costs, productivity, farm size, soil quality

Table 4 continued

Model	Country	Type	Main explanatory variables
Monela (1995)	Tanzania	Quadratic programming	Output and input prices, population, credit access and risk
Muñoz (1992)	Mexico	Regression	Transport costs, farm size, land tenure, poverty, and climate
Nghiep (1986)	Brazil	Linear programming	Input prices, productivity, land/labour ratio
Ozório de Almeida and Campari (1995)	Brazil	Regression	Input prices, wage rates, access to services, farmer characteristics, savings and indebtedness
Pichón (1997)	Ecuador	Regression	Transport costs, land tenure, cattle, farmer characteristics, access to services, off-farm employment, soil quality
Ruben *et al*. (1994)	Costa Rica	Linear programming	Output and input prices, wage rates
Sankhayan (1996)	Tanzania	Linear programming	Output and input prices
Walker and Smith (1993)	Indonesia	Simulation	Forest concession duration, probability of detecting contract violations

Economists have built linear and non-linear programming models using data from Brazil (Nghiep 1986), Costa Rica (Ruben *et al.* 1994), Indonesia (Holden and Simanjuntak 1995), Tanzania (Monela 1995; Sankhayan 1996) and Zambia (Holden 1991, 1993a,b, 1997) (Table 4). The Brazilian model analyses the conditions under which farmers will convert from shifting cultivation to sedentary production systems that require less forest clearing. The Costa Rican study focuses on the effect of different policy changes on land use. The Indonesian model examines the combination of on- and off-farm activities that will meet migrant farmers' multiple goals. The two Tanzanian cases look at the implications of population growth and policy changes for new land clearing and how price changes associated with structural adjustment affect crop mix and area cropped. The Zambian studies analyse how historical changes in technology, population, and market access have affected the balance between shifting and sedentary cultivation (Holden 1993a) and the viability of agroforestry systems (Holden 1993b), and how structural adjustment policies affect deforestation (Holden 1997).

Each programming model assumes farmers maximise a different objective function. Nghiep (1986) and Ruben *et al.* (1994) assume that to be net income. Holden and Simanjuntak (1995) claim they maximise the present value of profits and attempt to avoid activities other than family farming. Monela's (1995) and Sankhayan's (1996) objective functions include maximising income, minimising risk and trying to stabilise employment fluctuations. Holden (1993a,b) hypothesises that farmers want to meet basic needs, maximise the present value of income, minimise total labour input and avoid risk.

The models' assumptions regarding labour markets and how farmers value leisure also differ. Nghiep (1986), Monela (1995) and Sankhayan (1996) have no labour market and do not discuss leisure. Holden (1993a,b) and Holden and Simanjuntak (1995) assume farmers can sell but not purchase labour, while in Ruben *et al.* (1994) they can do both. In these latter models, farmers explicitly trade off labour (consumption) and leisure, and thus share certain characteristics associated with Chayanovian or subsistence models.

Finally, this section also discusses three simulation models based on analytical models presented previously (Bluffstone 1993; Walker and Smith 1993; Angelsen 1996). The latter two use stylised facts taken from surveys of small farmers and logging concessions respectively in Indonesia, while the first is based on a smallholder survey from Nepal.

Methodology and data

The type of regression technique used in these models depends largely on the characteristics of the dependent variable and the number of interrelated equations economists seek to estimate jointly. Where the dependent variables are expressed as a proportion of total land use, model makers generally use logit analysis (Muñoz 1992). If they are expressed as the number of hectares cleared per year, but many farms clear no forest at all, tobit analysis is often appropriate (Godoy 1997; Holden *et al.* 1997). To estimate several equations simultaneously, Pichón *et al.* (1994) and Jones *et al.* (1995) use simultaneous three-stage least squares regressions and Seemingly Unrelated Regression Equations (SURE), respectively. Foster *et al.* (1997) adopt an approach using instrumental variables and fixed effects to adjust for unaccounted differences between villages and weather effects. This was possible because they used panel data from two periods, not just cross-sectional data. Godoy *et al.* (1996) use several regression techniques (Ordinary Least Squares - OLS, OLS with Huber robust standard errors, median regressions, and censored normal regressions) to ensure their results were not sensitive to the specific techniques used or heteroscedasticity problems. Ozório de Almeida and Campari (1995) work with OLS regressions.

The programming models all share the traditional assumptions of Leontief-type production functions (no substitution between inputs within the same activity and constant returns to scale), but use different techniques to model farmers' multiple goals. Holden (1993a) weighs some goals, considers others fixed constraints, and identifies a third group as soft constraints; Holden and Simanjuntak (1995) use exclusively lexicographic preferences. Monela (1995) and Sankhayan (1996) work with compromise programming, a technique that optimises each goal separately and then seeks to minimise the distance between the optimums.[13]

Information on farmers' initial endowments of labour, land and capital in the programming models comes from survey data. The models allocate those resources to the combination of activities which maximises farmers' objective functions, subject to a detailed set of constraints that include factors such as seasonal labour requirements, land quality, household consumption requirements, and distinctions between cash and in-kind income.

About half the models are static (Nghiep 1986; Muñoz 1992; Pichón *et al.* 1994; Angelsen 1996; Sankhayan 1996) and half dynamic (Holden 1991, 1993b; Bluffstone 1993; Holden and Simanjuntak 1995; Monela 1995). The dynamic models are usually recursive, incorporating values derived from each optimisation into subsequent periods. Bluffstone (1993) also incorporates a biomass growth function. Holden and Simanjuntak (1995) include both changes in family age distributions over time and exogenous new livelihood opportunities. Monela (1995) assumes farmers' consumption requirements increase with population growth. Ozório de Almeida and Campari (1995) use their panel data to examine dynamic aspects of savings, investment and debt.

The models covered are all based on household survey data, collected under the authors' supervision. Sample size ranges from a few dozen in the programming models to several hundred in most of the regression studies. Typically, the data are of moderate to high quality, but the high costs of data collection limit feasible survey size. All the studies are based on single cross-sectional surveys, except Foster *et al.* (1997) and Ozório de Almeida and Campari (1995), that use panel data from surveys taken in 1970-71 and 1980-81, and 1981 and 1991, respectively.

Among all the surveys, the model by Foster *et al.* (1997) stands out for its ambitiousness, with regard to sample size, time periods examined and sources of forest cover data. That study was able to take advantage of detailed surveys by the Indian government of almost 5,000 households in 192 villages,

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[13] Monela (1995) also considers the farmer's objective of meeting minimum consumption levels of different foodstuffs as a fixed constraint.

most of which were interviewed in 1970-71 and again in 1980-81. The data on change in forest cover and biomass come from a detailed analysis by the authors of satellite images for each of the villages surveyed.

Model results

The household empirical and simulation models provide evidence confirming some basic conclusions from the analytical models, but have not contributed much so far to resolving issues where analytical models provide inconclusive results (Table 5).[14]

Every model that includes transportation costs shows that cheaper access to markets increases deforestation (Muñoz 1992; Pichón *et al.* 1994; Ozório de Almeida and Campari 1995; Angelsen 1996; Holden 1997; Pichón 1997).[15] Wage increases and greater availability of off-farm employment lower pressure on forests (Bluffstone 1993; Holden 1993a; Ruben *et al.* 1994; Ozório de Almeida and Campari 1995; Angelsen 1996; Godoy *et al.* 1996, 1997; Foster *et a*l. 1997; Holden *et al.* 1997; Pichón 1997).[16]

Only programming and simulation models examine the impact of high output prices, and their conclusions depend directly on the initial assumptions. Models that assume subsistence or Chayanovian - type behaviour show price increases lower deforestation (Ruben *et al*. 1994; Angelsen 1996), while other models show the opposite (Monela 1995; Angelsen 1996).

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[14] In our discussion of the regression models, we have chosen not to include either test statistics or elasticities. To correctly interpret a model's test statistics requires information on the procedures used and the statistical attributes of the data that cannot easily be presented in a broad review such as this. As a practical matter, we report model results that the model makers themselves describe as statistically significant. This generally – although not always – implies they have at least a 95% confidence level.

Similarly, to analyse elasticity estimates for so many models would have made the document excessively long and unwieldy. Besides, elasticities cannot be easily compared between models because the models use different indicators to reflect the same underlying variables.

[15] Godoy *et al.* (1996) find that households in villages farther from market towns clear less primary forest, but hypothesise that one reason for this may be because those villages have more secondary forest available for clearing.

[16] Bluffstone (1993, 1995) simulates the response of fuelwood and fodder availability in an open access regime in Nepal to changes in wage rates and availability of off-farm labour over a 50-year period. He proposes that making off-farm employment more available would greatly reduce pressure on forests. Large wage increases reduce fodder collection and induce farmers to shift from fuelwood to alternative fuels. Moderate wage increases also reduce fodder collection, but increase fuelwood consumption. The situation improves when there are off-farm employment opportunities, as producers no longer have to raise animals under conditions where excessive fodder collection leads to a spiral of environmental degradation and poverty.

Table 5: The effect of selected explanatory variables on deforestation in farm-level empirical and simulation models.*

Variable	Effect on deforestation	Comments
Higher agricultural prices	Increase or reduce	Depends on assumptions
Population growth	Increase	May increase at a decreasing rate due to induced innovation
Lower transport costs	Reduce	Supports analytical models
Higher agricultural productivity	Reduce	
Higher wages	Reduce	Supports models with labour markets
More off-farm employment	Reduce	
Higher fertiliser prices	Increase or no effect	May increase shifting cultivation
Higher non-fertiliser input prices	Reduce	Other inputs complement land
More credit available	Increase or reduce	Reduces in surveys with indigenous people
Fertiliser price increase	Increase or no effect	May increase shifting cultivation
Other input prices increase	Reduce	Other inputs complement land
Higher quality soil	Increase	

* Some conclusions are not based on empirical evidence but rather follow directly from model makers' assumptions.

The effect of input price increases on forest clearing also depends on the model, but here at least some of the conclusions are based on empirical data, not just the initial assumptions. Fertiliser price increases have practically no short-term effect on land use in studies by Ruben *et al.* (1994) and Monela (1995), although Monela suggests they increase deforestation in the long run. Holden Nghiep (1986) and (1993b, 1996) find that higher fertiliser prices lead farmers to change from sedentary farming to shifting cultivation and to clear more forest. Price increases in other inputs, such as pesticides, seeds and hand tools, and higher interest rates reduce forest clearing (Ruben *et al.* 1994; Monela 1995; Ozório de Almeida and Campari 1995).

Muñoz (1992), Monela (1995), Godoy *et al.* (1996) and Pichón (1997) all conclude larger households clear more forest each year and leave a smaller proportion of their land in forest.[17] Such households are said to have both a higher capacity and greater need to clear additional land. Godoy *et al.* (1997), however, found that larger indigenous households in Honduras actually cleared less land, and Holden *et al.* (1997) observed no significant relationship between the two variables in Northern Zambia.

Particularly interesting results with regard to demographic variables emerge from Foster *et al.* (1997). They assert that not only do higher village-level population density and average household size correlate with more deforestation in India, but also that these results cannot be fully explained by the effect of demographic variables on wages, land prices, incomes or consumption expenditures. The authors hypothesise that this may be due to institutional arrangements related to communal access to forest resources. Alternatively, it might imply that the farmers behave as suggested by subsistence or Chayanovian models.

Greater credit availability promotes deforestation in studies from Brazil and Tanzania, by allowing farmers to expand their cropped area and pastures (Monela 1995; Ozório de Almeida and Campari 1995). Indigenous households in Bolivia and Honduras, however, clear less forest when they receive more credit (Godoy *et al.* 1996, 1997). The authors of these latter studies suggest that families with credit may be less dependent on forest-based activities to smooth consumption and income or engage in off-farm employment to repay their loans, leaving them less time to work on their own farms. Pichón (1997) found no significant relationship between credit use and deforestation in Ecuador.

Higher incomes among small farmers correlate with more forest clearing over the long run in the Brazilian Amazon, but this does not necessarily hold in any given year (Ozório de Almeida and Campari 1995). Foster *et al.* (1997) say the effect of higher income in India depends on whether it is derived from non-agricultural rural employment opportunities or higher agricultural productivity. In the first case, it tends to lower deforestation; in the second case to raise it.[18] Forest clearing among indigenous families in Bolivia and

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[17] In the case of Godoy *et al.* (1996), however, this relationship was not statistically significant.

[18] The result corresponds well with analytical open economy models; in the first better non-agricultural employment opportunities switch labor away from forest clearing, in the second it attracts labor to agriculture. The effect on forest clearing of income increases *per se*, that is, the expenditure effects, is not tested, and will normally be difficult to undertake.

Honduras initially rises as income increases, but then falls, apparently because families with the highest incomes engage in more off-farm employment. Similarly, high discount rates among indigenous farmers in Bolivia lead them to clear *less* forest, since impatient farmers prefer to engage in more off-farm wage labour that provides them with immediate cash incomes (Godoy 1997).

Farm size does not affect annual clearing rates by colonists in Brazil (Jones *et al.* 1995), but larger farms of colonists tend to have a higher percentage of their total land in forests in Ecuador (Pichón 1997).

All the linear programming models analysed, except Ruben *et al.* (1994), assume farmers cannot purchase labour.[19] This implies that different productive activities compete directly for labour, and technological changes that induce farmers to devote more time to one activity leave less time for others. Under these circumstances, farmers who practise sedentary agriculture clear less forest that those involved in shifting cultivation. Any change that discourages shifting cultivation reduces deforestation. (The number of farmers is considered exogenous.) Nghiep (1986) and Holden (1993b) conclude that low input prices and land-labour ratios, and technological improvements in alley cropping and sedentary cultivation, all have that characteristic and hence reduce deforestation. They also conclude that as long as land - labour ratios are high, farmers will continue to engage in shifting cultivation under a wide variety of conditions.

In a separate publication, Holden (1993a) examines the same issues using subsistence and Chayanovian models with and without off-farm labour markets in the context of northern Zambia. He says the subsistence model is appropriate for modelling traditional Zambian society, where there was little market integration and institutions for risk sharing, while the Chayanovian model adequately reflects the current situation characterised by greater market integration, individual risk taking, and higher population densities. Farmers with subsistence model-type behaviour always prefer shifting cultivation, and clear less forest when they obtain access to labour-saving technological changes. Farmers with Chayanovian-type behaviour may choose either shifting cultivation or sedentary systems depending on the context, and their reaction to technological changes greatly depends on how risky they perceive the new technologies to be.

Jones *et al.* (1995) posit that increased farm productivity in the Brazilian Amazon leads to less total forest clearing because farmers who have success-

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[19] Even Ruben *et al.* (1994) limit the amount of labour farmers can purchase to three months, thus effectively constraining them to using only slightly more than their available family labour.

fully avoided soil degradation have more productive land and thus have no need to compensate for lost productivity on degraded lands by clearing forest. Godoy *et al.* (1997) potentially provides additional support for this hypothesis, by showing that the indigenous farmers in Honduras with higher rice yields clear less forest each year. These results stand in stark contrast, however, to those of Foster *et al.* (1997), who observed that in India agricultural productivity growth at the village level had a high positive correlation with deforestation.

Godoy *et al.* (1996); Godoy (1997) and Pichón (1997) found that Bolivian and Ecuadorian farmers with higher education levels cleared more forests. However, forest clearing declines with education among indigenous farmers in Honduras (Godoy *et al.* 1997).

Farmers who have been on their farms longer tend to have less forest (Pichón 1997). The amount they clear in any one year, however, may either increase (Godoy 1997) or decrease (Godoy *et al.* 1997) over time. Both Godoy *et al.* (1996) and Pichón (1997) report less deforestation when households have more secure tenure and there is less threat of encroachment on their land by outsiders.

The presence of more cattle and chainsaws is associated with both more forest clearing annually and a lower percentage of forests on farms in several Latin American contexts (Godoy *et al.* 1996; Pichón 1997). Holden *et al.* (1997) encountered a similar association with pig holdings in northern Zambia.

Pichón *et al.* (1994) and Pichón (1997) conclude that Ecuadorian farmers with poor soils have a higher percentage of remaining forest, and Muñoz (1992) says the same is true for larger farms in drier areas in Mexico.[20] Jones *et al.* (1995), however, report soil quality has no effect on forest clearing in Rondonia, Brazil.

On a completely separate issue, Walker and Smith (1993) use stylised facts from surveys in Indonesia to show that, unless governments can credibly threaten to revoke logging concessions if government guidelines are not followed, concessionaires will practise liquidation harvesting and permit subsequent conversion to agriculture. However, if there is even a relatively low probability of having their concessions cancelled because of violations, concession owners will switch to sustainable forest management and protect against encroachment. The probability of sustainable management has no simple relation to forest concession length, but decreases with higher dis-

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[20] Farmers in the Brazilian Amazon clear more forest when land prices are higher, although it is uncertain whether high prices reflect better soil quality, areas with more land speculation, or both (Ozório de Almeida and Campari 1995).

count rates. Governments can achieve long-term sustainable management even with short concessions by allowing timber companies that follow management guidelines to renew their concessions and carrying out threats to revoke their concessions if they do not.

Strengths and limitations

Unlike analytical models, farm-level empirical and simulation models can handle relatively large numbers of independent variables, and in the case of programming and simulation models endogenous variables as well. Farm-level regression models are the most appropriate modelling tool for analysing the empirical relationship between farmers' land use and their previous experience, cultural attributes and human capital. Programming models allow model makers to explicitly consider the resource requirements of different crop and livestock systems and technologies and once assembled can quickly and easily simulate the potential impact of a wide variety of policies. This allows them to evaluate the impact of changes in relative prices between agricultural commodities, rather than only composite price indices for the sector as a whole. Empirically based simulation models are well suited for dynamic analysis, using a recursive approach.

On the other hand, all these models require a lot of costly data and their conclusions only apply to the cases studied, which may or may not be representative of other areas. Cross-sectional farmer regression models, while good for studying the relationships between farmer characteristics, access to markets and services and forest clearing, have little to say about the effects of crucial variables such as prices, capital accumulation and population change. These variables can be examined with panel data, but such data are only rarely available. Programming and simulation model predictions depend heavily on initial assumptions regarding farmer preferences, labour markets, elasticities of substitution and economies of scale, which the models themselves cannot test.

Section Four

Regional-level Models

4.1 Spatial Simulation Models

Even though deforestation is inherently a spatial phenomenon, most economic models lack an explicit spatial dimension; thus they cannot answer the *where* question. Nevertheless, with the recent spread of Geographical Information System (GIS) technologies, it has become much easier to create models that analyse land use in a spatially explicit context and a growing number of models combine economic and spatial aspects. The Dynamic Ecological – Land Tenure Analysis (DELTA) model is one of these, and is the only model we are aware of that incorporates both household and regional-level analysis. DELTA stochastically simulates household behaviour in a spatial framework and is described in Southworth *et al.* (1991a,b) and in Dale *et al.* (1993a,b, 1994). Other, conceptually simpler, models include Bosquet *et al*. (1997) and Chomitz and Griffiths (1997), as well as several mentioned in Lambin (1997) that were not available to the authors.

Variables and assumptions

The DELTA model uses spatial data on soil quality, natural vegetation, distance to roads and markets, lot size, land use and length of occupation to rank the attractiveness to potential colonists of different lots in a settlement area. Then it randomly assigns new colonists to available lots, using an algorithm that ensures more attractive lots have a higher probability of receiving colonists.[21] The model makers exogenously determine how many colonists enter the area in each time period.

Once on a plot, each farmer clears forest and uses the land for annual crops, perennial crops, pasture or fallow. How much land the farmer clears and the proportion dedicated to each land use is again determined stochastically, based on probability distributions set by the model makers. After the first year, farmers can decide to stay on the same lot, move to another, leave the region, or become a landless labourer; and once again the model simulates these decisions by randomly selecting which farmers choose each alternative, using another pre-established probability distribution. Farmers who remain on their lots again choose how to use their land, subject to the constraints imposed by decisions made in the previous period. Different production systems degrade the land to a greater or lesser extent and that affects a lot's attractiveness. Farmers can also merge adjacent lots or split up existing lots.

The principal objective of the Bosquet *et al*. (1997) and Chomitz and Griffiths (1997) models is to simulate the depletion of fuelwood resources. In both models fuelwood regeneration is exogenously determined and spatially specific. In the first model, this regeneration is entirely biologically determined, while in the second policy makers arbitrarily designate which areas will be 'managed', and managing an area increases its regeneration rates. Transportation costs and population growth are key elements in both models, as are institutional rules regarding access to fuelwood resources in the Bosquet *et al*. model.

Methodology and data

DELTA consists of three linked sub-models that simulate settlement patterns, land-use changes and carbon release, respectively. Once its exogenous parameters and probability functions are set, the model can generate spatial scenarios showing how settlement patterns and land use change over time. The model is recursive, with the endogenous variables from each period determining the values of certain exogenous variables in the following period. The scenarios analysed typically have 40 or 50-year time horizons.

To date, DELTA has only been used to simulate land use in one 300,000-hectare area in Rondonia, Brazil, that model makers have divided into 3,000 lots of about 100 hectares each. The model's parameters were calibrated based on in-depth farmer surveys, satellite images and secondary sources. The Geographic Information System (GIS) used in the model incorporated

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[21] Typically, the modeller assumes farmers already occupy some lots prior to the arrival of the new colonists. These lots and their previous land-use histories are determined exogenously before running the model.

pre-existing soil, vegetation and road maps, and calculated the distance from each lot to roads and markets.

Like the DELTA model, Bosquet *et al.* (1997) and Chomitz and Griffiths (1997) divide up their respective regions into several thousand cells. For each cell they use GIS data to specify its initial state and a simple linear function to simulate biophysical changes over time. Within this context, agents, with exogenously defined locations, follow pre-established decision rules to obtain their fuelwood from the location with the lowest possible transportation costs where fuelwood is available. Bosquet *et al.*'s simulations are based on data from the Kayanza region of Burundi, while Chomitz and Griffiths analyse a 20,000-square kilometre area near the capital of Chad.

Model results

The models' most interesting results are not about the qualitative effects of different policies but their quantitative impact and physical location. Model makers assume, rather than prove, that greater access to roads and markets and better soil quality increase the probability a specific location will be deforested. They also assume larger regional populations tend to clear more land and use more fuelwood, although this can be partially offset by technological improvements, change in property rights and forest management schemes. The models simulate alternative scenarios, and examine the quantitative and spatial implications of assuming different possible magnitudes for the coefficients of the parameters.

Strengths and limitations

The models provide useful information about how infrastructure and settlement policies, property rights, technology and environmental characteristics influence land use over relatively long periods of time. Once constructed and calibrated, the model can examine the effects of a wide variety of infrastructure and settlement policies, zoning restrictions, changes in property rights, and technological alternatives on deforestation and land degradation. Unlike the models described in the last section, the model's outputs not only include estimates of the magnitude of forest clearing and degradation, but also predictions regarding its location.

Currently, the models still do not take into account output or input prices, although in the future they might. At present, the only economic behaviour incorporated into the models is farmers' preferences for clearing areas and extracting fuelwood from more accessible areas that have better soils.

Spatial models provide information not only on how much forest is likely to be cleared, but also specific locations which have the highest risk of being deforested. This provides insights about forest fragmentation, biodiversity conservation and watershed management that cannot be obtained from non-spatial models.

The DELTA model's stochastic and dynamic character also makes it somewhat more realistic and uniquely suitable for dealing with issues such as migration and land abandonment, which are difficult to address using static or deterministic models.

4.2 Spatial Regression Models

Variables, hypotheses and assumptions

Spatial regression models measure the correlation between land use and other geo-referenced variables. Independent variables used in these models include distance from markets and transportation infrastructure, topography, soil quality, precipitation, population density, forest fragmentation and zoning categories (forest concessions, national parks); all of which can be mapped and incorporated into a GIS. Recently, the models have also begun to incorporate indicators of more aggregate socioeconomic variables, using data from census results.

The models hypothesise that landholders are most likely to convert forest to agricultural use where good access to markets and favourable conditions for farming make agriculture more profitable. Forest conversion for small farm agriculture requires different levels of access and types of soil and climatic conditions than conversion for large-scale mechanised farming (Chomitz and Gray 1996). High population density and growth near forests, particularly of landless rural families, increase pressure on forest resources by farmers seeking land for agriculture (Rosero-Bixby and Palloni 1996).

Methodology and data

Most models use multivariate logit or probit analysis, since the dependent variable is typically a discrete category of land use (e.g., forest/non-forest or pasture/crops/forest). Others use simple univariate analysis of correlation or ordinary least square regressions.

The models focus on land use in a single time period or the change in land use over two or more periods. The majority of models relate the state of the independent variables in the first period to the probability that the forest in that location is removed between the first and second periods.

Spatial autocorrelation is a common problem with geographic data, since nearby locations are more likely to be similar than distant ones. This can lead to biased and inefficient coefficients, and inaccurate measures of statistical significance. Several methods exist for partially correcting for spatial autocorrelation, although none is fully satisfactory (Chomitz and Gray 1996;

Rosero-Bixby and Palloni 1996). Auto-correlation is a particularly serious problem if the research's main objective is to determine how each independent variable affects land use. Thus, for example, a study by Rosero-Bixby and Palloni (1996) initially identified a strong correlation between population density and deforestation, but found the relationship disappeared once they corrected for spatial autocorrelation. On the other hand, if a study's primary objective is to predict where deforestation will occur, rather than the relative importance of each explanatory variable, spatial autocorrelation may actually help.

The data used for these studies typically come from a random sample of locations (points) from a given region or country, each representing less than one square kilometre. The sample may include all types of locations, or just those locations that were covered with forest during the first time period. Sample sizes are often quite large (several thousand points or more). Forest cover and other land-use information comes from national forest inventories, remote sensing, aerial photographs, and ground truthing. The researchers take population and socioeconomic data from national censuses. The GIS programs themselves generate the information on distance to roads and markets using the maps in their databases. Most of the remaining information comes from local government departments.

Model results

In general, findings from these models support both their own hypotheses and the conclusions of the analytical household models. Not surprisingly, they find that forests closer to roads in distance and time are more likely to be cleared (Table 6). Most studies show that forest clearing declines rapidly beyond distances of two or three kilometres from a road, although Liu *et al.* (1993) and Mamingi *et al*. (1996) report significant forest clearing associated with much greater distances to roads in Cameroon, the Philippines and Zaire.

Similarly, Chomitz and Gray (1996) found locations closer to urban markets (in travelling time) have less remaining forest in Belize, and Mertens and Lambin (1997) say deforestation drops off dramatically beyond 10 kilometres from the nearest town in Eastern Cameroon.[22] Nelson and Hellerstein (1997) found that distance to villages had a much more significant effect on land use than distance to urban areas.

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[22] On the other hand, little deforestation occurred less than three kilometres from towns, as there was little forest left there to remove (Mertens and Lambin 1997).

Table 6: The effect of selected explanatory variables on deforestation in spatial regression models.

Study	Country	More roads soils and/ or drier	Closer to markets	Better	Nearer forest edge
Brown *et al*. (1993)	Malaysia	NA	NA	NA	Increase
Chomitz and Gray (1996)	Belize	Increase	Increase	Increase	NA
Deininger and Minten (1996)	Mexico	Increase	NA	Increase	NA
Gastellu-Etchegorry and Sinulingga (1988)	Indonesia	NA	NA	Increase	NA
Liu *et al*. (1993)	Philippines	Increase	NA	NA	Increase
Ludeke *et al*. (1990)	Honduras	Increase	NA	Increase	Increase
Mamingi *et al*. (1996)	Cameroon and Zaire	Increase	Increase*	Increase	NA
Mertens and Lambin (1997)	Cameroon	Increase	Increase	NA	Increase
Nelson and Hellerstein (1997)	Mexico	Increase	Increase	No effect	NA
Rosero-Bixby and Palloni (1996)	Costa Rica	Increase	NA	Increase	Increase
Sader and Joyce (1988)	Costa Rica	Increase	NA	Increase	NA

NA = Not applicable

* Only in Cameroon. No effect in Zaire.

Forest fragments have a higher risk of being lost than forests in large compact areas, with those close to the forest edge especially likely to be cleared. Proximity to roads and railroads are associated with deforestation in Cameroon and Zaire (Mamingi *et al*. 1996). In addition, areas with higher-quality soils (flat, adequate drainage, and high soil fertility) and drier climates are also more likely to be cleared (Table 6).

The effect of roads and environmental conditions interact, so that roads induce greater forest clearing in areas with good soils and favourable climatic conditions. In Belize, for example, Chomitz and Gray (1996) show the probability of an area being used for agriculture (rather than natural vegetation) on high quality land next to a road was 50 per cent, whereas lands next to roads with marginal soils had only a 15 per cent probability of being deforested. Mamingi *et al*. (1996) obtained similar results in Cameroon and Zaire.

On the other hand, roads actually appear to diminish the negative impact of high poverty levels on forests in Southern Mexico. Poverty and deforestation are highly correlated there, and the relationship is stronger in more isolated areas, far from roads (Deininger and Minten 1997).[23]

Mertens and Lambin (1997) note that variables affect forest clearing differently depending on the type of deforestation process. In peri-urban deforestation, forest clearing exhibits a circular pattern around the towns, and distance to towns and roads strongly affects forest clearing but proximity to forest edge does not. Along roads a ‘corridor pattern’ of deforestation emerges where proximity to roads and forest edges are significant determinants of forest clearing, but distance to towns is not. Finally, in areas where diffuse shifting cultivation dominates, proximity to forest edge increases the probability of forest clearing, whereas distance to roads and towns is less important.

Only Rosero-Bixby and Palloni (1996) have used spatial models to examine the relationship between rural population density and deforestation. As noted above, their model initially discovered a strong correlation between local population density and deforestation and an even stronger correlation between deforestation and the number of rural landless families. However, these correlations vanished when the model was adjusted to account for spatial autocorrelation.

Strengths and limitations

These models use relatively reliable data and their large sample sizes give model makers more degrees of freedom. Increasingly, appropriate GIS databases are being created for other purposes that can also be used for spatial regression models. For practical policy applications, it is often as important to predict and influence where deforestation takes place as how much occurs, and these models are particularly suited for that (Lambin 1994). Measuring how often they accurately predict where deforestation will occur can test the models’ robustness.

The models have a weak ability to separate correlation from causality or determine the direction of causality. Roads may be built or population densi-

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[23] The same study also found that deforestation was lower in protected areas and higher where a large proportion of farmers had received agricultural credit.

ty may be high because forests have been cleared, rather than vice versa. Locations with good soils and climate for agriculture may have both more deforestation and greater infrastructure or population, without the two necessarily being causally related. Researchers have attempted to address these problems by incorporating more independent variables and using data for the independent variables from prior to the land-use changes analysed, but have been only partially successful.

While the models do a good job of analysing the relationship between location specific decision parameters and forest clearing, they are not well suited for studying the effects of producer characteristics, underlying variables, or less location-specific decision parameters, such as prices and wage rates. Since these variables have been shown to be important, this is a significant limitation. In the future, however, the increasing availability of spatially referenced socioeconomic data may partially overcome this constraint.

4.3 Non-spatial Regional Regression Models

Variables, hypotheses and assumptions

The non-spatial, regional regression models focus on county, provincial, state or regional level and do not provide any information about the specific location of forest clearing.[24]

As Kummer and Sham (1994) note, model makers' choice of their dependent variable is key to the conclusions they draw. Economists who use different dependent variables may well end up studying quite distinct phenomena, thinking that they are looking at the same thing. The dependent variable in these models is usually forest cover, amount of forest cleared, or increase in cropping area, although a few authors have used estimated biomass or the area in national forest reserves (Table 7). Some authors who use forest cover as a proxy for deforestation claim the two variables are related and note that data quality for the former is much better (Palo 1994). Others simply state those were the only data they could obtain (Osgood 1994). Forest cover, however, reflects not only recent deforestation, but earlier deforestation as well, and current independent variables cannot explain past activities. Moreover, the percentage of land originally covered by forests differs by region (Kummer and Sham 1994).[25]

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[24] For convenience, we have also included one national regression model in this section (Chakraborty 1994) since it has more in common with the other models discussed here than with the models discussed in other sections.

[25] A few authors correct for this last aspect by excluding areas never covered with forest from their calculations (Pfaff 1997; van Soest 1998).

Table 7: Deforestation data used in regional regression models.

Study	Country	Dependent variable	Years analysed	Sample	Forest data source
Andersen (1997)	Brazil	Deforestation	1970/75/80/85	316 counties	Land surveys
Andersen (1996)	Brazil	Deforestation	1975/80/85	316 counties	Satellite/ land surveys
Angelsen *et al*. (1996)	Tanzania	Cropped area	1981/91	19 regions	Government statistics
Barbier and Burgess (1996)	Mexico	Crop and pasture area	1970/85	31 states	Government statistics
Chakraborty (1994)	India	Forest reserve area	1952-80	National	Government statistics
Cropper *et al*. (1997)	Thailand	Deforestation	1976/78/82/85/89	58 provinces	Satellite
Deininger and Minten (1996)	Mexico	Deforestation	1980/90	2267 counties	Satellite
Harrison (1991)	Costa Rica	Forest cover	1970/72/84	65 counties	Satellite/ aerial photos
Katila (1995)	Thailand	Deforestation	1976-89	4 regions	Satellite
Krutilla *et al*. (1995)	Nine countries	Peri-urban biomass	1990	33 cities	Vegetation maps
Kummer and Sham (1994)	Philippines	Defor. and forest cover	1957/70/80	72 provinces	Forest inventory
Lombardini (1994)	Thailand	Defor. and forest cover	1967/84	18 provinces	Government statistics
Osgood (1994)	Indonesia	Forest cover	1972-88	20 regions	FAO statistics
Panayotou and Sungsuwan (1994)	Thailand	Forest cover	1973/76/78/80	16 provinces	Satellite
Pfaff (1997)	Brazil	Forest cover	1978/88	316 counties	Satellite
Reis and Guzmán (1994)	Brazil	Forest cover	1985	151 counties	Satellite
Reis and Margulis (1991)	Brazil	Forest cover	1985	165 counties	Satellite
Southgate *et al*. (1991)	Ecuador	Deforestation	1977/85	20 counties	Satellite/ aerial photos
van Soest (1998)	Cameroon	Forest cover	1985	13 departments	WCMC forest data

These models focus more on the causes of deforestation rather than its sources (see Section 2). A few, however, examine the relative importance of logging, cattle, annual crops, and perennial crops as sources of deforestation (Harrison 1991; Reis and Margulis 1991; Chakraborty 1994; Kummer and Sham 1994; Osgood 1994).

Population in these models generates a direct demand for land for subsistence or pushes down implicit wage rates, thus making deforestation more profitable. However, it may not be exogenous, since inter- and intraregional migration is influenced by many of the same factors that affect deforestation (Reis and Guzmán 1994). To correct for this, several authors have used two-stage regressions and instrumental variables for population, to account for its endogenous character (Southgate *et al.* 1991; Pfaff 1997; van Soest 1998). Others have preferred to omit population variables altogether (Deininger and Minten 1996).

On the other hand, after experimenting with simultaneously estimating regression models for land clearing, rural and urban population, rural and urban output, and land prices using Seemingly Not related Regression Equations (SURE), Andersen (1997) concluded OLS regressions provided equally good results, and used them instead. Cropper *et al.* (1997) had a similar experience when they tried using instruments for population and roads.

Regional per capita income reflects local opportunity costs for labour, more than demand for agricultural and forest products (which is more closely related to national income levels).[26] Consequently, higher levels of income, like increased wages, are expected to be associated with less deforestation.

High agricultural output and logging prices and subsidised credit for livestock and crops increase the profitability of forest clearing, and thus are expected to promote deforestation, while high transportation costs would have the opposite effect. The latter are typically measured through indicators of road density, river length and distance to major cities. As noted earlier, it is not possible, *a priori*, to predict the effect of input price changes, since inputs can be either complementary or alternative to the use of land.

The model makers always predict better soils and flatter land lead to higher deforestation since landholders will prefer to deforest more productive lands first. Yield increasing technological change, however, has contradictory effects. It increases the marginal productivity of land and thus stimulates deforestation. But it may also lead to land being substituted by labour or capital, which reduces deforestation.

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[26] Krutilla *et al.* (1995), Barbier and Burgess (1996) and Andersen (1997) are exceptions, since they emphasise the role of urban income in generating local demand for agricultural and forestry products.

Secure land titles and protected areas are both expected to discourage forest clearing (Southgate *et al.* 1991; Krutilla *et al.* 1995). The anticipated effect of common property arrangements is uncertain (Deininger and Minten 1996).

The models rarely include macroeconomic variables such as exchange rates, foreign debt and foreign investment, since the variables show no cross-sectional variation within individual countries, and most models include data from only one or two points in time.

Methodology and data

These models use mostly multivariate OLS regressions or maximum likelihood methods, and cross-sectional or panel data. Barbier and Burgess (1996) point out that OLS regressions are often inappropriate for panel data, since the effects of different independent variables may not be constant over time and across all individual cross-sectional units. To avoid that problem they use Feasible Generalised Least-Squares (FGLS) estimations. In comparison, Andersen (1997) tested her data to see if there were any significant period- or region-specific effects, and concluded they were not a major problem. Several models try to account for region-specific effects by including regional dummy variables, but these are rarely significant.

In most cases, the authors have checked for heteroscadisticity and temporal autocorrelation and, where found, attempted to correct for them. Only Andersen (1997) has tested her data for normality and was forced to strongly reject this assumption. This finding is significant, considering practically all regression models assume their data are normally distributed, and when it is not conventional test statistics can be expected to provide misleading results.[27]

Provincial or district (county) level models are likely to exhibit strong spatial autocorrelation, just as is found in spatial regression models, since the trend in each county is likely to be influenced by what takes place in neighbouring counties. Andersen (1997) addressed this problem by using weighted averages of forest clearing, population and income in neighbouring districts as independent variables, while Reis and Guzmán (1994) use Maximum Likelihood estimation.

The number of observations depends largely on whether provincial or district-level data are used; in the first case, it ranges between 13 and 72, while in the latter it can be over 2,000. In most African and Asian countries,

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[27] This seems to be even more relevant for global regression models where several authors have found that outliers significantly influence their results (Inman 1993; Bilsborrow and Geores 1994).

data are only available at the provincial level (and in the African cases is often of poor quality), while in Latin America district-level data are more common. This, combined with higher-quality forest cover data, has made it possible to construct more accurate and informative models in Latin America.

Where aerial photos or satellite images exist for at least two points in time, they can provide high-quality estimates of deforestation to use as the dependent variable (Harrison 1991; Southgate *et al.* 1991; Katila 1995; Andersen 1996, 1997; Deininger and Minten 1996). Much of the forest cover and land use data used in these models come from aerial photography or satellite images, although some authors rely on general government statistics (Table 7).

Regional price and wage rate data are generally unavailable or of poor quality. This hinders the measurement of price responses in the models and sometimes leads authors to use proxies for local prices, such as the density of government grain purchasing depots (Deininger and Minten 1996), official government prices (as opposed to market prices) (Angelsen *et al.* 1996), national prices (Katila 1995; Barbier and Burgess 1996), and world prices (Lombardini 1994). National and world prices can only be used, however, when models have data from multiple time periods.

Model results

A summary of some of the main results from these models can be found in Table 8. Since the models have major differences in quality, however, it is inappropriate to discuss them as if their findings had similar merit, and the table should therefore be read with some care. In the following discussion special attention will be given to the results from Harrison (1991), Southgate *et al.* (1991), Kummer (1992), Kummer and Sham (1994), Katila (1995), Andersen (1996, 1997), Deininger and Minten (1996), Cropper *et al.* (1997) and Pfaff (1997), since they use reasonably accurate data and appropriate dependent variables.

The models tend to reinforce conventional wisdom regarding the sources of deforestation. In general, they conclude logging has been a major source of deforestation in Southeast Asia (Panayotou and Sungsuwan 1994; Kummer and Sham 1994; Osgood 1994; Katila 1995), but not in Brazil (Reis and Margulis 1991). Cattle ranching is important in Latin America (Harrison 1991; Reis and Margulis 1991; Barbier and Burgess 1996; Andersen 1997).[28]

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[28] Andersen (1996) found deforestation was higher in Brazilian counties with more logging, but claims that most logging is a by-product of forest clearing for agriculture.

Table 8: The effect of selected explanatory variables on deforestation in regional regression models.

Study	Higher agricultural prices	Population growth	Lower transport costs	Higher income	Higher agricultural productivity	More credit	Closer to down	Better/ flatter land
Andersen (1997)	NA	Increase	Increase	Increase	NA	Increase	Reduce	NA
Andersen (1996)	NA	Increase	Increase	No effect	NA	Increase	Reduce	No effect
Angelsen *et al*. (1996)	Increase	No effect	NA	No effect	Increase	NA	NA	NA
Barbier and Burgess (1996)	Increase	Increase	No effect	No effect	No effect	Increase	NA	NA
Chakraborty (1994)	NA	NA	NA	Increase	No effect	NA	NA	NA
Cropper *et al*. (1997)	Increase	Increase	NA	NA	NA	NA	Increase	Increase
Deininger and Minten (1996)	Increase	NA	NA	Increase	Reduce	NA	NA	Increase
Harrison (1991)	NA	No effect	NA	NA	NA	NA	NA	NA
Katila (1995)	No effect	Increase	NA	No effect	Increase	NA	NA	NA
Krutilla *et al*. (1995)	NA	NA	Increase	Increase	NA	NA	Reduce	Increase
Kummer and Sham (1994)	NA	Increase	Increase	NA	NA	NA	No effect	NA
Lombardini (1994)	NA	No effect	No effect	Increase	NA	NA	NA	NA
Osgood (1994)	NA	NA	No effect	NA	NA	NA	NA	NA
Panayotou and Sungsuwan (1994)	Increase	Increase	Increase	Reduce	Reduce	NA	Reduce	NA
Pfaff (1997)	NA	Increase	Increase	NA	NA	NA	Reduce	Increase
Reis and Guzmán (1994)	NA	NA	NA	NA	NA	NA	NA	NA
Reis and Margulis (1991)	NA	Increase	Increase	NA	NA	NA	No effect	NA
Southgate *et al*. (1991)	NA	Increase	Increase	NA	NA	NA	NA	Increase
van Soest (1998)	NA	Increase	Increase	Increase	NA	NA	NA	NA

NA = Not applicable

The results also tend to support the initial hypotheses regarding the effect of different variables, based on the analytical models. Higher population, agricultural prices, regional per capita incomes, access to markets, better-quality soils and flatter lands are all said to be associated with greater deforestation (Table 8). A more careful examination of the study results, however, suggests one should be cautious about drawing conclusions regarding population and incomes.

In the case of population, local population density is highly correlated with road density, soil quality and economic activity (Southgate *et al.* 1991; Reis and Guzmán 1994; Katila 1995; Krutilla *et al.* 1995; Andersen 1997; van Soest 1998). The simple correlation between population and deforestation tends to disappear when additional independent variables are added. Harrison (1991), Southgate *et al.*(1991), Andersen (1997), Pfaff (1997) and van Soest (1998) claim that most population growth in previously forested, low population, areas occurs in response to road construction, available high-quality soils and growing demand for agricultural products. This implies the latter factors, rather than population growth *per se*, are the underlying causes of deforestation in these areas. After Cropper *et al.* (1997) used instrumental variables to control for population's potentially endogenous character, they still found a positive correlation between rural population density and forest clearing in Thailand. The elasticities they obtained, however, were much smaller than those reported in the earlier study of Thailand by Panayotou and Sungsuwan (1989).[29]

Deininger and Minten (1996) found less deforestation in Mexican municipalities with higher per capita incomes and less poverty, a conclusion which lends support to the hypothesis that high wages lead to lower deforestation. This relationship only held, however, in municipalities where pasture accounted for more than half of all agricultural land and less than 70 per cent of the land was in forest. Similarly, Barbier and Burgess (1996) conclude higher per capita incomes are associated with more pasture, but not with larger cropped areas. Most other studies have definitional or methodological problems that make their conclusions regarding the effect of income levels on deforestation suspect.

The evidence is stronger with respect to agricultural prices, access to markets and land quality. Angelsen *et al.* (1996) and Barbier and Burgess (1996) found agricultural prices were positively related to expansion of cropped area in Tanzania and Mexico, as were livestock prices and pasture

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[29] Another interesting – and intuitive – result from this study is that population density had a much stronger relation to deforestation in northern Thailand, where small farmers dominate, than in southern Thailand, where commercial farms are more important.

area in Mexico. Deininger and Minten (1996) also associate higher maize prices and deforestation in Mexico. Katila (1995) and Panayotou and Sungsuwan (1994) conclude that higher wood prices are correlated with lower forest cover and deforestation in Thailand. Most studies that include access variables show deforestation is higher in locations with more roads and/or proximity to major urban markets. In Thailand, at least, this effect is stronger in regions with large-scale commercial farming (Cropper *et al.* 1997). Krutilla *et al.* (1995) found islands also had higher deforestation, presumably because they have more accessible forests. Southgate *et al.* (1991), Krutilla *et al.* (1995), Deininger and Minten (1996), Cropper *et al.* (1997) and Pfaff (1997) show that flatter land with better soil quality has a much higher chance of being deforested.

The models offer mixed evidence on the relationship between deforestation and technological change in agriculture. Katila (1995) says higher agricultural productivity (measured in value of production per unit of land) is associated with higher deforestation in Thailand, but Panayotou and Sungsuwan (1994) conclude the opposite with respect to rice yields and forest cover in the northeast region of the same country. Angelsen *et al.* (1996) claim cropped area expands more rapidly in regions with higher fertiliser use in Tanzania, while Deininger and Minten (1996) conclude technical assistance reduces deforestation in Mexico.

In Brazil and Mexico, credit and fiscal subsidies for livestock and crops seem to have stimulated deforestation (Andersen 1996, 1997; Barbier and Burgess 1996; Pfaff 1997), and land speculation also appears to be an important factor in Brazil (Andersen 1997.)

Finally, Deininger and Minten (1996) and Krutilla *et al.* (1995) found that giving protected area status to an area marginally reduced the probability of it being deforested. Southgate *et al.* (1991) reports that municipalities where more farmers had secure land tenure had lower levels of deforestation.

Strengths and limitations

Like spatial regression models, these models are most appropriate for studying location-specific decision variables. They are often not the most appropriate tools for analysing the role of farmer characteristics and most underlying variables. The frequent lack of suitable data for more than one or two time periods often limits their usefulness for analysing price response.[30] Unlike most spatial regression models, these models often use administrative units as their basic units of analysis. This makes it easier to incorporate variables such

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[30] Unfortunately, given that few countries make frequent reliable estimates of forest cover, models which meet this condition will generally have to use poor-quality deforestation data.

as population, availability of technical services, credit utilisation, and land prices, which cannot easily be included in most spatial regression models.[31] On the other hand, model makers may find it more difficult to obtain data or interpret results for physical attributes, such as soil quality and topography, since these often vary greatly within a single administrative unit.

Focusing on only one country allows model makers to include a number of variables typically excluded in multi-country regression models, and whose absence biases the results. Furthermore, independent variables are more likely to affect deforestation in a more similar manner between provinces and districts within one country than between countries.

For these same reasons, regional and national regression models may be more appropriate than global regression models for evaluating the relative importance of different sources of deforestation. Nevertheless, as previously underscored in Section 2, it is necessary to distinguish between different levels of variables in explaining the causes of deforestation. Fundamental problems arise when explanatory variables from different levels of the chain of causality, such as cropped area, agricultural prices and population, are mixed in the same equation. In this case, some explanatory variables become functions of others and interpretations of the causal effects are hindered. Statistically, it may result in high multicollinearity.

For certain countries, one can obtain much higher-quality data on deforestation and other variables for use in regional and national models, than what is available at the global level, and this allows the former models to be more accurate. Nevertheless, many regional and national models also suffer from major data quality problems that limit their reliability.

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[31] As noted previously, however, the relative ease of within-country migration means that population may be endogenous when looking at sub-national levels of aggregation, particularly in areas with significant migration and active labour markets.

Section Five

National and Macro-level Models

This section looks at deforestation models where countries are the main units of analysis. We have divided these models into four main groups: (1) analytical models for economies of unspecified regions or countries; (2) computable general equilibrium (CGE) models, which can be seen as empirical applications of the first type of models, but often add new elements; (3) trade and commodity models; and (4) multi-country regression models that use country-level data from a large number of countries to assess links between independent variables and deforestation.

Compared to the household and firm-level models discussed in Section 3, type (1) and (2) models add at least two important dimensions to the analysis. First, they make some prices endogenous (general equilibrium effects). In terms of the framework in Section 2, they explore how some underlying variables help determine decision parameters. This provides an important link to macroeconomic variables and policy instruments. Second, most general equilibrium models include the interactions between different sectors, e.g., agriculture, forestry and manufacturing.

5.1 Analytical Models

Variables and assumptions

These non-linear models highlight the feedback mechanisms that link specific sectors involved in deforestation to the broader economy through changes in prices, incomes, taxes and subsidies. The models have between one and three sectors of production and take into account producers, consumers and government. Jones and O'Neill (1992a,b, 1993a) use only an agricultural sector. Jones and O'Neill (1992c) divide that sector into modern and traditional components. Jones and O'Neill (1992d) also study two agricultural subsectors, but in this case one is peri-urban and the other peripheral. Brander and Taylor (1994), Deacon (1995) and Jones and O'Neill (1995) research an agricultural sector and a manufacturing sector, for which land is only an input in the former. They assume all land comes from cleared or logged forest. Agriculture and managed forests are studied by von Amsberg (1994), while van Soest (1998) considers three sectors: agriculture, forestry and manufacturing. Most models focus on a single tropical developing country, but Jones and O'Neill (1993b) also include a prototypical developed country that trades with the developing world.

The distinction between the modern and traditional agricultural subsectors in Jones and O'Neill (1992c) is that the former resolves its nutrient depletion problems by applying fertilisers, while the latter leaves land in fallow so it can recuperate. In the model, the modern sector is portrayed as being more labour intensive and located closer to the city. It apparently produces high-value labour-intensive products, such as vegetables and dairy products, while the traditional subsector produces less labour- and capital-intensive foodstuffs using shifting agriculture in the more distant areas.

In van Soest's (1998) model, loggers only clear a small fraction of the land, but they facilitate subsequent conversion of forest to small-scale agriculture. The 'agricultural sector' includes only activities involving deforestation. All other agriculture implicitly forms part of the manufacturing sector.

The distinction is made by von Amsberg (1994) between mature unmanaged forests and managed forests, such as plantations and forests logged as part of a permanent rotation. Mature forests are not net timber producers, and hence can be modelled as non-renewable resources. Managed forests are renewable resources and are affected quite differently by changes in economic parameters.

Typically, land and labour are the only factors of production in these models.[32] Agents choose how to allocate labour between activities. Farmers can use their labour to:

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[32] Jones and O'Neill (1995) also include a factor called urban infrastructure, used as an input into industrial production, and several of the Jones and O'Neill models (1992c,d,e) include agricultural inputs as a separate factor of production in the agricultural sector.

- clear land that still has forest or cultivate already cleared land (Deacon 1995; van Soest 1998);
- participate in direct production activities or conservation and maintenance activities (Jones and O'Neill 1992a,e);
- work in the traditional or modern subsectors of agriculture (Jones and O'Neill 1992c);
- clear forest in logged-over areas or in other areas (van Soest 1998); and
- cultivate their fields or take measures to control malaria (Jones and O'Neill 1993c).

Farmers can assign forestry labour to logging or preventing encroachment (van Soest 1998). They can also choose between work and leisure (thus making their labour supply elastic).

Several models analyse the possible impact of changes in taxes and subsidies, particularly the impact of taxing agriculture and forestry and subsidising agriculture or manufacturing, as well as of taxes designed specifically to reduce suboptimal levels of deforestation. Revenue from taxes not used for subsidies can either be redistributed equally among families (Deacon 1995) or used by governments to purchase manufacturing and agricultural goods (Jones and O'Neill 1995). Governments cannot engage in deficit spending.

Each model has its own assumptions regarding the exogeneity of output and factor prices. Jones and O'Neill (1994) assume agricultural and manufacturing output prices are both exogenous, but an earlier model assumes both are endogenous. In other models (1993b, 1995) the same authors have endogenous agricultural prices, but exogenous manufacturing prices. Timber prices are exogenous in van Soest (1998), but all other prices are endogenous. Both situations are considered by von Amsberg (1994); where timber prices are exogenous and where they are endogenous. He assumes, however, all agricultural and factor prices to be exogenous. In van Soest (1998), wage rates are endogenous, while in most, but not all, Jones and O'Neill models urban wage rates are exogenous whereas rural wage rates are not. The latter models explicitly take into account urban unemployment, and families migrate between rural and urban areas depending on wage rate differentials and their expectations regarding the probability of obtaining a manufacturing job.

Methodology

The comparative statics in these models are similar to those in open economy household or firm models. Producers maximise profits subject to constraints, and equilibrium outcomes are determined using first order conditions.

Cramer's rule is then applied in the comparative statics analysis to assess the effects of shifts in different exogenous variables on deforestation.

The models' production functions can be either Cobb-Douglas (Reis and Guzmán 1994; van Soest 1998) or have no specified functional form, beyond fulfilling all the usual conditions for optimisation (Deacon 1995; Jones and O'Neill 1995).

All the models reviewed are static, except those of Brander and Taylor (1994) and von Amsberg (1994). The dynamic element in Brander and Taylor comes from the interaction between forest harvest and growth rates. Since excessive logging in one period reduces the marginal productivity of logging in the following period, and this, in turn, leads to less timber being harvested, it is possible to have a stable state equilibrium where timber is left to be harvested in later periods, even in open access situations. To make his model dynamic von Amsberg assumes timber prices rise over time (at a decreasing rate) and that landholders adjust their behaviour accordingly.

Farmers in Jones and O'Neill (1992b, 1993a) make their decisions based on expectations regarding future prices and yields. These expectations are exogenously determined in Jones and O'Neill (1992b) and are formed rationally in Jones and O'Neill (1993a).

Model results

The major results are summarised in Table 9. When agricultural prices are exogenous, policies that tax sectors involved in forest clearing or logging will reduce these activities, while subsidising those sectors has the opposite effect (Jones and O'Neill 1994, 1995; Deacon 1995; Andersen 1997). The converse is true for sectors not engaged in forest clearing. Higher agricultural prices also reduce the period of time that farmers leave their lands fallow, thus reducing the area of secondary forest (Jones and O'Neill 1992b, 1993a). The effects will be stronger when agricultural supply is more elastic (Deacon 1995).

These results imply that *ad valorem* and export taxes, tariffs and subsidies biased in favour of urban/manufacturing activities and against activities associated with deforestation affect forest cover positively. Policies such as these can reduce the profitability of agriculture by lowering the effective (after tax) output price for agriculture goods, bidding up rural wage rates, or raising the costs of agricultural inputs (Jones and O'Neill 1993d, 1994). Subsidising agriculture or logging through public road construction, protectionism, high guaranteed agricultural prices, and low stumpage rates for timber on public lands, and eliminating trade and marketing policies biased against agriculture will have the opposite effect. Devaluations generally stimulate deforestation by increasing real agricultural and timber prices (von

Amsberg 1994). These conclusions suggest the current trend towards policies designed to eliminate pro-urban, anti-export and anti-agricultural biases and remove restrictions on log exports may increase pressure on forests. This is a very significant result, which we will return to in Section 6.4.

The outcome can be different, however, if one assumes agricultural prices to be endogenous.[33] Under those circumstances, policies biased in favour of urban areas and non-agricultural activities will also stimulate urban demand for food, and hence raise agricultural prices, and the net effect on deforestation becomes indeterminate (Jones and O'Neill 1995). If, conversely, devaluations have a recessionary impact and reduce urban food consumption, they could also lower pressure on forests.

The situation also becomes rather complex when one divides agriculture into several subsectors. In that case, higher prices for crops and livestock products from non-agricultural frontier areas could have a similar effect as higher manufacturing prices and draw labour away from the agricultural frontier (Jones and O'Neill 1992, 1993f).

This being said, at least in theory, there are more efficient instruments for reducing deforestation than agricultural output taxes, whether they be explicit or implicit. In particular, Jones and O'Neill (1993g) claim that both land and fuel taxes are more efficient in that regard.

Rural road construction and higher agricultural productivity induce more forest clearing when agricultural prices are exogenous or demand is inelastic. The increased production they generate does not produce feedback that leads to lower prices, as one would normally expect as a result of a move to the right of the agricultural supply curve (von Amsberg 1994). Rural population growth clearly stimulates forest clearing by reducing real wages when agricultural prices are exogenous, but its effect is indeterminate when prices become endogenous.[34] The option of allocating labour to profitable soil conservation activities also tends to dampen the effects of agricultural price rises and road construction, as some of the labour that farmers might otherwise put into forest clearing is diverted to conservation activities (Jones and O'Neill 1992e).

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[33] The impact of government investments in urban areas may also depend on how those investments are financed. Financing urban infrastructure investments through taxes on manufacturing, for example, may increase urban unemployment, putting downward pressure on rural wages, and thus stimulating deforestation (Jones and O'Neill 1993e).

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Table 9: The effect of selected explanatory variables on deforestation in analytical general equilibrium models.

Variable	Effect on deforestation	Comments
Devaluation	Indeterminate	Increases deforestation unless very recessionary
Agricultural export taxes	Reduces	Shifts terms of trade against agriculture
Higher demand for peri-urban agricultural products	Reduces	
Restrictions on timber exports	Indeterminate	Reduces deforestation unless loggers stop guarding against encroachment due to low timber prices
Population growth	Indeterminate	Depends on assumptions about product and labour markets
Lower transport costs	Increase	Makes agriculture more profitable
Spending on urban services and infrastructure	Indeterminate	Reduces deforestation if agricultural prices exogenous
Higher industrial tariffs	Indeterminate	Same as above
Higher urban minimum wages	Indeterminate	Same as above
Higher agricultural input prices	Reduce	Makes agriculture less profitable
Higher productivity of agriculture	Indeterminate	Depends on assumptions about type of technology and product and labour markets
Higher land taxes	Reduce	
Subsidised agricultural credit	Increase	Same as above

With exogenous timber prices, increases in timber harvesting productivity, demand for timber or labour supply will all reduce the steady state stock of timber, and may cause the resource to be completely eliminated (Brander and Taylor 1994). The same result will occur if greater integration into the world economy opens new market opportunities and leads to higher agricultural and/or timber prices (Findlay and Lundahl 1994).

Agricultural and timber prices behave more like exogenous variables when export products are involved and the country's total exports of those products are too small to affect world prices. They behave more like endogenous variables when output is sold in thin local markets, transport costs are high, or government policies restrict trade.

Deacon (1995) and van Soest (1995) reach diverging conclusions regarding the impact of log exports and other restrictions on timber trade because the first looks at the agricultural and forestry sectors separately (in two different models), while the second examines both simultaneously. In Deacon's models, taxes on timber and log export bans reduce log prices, which leads to less logging and lower deforestation.[35] In the van Soest model, lower log prices also lead loggers to refrain from investing to ensure that small farmers do not encroach upon their concessions. Since farmers remove almost all trees, while logging removes only a portion, such taxes or bans could result in greater deforestation.[36] Deacon's conclusion, that lower timber prices lead to less clearing of mature unmanaged forests, is supported by von Amsberg (1994) but he notes that the area of managed forests will be also reduced.

The effects of different policies also vary depending on the assumptions made about labour markets and labour supply. When population is assumed to be fixed, higher output prices or productivity improvements in agriculture or logging have an indeterminate effect on deforestation because per hectare revenues from agriculture and logging increase, but the higher demand for labour also bids up wage rates, and hence costs. The same applies to policies which improve market access, such as road construction. On the other hand, when population is endogenous – as perfect labour markets imply – these

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[35] These models cannot fully capture two arguments often used to support the claim that timber export taxes and log export bans lead to more logging. The first is that low log prices offer no incentive to improve the efficiency of timber processing, and the second is that they induce excessive investment in processing plants that subsequently need to log larger areas to avoid under-utilisation (Barbier *et al.* 1995).

[36] The same author (van Soest 1996) also argues shifting cultivation may be more extensive in areas that have never been logged, and this could also lead to more forest clearing if less area is logged. However, these arguments ignore the fact that logging operations often improve farmers' access to forested areas.

policies raise wage rates by much less and, without the dampening feedback effect of higher wages, induce much greater deforestation (Jones and O'Neill 1992a).

The same reasoning applies with respect to agricultural inputs. Exogenous population implies that part of the effect of higher input costs on discouraging agricultural expansion will be offset by lower wages resulting from less demand for agricultural labour.

Finally, Jones and O'Neill (1994, 1995) conclude that rural road construction not only favours farmers and agricultural labourers, but also urban workers and industrialists. Thus, even though road construction in forested areas unambiguously leads to more deforestation in almost all models, it is likely to be politically popular. This suggests a conflict between the policy objectives of higher rural and urban incomes and forest conservation.

Strengths and limitations

Analytical general equilibrium models allow model makers to make *general* conclusions about how policies affecting terms of trade and profitability in different sectors influence deforestation, that cannot be obtained from any other type of model. In particular, they provide important insights into the potential *indirect* effects of different policies through adjustments in factor markets and changes in demand resulting from shifts in the sectoral distribution of income.

To model such complex processes in a strictly analytical framework and still reach interesting (unambiguous) conclusions, model makers have to greatly restrict the number of variables they analyse and make strong assumptions. They have generally had to limit themselves to a maximum of three – presumably homogeneous – sectors and a similar number of factors of production, and have found it difficult to obtain clear conclusions when working with more than two of either. At the same time, given these limitations, the number of distinct issues and alternatives that economists such as Jones and O'Neill have been able to address with these models, by making multiple iteration of the same basic models, is impressive.

Even with their extreme simplifying assumptions, the models cannot predict how most policies will affect forest clearing without making additional strong assumptions regarding the elasticities of supply and demand of outputs and labour. Many policies simultaneously encourage and discourage deforestation, and one can only evaluate the net effect of these tendencies by making assumptions regarding their relative magnitude. The models tell us nothing about either the location or extent of deforestation induced by policies.

5.2 Computable General Equilibrium (CGE) Models[37]

Variables and assumptions

In these models, homogeneous production sectors supply goods and services. Firms, consumers, governments and the rest of the world demand these goods and services, using money obtained from payments for their labour, capital and land, or from taxes and transfers. The models can have one homogenous consumer (Mwanawina and Sankhayan 1996) or several consumer groups based on income level (Cruz and Repetto 1992; Coxhead and Shively 1995) or source of income. Typically, they include markets for outputs, factors and foreign exchange, and generally assume perfect competition, constant returns to scale and no money illusion (Piketty 1994).

The models' agricultural sector may be disaggregated into commercial or non-commercial (Mwanawina and Sankhayan 1996), crops and livestock (Wiebelt 1994), production for export or domestic consumption (Thiele 1995), upland and lowland (Coxhead and Jayasuriya (1994), or by individual products (Cruz and Repetto 1992; Aune *et al.* 1996). Persson and Munasinghe (1995) also examine a specific sector where squatters clear forest for the sole purpose of selling cleared land and obtaining land rents.

Capital and labour supply are exogenous in the short run but may change over time in the dynamic models, while the amount of land farmed (and/or logged) is endogenous. When the models assume open access to land, the amount of land used is strictly determined by the demand for land. Unskilled labour moves freely between sectors, and in recursive dynamic models capital moves towards sectors with higher profit rates.

Export and import prices are usually exogenous, while most domestic prices are endogenous.[38] Government consumption is exogenous, with differences between government income and expenditures reflected in savings. Net capital flows can be either exogenous (Wiebelt 1994) or endogenous (Thiele and Wiebelt 1994).

Both analytical and computable general equilibrium (CGE) models typically use one of three approaches to model deforestation agents' behaviour,

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[37] Other papers about CGE models related to deforestation cited in the literature, but that we could not access or have not included in the review, include Devarajan (1990), Didia (1993), López (1993), Boyd (1994), Coxhead and Jayasuriya (1994), Hoogeveen (1994), Bandara and Coxhead (1995) and Persson (1995). We report some results from these papers based on references to them in other sources.

[38] Wiebelt (1994), however, assumes that Brazil faces a downward sloping demand curve for its exports, while Piketty (1994) makes a similar assumption for Indonesia's forestry exports.

which we refer to as the conventional, property rights and forest rotation approaches.[39]

In the *conventional approach,* agents clear forest up to the point where the marginal profit or land rent is zero. This is in line with the simplest open economy models presented in Section 3.1. The production functions for the agricultural and/or forestry sectors include land as a factor of production. This approach is relevant for contexts with well-established property rights, as well as certain open access situations. Examples of models using this approach include Coxhead and Shively (1995), Deacon (1995) and the various articles by Jones and O'Neill.

Models using the *property rights approach* explicitly consider the property rights to forests, (or lack thereof) and their implications for forest use. Unemo (1995), for example, compares situations where land expansion is based on *marginal* benefits and costs (as in the case of private property and functioning land markets) with others where expansion is based on *average* benefits and costs (common property or open access). Persson and Munasinghe (1995) similarly discuss two different property regimes. The first has well-defined property rights and farmers make intertemporal choices, taking into account the future value of forest conservation. The second is open access and farmers only pay attention to current costs and benefits.

Forest rotation approach models describe decision making about forest use (logging) as an intertemporal allocation problem. Examples of this approach include Dee (1991), Thiele and Wiebelt (1993a,b, 1994) and Thiele (1995). These authors assume concession holders have clear property rights over forest, and calculate a steady state optimal harvest age (rotation period) for their logging operations, based on timber prices, harvesting costs, interest rates and physical growth characteristics of trees (Faustmann approach).

Methodology and data

CGE models typically have Linear Expenditure Systems (LES), that imply Stone-Geary utility functions. This type of function, unlike Constant Elasticity of Substitution (CES) or Cobb-Douglas (CD) utility functions, allows income elasticities of demand to differ depending on the product (Piketty 1994).

On the supply side, the models generally assume a fixed (Leontief type) relationship between value added and intermediate goods in each sector, and derive the coefficients used to quantify that relationship from input-output models. To describe the portion of production that adds value, they employ

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[39] This classification is inspired by Vosti *et al.* (1996). Xie *et al.* (1996) use a similar typology.

CES or CD production functions which, following from duality theory, can be used to derive factor demand functions. Of the two functional forms, model makers often prefer CES functions because they do not assume unitary elasticities of substitution. CES-Armington input aggregation functions and Constant Elasticity of Transformation (CET) functions are used to specify that domestically produced goods and imports not be perfect substitutes.

The specification of the forestry subsector model in Thiele (1995), Dee (1991) and Thiele and Wiebelt (1993a,b, 1994) uses a logistic functional form to describe per hectare tree growth. The total amount of non-land inputs used in each rotation is fixed, independent of the harvest rotation period, which leads to a form of increasing returns to scale. They also assume annual tree harvest is equally distributed over the rotation period.

Some CGE models are static, while others permit capital accumulation, population growth or technological change. Population growth and technological change are typically exogenous, while capital accumulation is modelled recursively with investment in each period being incorporated into the capital stock in the following period.[40] Some dynamic models do not require all markets to clear in each period (van Soest 1995).

The only CGE models we were able to identify that disaggregate their analysis regionally are Coxhead and Shively (1995) and Wiebelt (1994). Wiebelt distinguishes between primary production inside and outside the Brazilian Amazon. Coxhead and Shively separate upland from lowland agriculture in the Philippines.

Model results

In general, CGE models have found that currency devaluations increase deforestation (Table 10). Wiebelt (1994) says that a real devaluation in Brazil would lead to a significant short-run expansion of crop production in Amazon and a small expansion of timber and livestock output. Medium-term impacts are smaller. Devaluations affect crops more than livestock and timber in Brazil because they are more trade oriented. They have a contradictory impact on timber production because they simultaneously promote exports but reduce timber demand for national construction. In the Philippines, Cruz and Repetto (1992) report that devaluations increase logging. Aune *et al.* (1996) find that real devaluations prompt agricultural land expansion in Tanzania, both through increasing output prices, and by having land substitute for agricultural inputs in response to input price increases. Mwanawina

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[40] Rural-urban migration can also be modelled as a gradual process in dynamic recursive CGE models (van Soest 1995), but this has not been attempted in any models reviewed here.

Table 10: The effect of selected explanatory variables on deforestation in computable general equilibrium models.

Study	**Country**	**Devaluation**	**Trade liberalisation**	**Lower agricultural export taxes**	**Lower agricultural subsidies**	**Lower fiscal spending**	**Lower industrial subsidies**	**Higher land taxes**
Aune *et al.* (1996)	Tanzania	Increase	NA	NA	No effect	Reduce	NA	NA
Barbier and Burgess (1996)	Mexico	NA	Increase	NA	Indeterminate	NA	NA	NA
Coxhead and Shively (1995)	Philippines	NA	NA	NA	Reduce	NA	NA	NA
Cruz and Repetto (1992)	Philippines	Increase	Increase	NA	NA	NA	Increase	NA
López (1993)*	Ghana	NA	Increase	Increase	NA	Increase	NA	NA
Mwanawina and Sankhayan (1996)	Zambia	Increase	NA	NA	Increase	NA	NA	NA
Panayotou and Sussengkarn (1992)	Thailand	NA	NA	Increase	NA	Increase	NA	NA
Persson and Munasinghe (1995)	Costa Rica	NA	NA	NA	No effect	NA	Reduce	Reduce
Thiele (1995)	Indonesia	NA	NA	NA	NA	NA	NA	NA
Thiele and Wiebelt (1994)	Cameroon	NA	Reduce	Increase	NA	NA	NA	NA
Wiebelt (1994)	Brazil	Increase	NA	NA	No effect	NA	NA	Reduce

* As cited in Mäler & Munasinghe (1996)
NA = Not applicable

and Sankhayan (1996) also conclude that real devaluations increase deforestation in Zambia, but not by much, since Zambian exports are rather inelastic.

Reducing agricultural export taxes generates many of the same effects as currency devaluations. López (1993) – as reported in Mäler and Munasinghe 1996 – and Thiele and Wiebelt (1994) conclude that eliminating agricultural export taxes would foment forest clearing in Cameroon and Ghana, respectively. Panayotou and Sussengkarn (1992) reach a similar conclusion with respect to rubber export taxes in Thailand.

Trade liberalisation is also said to increase deforestation. Cruz and Repetto (1992) claim trade liberalisation in the Philippines can be expected to both increase logging and expand production of upland crops. Mäler and Munasinghe (1996) report that López (1993) obtained a similar result in Ghana. A study by Boyd (1994), cited in Barbier and Burgess (1996), concludes that the North American Free Trade Association (NAFTA) is likely to reduce industrial employment in Mexico, swelling the ranks of the rural labour force and thus lead to greater deforestation. Thiele and Wiebelt (1994), on the other hand, predict trade liberalisation would reduce deforestation in Cameroon, but base their prediction on a very optimistic view of the competitiveness of Cameroon's industry.

In Persson and Munasinghe's (1995) CGE model of Costa Rica, subsidies to industry decrease deforestation by attracting resources away from rural activities. However, higher urban minimum wages, increase deforestation, since less employment in industry leads people to move into agriculture, rather than into urban unemployment, as envisioned in the Jones and O'Neill (1994, 1995) models. In contrast, Cruz and Repetto (1992) report that industrial subsidies can be expected to marginally increase deforestation in the Philippines.

Lower overall public expenditure reduces deforestation in Aune *et al.*'s (1996) CGE model of Tanzania, since it reduces economic growth, and that lessens the demand for agricultural products. In Panayotou and Sussengkarn's (1992) model for Thailand, however, lower government spending increases deforestation, despite reducing economic growth, because it favours exports, and agricultural goods have a high export demand elasticity. Mäler and Munasinghe (1996) note that López (1993) obtained the same general conclusion for Ghana, but in that case reduced public employment led the urban unemployed to return to the countryside and expand the area under production.

Conclusions regarding the impact of reducing subsidies for agriculture are also mixed. The removal of fertiliser subsidies is expected to have little effect on cropped area in Tanzania, where more extensive production by farmers using less fertiliser compensates for the decline in land use caused by lower profitability of production (Aune *et al.* 1996). In contrast, Mwanawina and Sankhayan (1996) found that eliminating fertiliser subsidies would greatly increase forest clearing in Zambia. In Mexico, Barbier and Burgess (1996) say reduced fertiliser subsidies and the elimination of price supports for maize will directly affect agricultural profitability, thus reducing the area in agriculture, but also indirectly lower employment – and the newly unemployed may open new forest areas for crops. The net effect is indeterminate. Coxhead and Shively (1995) report subsidies for processing grain induce greater area in crops in the Philippines. Wiebelt (1994), however, found that eliminating fiscal incentives to agriculture had only a small effect on agricultural expansion or timber production in the Brazilian Amazon.

Productivity improvements in agriculture may affect deforestation in a general equilibrium context quite differently than in microeconomic models. When agricultural production is for a domestic market (prices are endogenous), and demand for agricultural products is inelastic, small increases in output may lead to large declines in agricultural prices. This could make agricultural production less, rather than more, profitable, and thus reduce deforestation. Such seems to be the case, for example, with maize production in the Philippines (Coxhead and Shively 1995). It is also possible that, even if the area of subsistence crops declines following a general improvement in agricultural technology, producers will become more oriented towards cash crops with higher demand elasticity, and the net effect will be higher pressure on the forest margin (von Amsberg 1994).

With regard to technological change in forestry, Dufournaud *et al*. (1992), as cited in Xie *et al.* (1996) reach the surprising conclusion that introducing more-efficient wood stoves in Sudan might actually increase deforestation by stimulating fuelwood consumption.

Land taxes substantially reduce deforestation in models from Brazil (Wiebelt 1994) and Costa Rica (Persson and Munasinghe 1995). However, in many cases it is not feasible to impose these taxes due to political and administrative obstacles.

In Persson and Munasinghe's (1995) and Thiele's (1995) models of Costa Rica and Indonesia, higher taxes on logging and log export bans reduce logging, but they also shift resources into agriculture, with the net result being little change in forest clearing. In Dee's (1991) and Thiele and Wiebelt's (1994) models, however, forestry and agriculture do not interact much. This restricts almost all the effects of changes in minimum diameters for logging, per hectare logging concession fees, concession duration and designating forests as national parks to within the forestry sector.

Strengths and limitations

CGE models are appropriate for analysing the interactions between different sectors and markets, but because these interactions are complex, the models have substantial data requirements, which can often not be satisfactorily met. Building a CGE model demands economic data such as input-output and social accounting matrices (SAM), which are frequently unavailable in developing countries or of poor quality. Moreover, since most countries produce input-output and social accounting matrices infrequently, model makers may be forced to use outdated information. These problems are particularly severe in Africa, where national statistics tend to be less complete and reliable than in Asia or Latin America. The models' conclusions are also largely driven by the price and income elasticities, but typically these parameters are copied from models made in other contexts, are based on strong assumptions regarding the functional forms of the production or utility functions, or have simply been set arbitrarily.

The lack of disaggregated regional data for most countries is especially problematic, since deforestation is typically concentrated in a few regions, which account for a small proportion of agricultural production. In such situations conclusions regarding changes in national agricultural area may provide little insight into deforestation. Whether these models help predict the magnitude of expected impacts is debatable. They are more likely to be useful as tools for understanding feedback mechanisms which can invalidate otherwise intuitive results based on partial equilibrium models (Piketty 1994).

Because of their limitations, CGE models are best used when no alternative approach can be found to analyse an issue. For example, devaluations, broad trade liberalisation, changes in foreign capital flows and general tax increases have widespread effects that are almost impossible to examine in a partial equilibrium framework. Even in more sectoral contexts, CGE models may suggest results that could not be fully anticipated based on partial equilibrium analysis because they incorporate feedback effects that a partial equilibrium approach could not (Xie *et al.* 1996). For analysing sectoral policies, however, one must consider the trade-offs between the benefits of incorporating indirect economic effects as against the costs involved in using less transparent models that depend more on poor data and arbitrary assumptions.

Attempts are currently under way in several places to improve the micro-level foundations of the CGE models, by incorporating nested linear programming models that use data from farmer and logger surveys (S. Vosti, personal communication, 1997). These techniques remain rather experimental and, to the best of our knowledge, have yet to successfully applied to analysing deforestation.

Each of the three main approaches mentioned previously, and adopted in the models to characterise forest users' behaviour, has its own limitations.

The conventional approach's use of land as a factor of production raises important issues (Piketty 1994). Authors such as Thiele and Wiebelt (1993b) assume land is mobile between sectors, and that markets serve to allocate land to different sectors. However, it is probably inappropriate to think in terms of a uniform national price of land. The existence of non-utilised forest land implies this factor is partially unemployed, and can be obtained *either* through purchase/rent or through clearing open access land. CGE model makers have yet to find a way to adequately account for this.

Of the different farm-level modelling approaches discussed in Section 3, the idea that land is a fully tradable factor of production is only compatible with an open economy approach with secure (private) property rights. Such an approach implies that poverty-driven deforestation cannot be explicitly analysed in the models (i.e., there are no income effects in the micro-behaviour). It also generally makes it difficult to model 'land grabbing' for speculative purposes.

The property rights approach has the great merit of being one of the few approaches to modelling deforestation that explicitly consider institutional issues. Nevertheless, the current tools for representing different property right regimes are still rather crude and primitive, and strictly apply only to extreme cases, rather than to more common situations with partial tenure security and combinations of private and common property.

The optimal forest rotation approach often obscures the distinction between the *expansion* of logged area and shortening of *rotation* period for a managed forest. As von Amsberg (1994) shows, this distinction is critical because the policy effects are generally very different.

In most tropical countries it is probably more appropriate to model the logging sector as a 'mining' activity, rather than a sector where forest concessionaires manage a renewable resource. Typically, timber concessions are characterised by limited tenure security (due to policy fluctuations, relatively short concession periods and encroachment), slow timber growth, high discount rates, harvesting techniques that damage many non-logged trees, and strong market fluctuations. Given that situation, concession holders can be expected to log as much and as quickly as possible, within the limits imposed by availability of capital and forest land. Under these circumstances, the optimal timber harvest rotation models used in some CGE models are probably not appropriate (Piketty 1994).

The relationship between logging and agricultural land expansion by smallholders is another critical issue. Many CGE models assume logging and agriculture compete for land, and that landholders allocate total forest land between virgin forest, logged forest and agricultural land based on relative profitability of the two latter activities. Empirical evidence, however, suggests that logging and smallholder agriculture are often complementary rather than competing activities. In many regions, a logging-shifting cultivation tandem is observed in which logging operations build roads that provide farmers with access to new land and lower their transport costs. Logging companies have few incentives to keep migrants from invading this land since they have a short time horizon and are interested only in the trees, not the land, which is the farmers' main interest. Modelling logging and agriculture as complementary rather than competing activities would have important implications for the results.

5.3 Trade and Commodity Models

These are traditional supply models or partial equilibrium trade models for specific agricultural or forest commodities. The model makers claim production of these commodities is a direct source of forest clearing. Hence, any factor that stimulates production indirectly induces deforestation. As with other supply and trade models, the principal explanatory variables in these models are prices, income and population.

Since these models only differ from other timber and agricultural supply and trade models in that the authors explicitly note the link between greater production and deforestation, practically any supply or trade model for a commodity implicated in deforestation could be considered a deforestation model. A general review of such models, however, is well beyond the scope of this study. Thus, we have selected just a few representative models to give the reader an idea of their use in modelling deforestation.[41]

Variables, hypotheses and assumptions

The models can be divided into timber models and agricultural commodity models. Barbier *et al.* (1995) provides a good example of a timber model, while the agricultural models we have chosen to examine are Cannock and Cuadra (n.d.), Elnagheeb and Bromley (1994) and Gockowski (1997).

Barbier *et al.* (1995) use the (logarithm of) the percentage of Indonesian land under forest cover in each province as their dependent variable, which is a function of the logarithm of roundwood production/square kilometre, population density and national income. It assumes greater roundwood production leads to lower forest cover but offers no explicit *ex ante* hypotheses regarding the other variables. Roundwood production itself is a function of supply and demand in the roundwood, sawnwood, and plywood markets which, in turn, depend on prices, tax rates, exchange rates, the price of substitutes, processing capacity and population and income levels in importing countries.

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[41] Buongiorno and Manurung (1992) and Manurung and Buongiorno (1997) are examples of studies not included in this review which focus on the timber trade without directly addressing the issue of deforestation. The former uses a non-spatial equilibrium model to study the effects of the Indonesian log export ban, whereas the latter applies a spatial equilibrium model to explore the effects of an import tax on tropical timber trade.

Cannock and Cuadra's (n.d.) model cropped area of corn, rice, beans and cassava in the Peruvian Amazon as a function of previous area, output prices, an index of production costs, credit availability and public investment in agriculture. Output prices, in turn, are functions of international prices, exchange rates, the price of substitutes and government subsidies to grain markets. All these variables, except the price of substitutes, are hypothesised to have a positive effect on cropped area.

Elnagheeb and Bromley (1994) present an acreage response model for mechanised sorghum production in eastern Sudan, which they claim to be a proxy for deforestation. Expected sorghum prices, rainfall, yield, charcoal prices, production costs and risk determine sorghum area. The authors hypothesise that the first four variables are correlated with higher acreage (and deforestation) and the second two with lower acreage. They say high charcoal prices can be expected to encourage greater land clearing because farmers can partially recoup their land clearing costs by selling the timber removed for charcoal.

Gockowski (1997) emphasises how changes in cocoa prices affect forest clearing by changing the relative profitability of the various crops planted by farmers. He proposes that a decline in cocoa prices will lead farmers to shift their attention towards plantains and cocoa yams, both of which require more forest clearing.

Methodology and data

Despite using data from multiple years, these models all have an essentially static approach. The models that endogenously determine both levels of production and prices (Cannock and Cuadra, n.d.; Barbier *et al.* 1995) use simultaneous equation systems and two-stage least squares regression. Barbier *et al.*'s equation system for the supply and demand of Indonesia's roundwood, sawnwood and plywood has 12 endogenous variables while Cannock and Cuadra have six. In the first case, the authors then take the predicted value of roundwood production for each year from their model and feed it recursively into a logit equation to estimate the relationship between timber production and deforestation; the second model determines cropped area (considered a proxy for deforestation) directly.

Models that have exogenous prices tend to be simpler. Elnagheeb and Bromley (1994), for example, use standard multiple regression with Maximum Likelihood Estimation. Production and acreage data for these models generally come from government sources and are of moderate quality, although in Gockowski (1997) this information comes from household surveys. Price data come from international or national databases, and hence is only a proxy for the prices actually received by producers.

Model results

Given their roots in traditional agricultural and timber supply and trade models, it should hardly come as a surprise that all three models find higher agricultural and timber prices lead to greater deforestation, see Table 11. Following from this same logic, taxes on sawnwood exports, timber import bans and increased logging costs all reduce deforestation (Barbier *et al.* 1995). Exchange rate devaluations, government intervention in cereal markets and greater credit availability promote forest clearing in Peru, while increased interest rates, fertiliser prices and wage rates reduce crop acreage (Cannock and Cuadra, n.d.). Policies that subsidise charcoal substitutes contribute to less deforestation in Sudan (Elnagheeb and Bromley 1994). Barbier *et al.* (1995) find population density to be positively correlated with deforestation, but national income to be negatively correlated.

Gockowski's (1997) paper provides an important reminder that, while general improvements in the terms of trade for agriculture tend to encourage deforestation, this does not necessarily hold for relative price changes between agricultural products. In this case, lower cocoa prices stimulate higher deforestation, as they induce farmers to shift from perennial crops into more land-intensive annual crops.

Strengths and limitations

Trade and commodity models can be appropriate for examining the short- and medium-term impact of output and input prices, and the policies that determine them, on forest clearing in a partial equilibrium framework, *to the extent that* timber production or cropped areas prove to be good proxies for deforestation. However, these variables may often not be good proxies for deforestation for

Table 11: The effect of selected explanatory variables on deforestation in trade and commodity models.

Policy	Effect on deforestation
Devaluation	Increase
Timber export taxes and bans	Reduce
Higher interest rates	Reduce
Higher wage rates	Reduce
Higher fertiliser prices	Reduce
Restrictions on logging	Reduce

several reasons. Forest can be cleared for different uses. Logging frequently does not lead to complete removal of tree cover. Agriculture can expand either at the expense of forest or of fallow and other land uses.

Authors using these models have been able to take advantage of a very large and rich literature on agricultural and timber markets to define the most appropriate econometric methods and functional forms for their models. Usually they can assess their model's robustness by simulating the outcomes of one time period using coefficients derived from running the model in another. The data cover a number of years and tends to be of higher quality than that used in global regression models, although this is less true of timber studies due to the widespread prevalence of illegal logging. As a result, the models generate somewhat more reliable elasticities, and thus can give useful insights into the possible magnitudes of effects from different policies.

These models tell us little about the role of farmer characteristics, environmental factors, factors affecting the efficiency of production, politics or general equilibrium effects. Population is only considered to the extent it affects demand for these commodities. Since many of these variables change slowly over time, but significantly affect deforestation, commodity and trade models probably should not be used to analyse long-term trends.

5.4 Multi-country Regression Models

These models use national-level data to make regional or global generalisations regarding the major processes affecting tropical deforestation. Their ability to generate quantitative conclusions at the global scale, using readily available international data sets, has made them quite popular, and are thus the single largest category of deforestation models. Data availability is also their major weakness, since empirical models are no better than the data on which they are based.

Variables, hypotheses and assumptions

Some models use different proxies for deforestation as their dependent variables such as percentage of land covered with forest at a specified time period, wood production, area logged and expansion of land in agriculture. Others use either the absolute or percentage decline in forest cover between two periods (Table 12). Low deforestation can reflect either forests that are still intact or highly deforested areas that have little forest left to clear (Shafik 1994a). As noted earlier, the use of distinct dependent variables has major implications for the interpretation of a model's results.

To explain the independent variables' role in global deforestation, rather than their average importance in each country, Rudel (1989) weighs each country's contribution to his model results by the size of its forests. This leads him to base his conclusions largely on the situation in Brazil, Indonesia, Papua New Guinea, Peru and Zaire, which together have over 60 per cent of the world's tropical moist forest.

Because the absolute area of forest cleared can be expected to be higher in larger countries, the models usually scale their deforestation levels by land area, forest area, population or national income (Capistrano 1990; Kahn and McDonald 1994; Enroth 1996). Others adjust for this factor by including total forest cover as an independent variable (Allen and Barnes 1985; Rudel 1989; Inman 1993; Kant and Redantz 1997).

It is unclear how the absolute amount of forest area is likely to affect the *rate* of deforestation (percentage of forest lost each year).[42] Rudel (1989) and Rudel and Roper (1996, 1997a,b) hypothesise that deforestation processes differ between countries with large and small forest areas. Large compact forests are less accessible and difficult to clear on a large scale without sizeable, capital-intensive, infrastructure projects, which countries can only afford if they have large economies or preferential access to foreign loans (Rudel 1989). On the other hand, countries with little remaining forest may have a higher proportion of their forest in hilly areas with rugged terrain, making it less likely to be cleared (Rudel and Roper 1996, 1997b). Further, governments of countries with large forests may not perceive them as endangered and thus lack concern for forest conservation (the forest transition hypothesis) (Kimsey 1991).

As in Section 2, the model's independent variables can be divided into three classes: (1) direct *sources* of deforestation, (2) *immediate causes* of deforestation, and (3) *underlying causes*. With regard to the first class of variables, most authors agree that the expansion of crops and pasture are major sources of forest clearing. Logging and fuelwood extraction are more controversial. Many authors argue these activities only degrade forests, but usually do not lead to complete forest clearing (Burgess 1993a). Only Mainardi (1996) mentions mining's role in deforestation. He distinguishes between countries involved mostly in underground mining, which he says is not linked with deforestation and countries that have extensive alluvial and open pit mining in forested areas.

The units model makers have used to measure forest and agricultural production and exports include value, volume, land area and percentage of total exports. The literature largely ignores issues regarding the relative advantages of these different measures.

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[42] Although by definition, the same absolute change in forest cover will have a smaller effect on deforestation *rates* when total forest area is larger.

In general, the multi-country models give relatively little emphasis to the immediate causes of deforestation. They concentrate more on sources of deforestation and underlying causes. The main immediate causes of deforestation analysed in these models are forest accessibility and environmental factors. Following the same logic used in the models discussed previously, road construction and drier climates are expected to be associated with greater deforestation. Some models contain variables related to prices and technology, but these tend to be defined in such a way that they are more likely to reflect underlying variables (such as world prices and general yield trends) rather than producers' direct decision-making parameters.

Among the different underlying variables considered in these models are population, exchange rate and price policies, national income, life expectancy, external debt, political stability and democracy, technological change and land distribution.

Unlike regional models, population in the global models can largely be considered exogenous. International migration is of limited significance and natural population growth is too slow to be affected in the short term by the other variables analysed in these models.

The models use different indicators to reflect the general concept of population pressure, including total, urban, and rural population, and their density and growth, and the ratio of rural population to arable land (Table 14). Each of these has different implications for the causal mechanisms implied in the link between population and deforestation. Total population and urban population are likely to influence forest clearing through their roles in the demand for agricultural and forest products. Rural population, or the ratio of rural population to arable land, is often associated with rural families' need for farmland to maintain their livelihoods.

Demographic variables may also influence forest clearing indirectly through their effect on agricultural technologies (the Boserup hypothesis), labour markets, property rights and institutions, gender relations, the balance of political power, and a number of other variables. Similarly, other variables interact with population and affect its influence on agricultural intensification and migration and consumption patterns (Bilsborrow and Geores 1994). This makes the relationship between population and land use quite complex, particularly at the national levels analysed in these models. Existing models partially capture population's total net effect, but say little about the relative importance of the different components and how they interact with other variables.

The literature mentions that higher national incomes and economic growth have several, contradictory, effects on forest conversion, the net consequence of which is uncertain. Higher incomes promote greater consumption of agricultural and forest products, which in turn puts greater pressure on forests (Capistrano 1990). But they are also associated with less fuelwood utilisation, more capital-intensive (as opposed to land-intensive) agriculture, and more attractive employment opportunities away from the agricultural frontier (Palo and Lehto 1996b). Countries with higher incomes may also have greater demand for forest preservation (Capistrano 1990). Some authors hypothesise that there may be an 'environmental Kuznets curve', whereby at low levels of development the first effects tend to dominate and increased income leads to higher deforestation, but beyond a certain income threshold the opposite occurs (Stern *et al.* 1996).

Several authors speculate that high external debt may induce policy makers to implement export-oriented policies that stimulate greater forest clearing to produce agricultural and forest product exports (Capistrano and Kiker 1995), and/or encourage them to take myopic decisions that ignore long-term natural resource concerns (Kahn and McDonald 1994). It may also make a country poorer, stimulating poverty-driven deforestation (Kimsey 1991). Others emphasise the role of debt in curtailing transportation investments, particularly in countries with large forests (Rudel and Roper 1997b). A third group (Gullison and Losos 1993; Shafik 1994a) claims there is no reason to expect debt and deforestation to be related.

As with other variables, the use of different proxies for indebtedness makes it more difficult to compare model results concerning debt. Among the indicators of indebtedness used in the models are total external debt (Kant and Redantz 1997), external debt per capita (Shafik 1994; Rudel and Roper 1997b), total debt to the IMF (Inman 1993), growth in debt to the IMF (Inman 1993), ratio of total external debt to GDP (Kahn and McDonald 1995), total long-term external debt (Kimsey 1991), per capita long-term external debt (Kimsey 1991), ratio of long-term external debt to exports (Gullison and Losos 1993; Inman 1993), ratio of debt service to exports (Burgess 1991; Mainardi 1996), and the World Bank's assessment of a country's international credit standing (Capistrano 1990). While these indicators are probably correlated, each reflects slightly different phenomena.

With regard to general price trends, many economists hypothesise that improved terms of trade for agricultural and forest product exports and higher real exchange rates make it more profitable to convert forests to other uses (Capistrano 1990; Gullison and Losos 1993; Kant and Redantz 1997). Among the variables they use to test this hypothesis are overall terms of trade (Kant and Redantz 1997), agricultural and forest export price indices (Capistrano 1990; Gullison and Losos 1993), real currency devaluation (Capistrano 1990), and an indicator of exchange rate overvaluation (Shafik 1994a; Mainardi 1996).

Deacon (1994) and Didia (1997) consider landholders' decisions to conserve a forest and not convert the land to some other use to be an investment in an asset with long-term maturity. They hypothesise that political instability and authoritarian governments make such investments more risky and insecure, and hence lead to greater deforestation. Mainardi (1996), however, points out that the same logic may be used in the opposite direction. Since forest conversion itself requires investment, political instability may discourage *those* investments.

Methodology and data

Most global regression models use multivariate OLS regressions. Logit models are used when the dependent variable is discrete, e.g., high/low rates of deforestation. Because of insufficient data for time-series analysis, most existing models are cross-sectional, although a few authors analyse panel data using FAO Production Yearbook data. Since variables such as population, income, debt and prices influence deforestation only indirectly through their effect on deforestation agents' decisions related to logging and agricultural expansion, it would be preferable to estimate their effect through two-stage procedures, but this is rarely done.

One model (Rudel and Roper 1996) uses Boolean algebraic techniques, rather than regression analysis to identify relevant deforestation factors. This is a clustering technique to find common characteristics among countries with high (low) deforestation within a region. Strictly speaking this is not a quantitative model, but it shares many characteristics of the models discussed here (L. Muñoz, personal communication, 1997).

Lagged variables have been used only occasionally. Rudel (1989) and Rudel and Roper (1997b) use lags of 15 years to account for the time required for rural population growth to influence the availability of rural labour. Allen and Barnes (1985) use 5-year lags to account for the role of roundwood extraction on subsequent deforestation. Mainardi (1996) posits approximately a 5-year lag between when roads are built and forests are cleared.

Regional dummy variables or separate regressions for each region are often used to identify regional differences in deforestation processes. Only one model, however, has used interaction terms which make it possible to assess how specific independent variables affect deforestation in different regions, and still take advantage of the degrees of freedom available from the full data set (Kant and Redantz 1997). Given the high level of aggregation of these models, to obtain statistically significant results the variables included must affect deforestation in a similar manner across countries (Angelsen *et al.* 1996).

Most, although not all, data sets include between 20 and 90 developing countries, with one observation for each country. A small number of countries implies limited degrees of freedom, which restricts the number of independent variables that can be assessed and makes it difficult to obtain statistically significant results.[43]

Heteroscedasticity, multicollinearity and the presence of outliers that greatly affect the regression results are common in global models. Capistrano (1990) corrected for heteroscedasticity between periods, resulting from her use of panel data, by dividing the observations in each period by the square root of the mean square error from the respective period regressions. Most authors correct for multicollinearity by eliminating independent variables that are highly correlated with others. To deal with outliers, authors frequently estimate their models with and without those countries (Bilsborrow and Geores 1994; Inman 1993).

Almost all the models use forest cover and/or clearing data taken from the 1980 or 1990 FAO Forest Resources Assessments or the annual FAO Production Yearbooks (Table 12). In theory at least, the forest resources assessments include only tropical closed, broad-leaved forests, while the production yearbooks include all forest and woodland, whether it be open or closed, coniferous or broad-leaved (Kimsey 1991).

The 1980 Forest Resources Assessment (FAO 1981) considered the data for 40 of the 76 countries included to be of poor reliability, meaning it was based solely on partial deforestation information and rural population growth rates, without aerial photography or satellite imagery (Ludeke 1987). In the 1990 Assessment (FAO 1993), only 21 of the estimates for the 90 countries were based on two or more national forestry inventories. For the remaining 72 countries, deforestation in the period 1980-1990 is based on only one inventory (some as old as 1965). Forest cover and deforestation were then extrapolated from that single data point using a deforestation model where population density and ecological classes are the only explanatory variables (Scotti 1990; FAO 1993). In other words, the data more reflect population growth than actual deforestation.

FAO Production Yearbook forest cover data come mostly from national government responses to annual questionnaires, and often has no empirical basis. Most observers consider them extremely unreliable (Lambin 1994; Rudel and Roper 1997a). This also applies to data on crops and pasture from this source. Despite this situation, however, most global regression model makers use Production Yearbook or Forest Resources Assessment data.

Allen and Barnes (1985) find a very weak correlation between the rank orders of deforestation rates reported in the 1980 FAO Assessment, FAO

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[43] In this regard, Palo *et al.* (1997) is a kind of hybrid between a regional and a multi-country regression model, since it includes information on forest cover (but not deforestation) from 477 subnational units in 67 countries.

Table 12: Information on deforestation used in global regression models.

Study	Dependent variable	No. of countries in sample	Years analysed	Forest data source
Allen and Barnes (1985)	Decline in forest area	39	1968-78	FAO yearbooks
Bawa and Dayanandan (1997)	Decline in forest area	70	1980-90	WRI (1994), based on FAO data
Binswanger *et al.* (1987)	Agricultural land	58	1969-78	FAO yearbooks
Burgess (1993b)	Decline in forest area	53	1980-85	Lanly (1988)
Capistrano (1990)	Area logged	45	1967-85	FAO yearbooks
Cropper and Griffiths (1994)	Decline in forest area	65	1961-91	FAO yearbooks
Deacon (1994)	Decline in forest area	129	1980-85	Lanly (1988) and FAO yearbooks
Enroth (1996)	Decline in forest area	44	1980-90	1990 FAO forest assessment
Gullison and Losos (1993)	Roundwood production	9 (Latin America)	1976-85	FAO yearbooks
Inman (1990 and 1993)	Decline in forest area	102	1976-85	FAO yearbooks
Kahn and McDonald (1995)	Decline in forest area	55	1976-80	1980 FAO forest assessment
Kahn and McDonald (1994)	Decline in forest area	55	1981-85	Lanly (1988)
Kant and Redantz (1997)	Decline in forest area	65	1980-90	1990 FAO forest assessment
Kimsey (1991)	Decline in forest area	57	1976-80	1980 FAO forest assessment
Lugo *et al.* (1981)	Forest cover	33 (Caribbean)	1975	FAO yearbook
Mainardi (1996)	Decline in forest area	48	1980-90	WRI (1994) based on FAO data
Palo (1994)	Forest cover	60	1990	1990 FAO forest assessment
Palo and Lehto (1996a)	Decline in forest area, Forest cover	67	1953-91	1990 FAO forest assessment
Palo and Lehto (1996b)	Forest cover	29 (Asia)	1978-90	1990 FAO forest assessment

Table 12 continued

Study	Dependent variable	No. of countries in sample	Years analysed	Forest data source
Palo *et al.* (1996)	Forest cover	33 (Latin America)	1980-90	1990 FAO forest assessment
Palo *et al.* (1987)	Forest cover	72	1980	1980 FAO forest assessment
Panayotou (1993)	Decline in forest area	68	mid-1980s	FAO data
Rock (1996)	Decline in forest area Forest cover	39 39	1990	WRI (1994) based on FAO data
Rudel and Roper (1997a)	Decline in forest area	51	1980-90	1990 FAO forest assessment
Rudel and Roper (1997b)	Decline in forest area	68	1976-90	Authors' estimates
Same as above	Decline in forest area	24		1990 FAO forest assessment
Rudel and Roper (1996)	Decline in forest area	68	1976-90	Authors' estimates
Rudel (1989)	Decline in forest area	36	1976-80	1980 FAO forest assessment
Shafik (1994a)	Decline in forest area	77	1962-86	FAO yearbooks
Shafik (1994b)	Decline in forest area	149	1961-86	FAO yearbooks
Southgate (1994)	Agricultural land	23 (Latin America)	1982-87	FAO yearbooks

Production Yearbooks, and a 1980 deforestation study by Myers. This implies models can be expected to give quite different results depending on which set of deforestation estimates they use.

Because of the poor deforestation data quality, some authors divide countries into those with high and low deforestation, rather than using particular estimates (Deacon 1994; Rudel and Roper 1996, 1997a,b). Others use only data that they believe to be more reliable, and develop their own estimates based on data from multiple sources (Rudel and Roper 1996; 1997b).

International data on external debt, national income, population, roads and trade are generally more reliable than land-use data, and typically come from reports produced by the FAO, International Monetary Fund (IMF), World Bank, or World Resources Institute (WRI). Different authors' use of different sources for these data limits the comparability of their results. The indices used of political instability and the degree of democracy take into account a number of criteria and have been assembled using various sources (Deacon 1994; Mainardi 1996; Didia 1997).

Most models focus on some part of the period between 1975 and 1990 and assume the relationship between deforestation and the explanatory variables to be independent of the period chosen. Capistrano (1990) argues, however, that the factors influencing deforestation varied over time between 1967 and 1985. Similarly, Dore *et al.* (1996) criticise most multi-country models for ignoring the rapid changes occurring in the international economy that may affect the deforestation processes analysed.

Model results

Given that the previous discussion emphasises the poor quality of the forest data used in most global regression models and the tendency not to distinguish direct *sources* of deforestation from *causes*, it might seem superfluous to present their results. Nevertheless, they are often cited in the literature and model users should be familiar with them (Tables 13, 14, and 15).

Most models associate the expansion of agricultural land, agricultural self-sufficiency and strong agricultural exports with greater forest clearing (Table 13). Seven models identify a positive relationship between logging and deforestation, while three find no correlation, and two yield mixed conclusions. Mainardi (1996) shows the presence of large open pit mines and/or alluvial deposits located in forest areas to be positively correlated with higher deforestation.

According to Kant and Redantz (1997), forest product exports are more important in Asia, but have a greater impact on deforestation in Latin America, per dollar exported. An additional hectare of land in crops results in more deforestation in Africa than in Asia or Latin America, perhaps because of the importance of shifting cultivation in Africa. Pasture expansion is concentrated in Latin America. Bawa and Dayanandan (1997) obtained a positive correlation between greater cropped area and deforestation in all three regions, but logging and deforestation were only correlated in Asia and Latin America and cattle and deforestation only in Latin America and Africa.

Most, although not all, studies identify a positive correlation between at least one measure of population pressure and deforestation (Table 14). The studies show a stronger correlation between high population density and the percentage of a country's land in forest, than between population density and changes in forested area (Bilsborrow and Geores 1994).

Table 13: The effect of agriculture and logging on deforestation in multi-country regression models.

Study	Agriculture	Agriculture variable used	Logging	Logging variable used
Allen and Barnes (1985)	Increase	Change in agricultural area	Increase	Per capita roundwood production
Bawa and Dayanandan (1997)	Increase	Crop land as a percentage of total land area	Increase	Roundwood production
Burgess (1993b)	NA	NA	Increase	Per capita roundwood production
Burgess (1992)	NA	NA	Increase	Per capita roundwood production
Burgess (1991)	Increase	Index of per capita food production	Increase	Roundwood production
Capistrano (1990)	Increase	Food self-sufficiency	NA	NA
Enroth (1996)	No effect	Growth of per capita food production	Mixed	Several
Inman (1993)	Reduce*	Agricultural GDP growth	NA	NA
Kant and Redantz (1997)	Increase	Change in agricultural area	Increase	Roundwood production and forest exports
Mainardi (1996)	Increase	Change in agricultural area	No effect	Roundwood production
Palo *et al.* (1987)	Increase	Index of per capita food production	No effect	Roundwood production
Rudel and Roper (1997a)	Increase	Agricultural exports as percentage of GNP	NA	NA
Rudel and Roper (1997b)	NA	NA	Mixed*	Roundwood production /hectare forest
Rudel and Roper (1996)	Increase	Agricultural exports as percentage of GNP	Increase	Roundwood production
Rudel (1989)	No effect	Agricultural exports as percentage of GNP	No effect	Timber exports
Southgate (1994)	Increase	Agricultural export growth	NA	NA

* No effect when outliers removed   ** Higher in 1970s, no effect in 1980s
NA = Not applicable

Table 14: The effect of population on deforestation in multi-country regression models.

Study	Population Variables Analysed	Effect	Comments
Allen and Barnes (1985)	Growth and density	Mixed	Density increases. Growth: no effect
Bawa and Dayanandan (1997)	Rural and urban density	Increase	
Burgess (1991)	Growth	Lower	
Burgess (1993b)	Density	Increase	
Capistrano (1990)	Population/arable land	Increase	No effect when other variables were added
Cropper and Griffiths (1994)	Growth and density	No effect	Density in Africa: Increase
Deacon (1994)	Lagged growth	Increase	No effect when other variables were added
Enroth (1996)	Total, urban growth and density	No effect	Urban growth in Latin America: Increase
Gullison and Losos (1993)	Growth	Increase	
Inman (1993)	Total and rural growth	Mixed	Total: lower. Rural growth: Increase
Inman (1990)	Growth	Lower	Latin America and Africa: Increase
Kahn and McDonald (1995)	Labour force	No effect	
Kahn and McDonald (1994)	Labour force	No effect	
Kant and Redantz (1997)	Total	Increase	
Kimsey (1991)	Growth	Increase	
Lugo *et al.* (1981)	Density	Increase	
Mainardi (1996)	NA	NA	
Palo (1994)	Growth and density	Mixed	Density increases. Growth no effect
Palo and Lehto (1996a)	Total, density and growth	Increase	Subnational-level data: Increase
Palo and Lehto (1996b)	Density and growth	Increase	
Palo *et al.* (1996)	Density and growth	Increase	
Palo *et al.* (1987)	Growth and density	Increase	
Panayotou (1993)	Density	Increase	
Rock (1996)	Growth and density	Increase	
Rudel and Roper (1997a)	Rural density	Increase	
Rudel and Roper (1997b)	Rural growth	Increase	Only countries with small forests
Rudel and Roper (1996)	Growth	Increase	
Rudel (1989)	Lagged rural and total growth	Increase	
Shafik (1994a,b)	NA	NA	
Southgate (1994)	Growth	Increase	

However, since both the 1980 and 1990 FAO Forest Resources Assessments used population data to estimate deforestation for many countries, the significance of this result must be greatly qualified (Ludeke 1987; Scotti 1996; Rudel and Roper 1997a,b).[44] The only reason the correlation between deforestation and population in the models that use the FAO estimates is not even stronger is that the FAO used non-linear functions that included several other variables and did not apply the functions to the few countries that had reliable deforestation data.

The apparent influence of population in these studies may partially reflect the role of other variables correlated with population. Deacon (1994), for example, found that lagged population growth was highly associated with deforestation in a simple regression where population growth was the only independent variable, but ceased to be significant when political variables were also included. Capistrano (1990) had a similar result when she introduced dummy variables for region, income group and level of indebtedness in her model for 1971-1976.

Higher per capita income levels correlate with greater deforestation in most studies where the relationship between the two is statistically significant[45,46] (Table 15). Panayotou (1993), Cropper and Griffiths (1994) and Rock (1996) find evidence of an environmental Kuznets curve, but estimate very different threshold levels for per capita GNP ($5,000, $800 and $3,500 respectively). Most tropical forests have income levels well below at least two of these three thresholds.

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[44] Important exceptions include Binswanger *et al.* (1987) and Rudel and Roper (1996, 1997b). Rudel and Roper avoid using any deforestation estimates where population data were used to create the estimate, but still find a positive relationship between rural population growth and deforestation, at least for countries with small forests. Binswanger *et al.* (1987) use total agricultural area as their dependent variable and still observe a positive correlation between rural population density and land in crops and pasture.

[45] Binswanger *et al.* (1987) finds the opposite, but the estimated elasticity is very small. Rudel and Roper (1997b) found a similar result for the 1970s for countries with small forests. For the 1980s, developing countries with higher incomes had higher deforestation, although this relationship is not statistically significant. Enroth (1996) associates higher incomes with more deforestation in Asia and Latin America, but not in Africa. Palo *et al.* (1996) find higher incomes in Latin America lead to lower deforestation, but have the opposite effect in the other regions. They cite this as evidence of a Kuznets curve, since Latin America has higher per capita incomes.

[46] A positive correlation between high income levels and forest clearing does not rule out a positive correlation between poverty and forest clearing, since richer countries may not have fewer poor people.

Table 15: The effect of selected explanatory variables on deforestation in multi-country regression models.

Study	**Per capita income**	**Debt**	**Timber export prices**	**Devaluation**	**Roads**	**Political factors**
Allen and Barnes (1985)	Growth: no effect	NA	NA	NA	NA	NA
Bawa and Dayanandan (1997)	Level: no effect	Increase	NA	NA	NA	NA
Binswanger *et al*. (1987)	Level: reduce	NA	NA	NA	NA	NA
Burgess (1993b)	Level: increase	NA	NA	NA	NA	NA
Burgess (1992)	Level: increase	NA	NA	NA	NA	NA
Burgess (1991)	Level: increase	Increase	NA	NA	NA	NA
Capistrano (1990)	Level: increase	Mixed	Increase	Increase	NA	NA
Cropper and Griffiths (1994)	Level: Kuznets*	NA	Increase	NA	NA	NA
Deacon (1994)	Growth: no effect	NA	NA	NA	NA	Stability: reduce
Didia (1997)	NA	NA	NA	NA	NA	Democracy: reduce
Enroth (1996)	Level: mixed	NA	NA	NA	Mixed	NA
Gullison and Losos (1993)	Level: no effect	No effect	Increase	NA	NA	NA
Inman (1993)	Level: no effect	Mixed	NA	NA	NA	NA
Inman (1990)	Growth: mixed	Mixed	NA	NA	NA	NA
Kahn and McDonald (1995)	NA	Increase	NA	NA	NA	NA
Kahn and McDonald (1994)	NA	Increase	NA	NA	NA	NA
Kant and Redantz (1997)	Growth: increase	Increase	NA	NA	NA	NA
Kimsey (1991)	NA	No effect	NA	NA	NA	NA
Lugo *et al*. (1981)	NA	NA	NA	NA	NA	NA
Mainardi (1996)	Level: increase	Increase	NA	Increases	Increases	Stability: increases
Palo and Lehto (1996a)	Mixed	NA	NA	NA	NA	NA

Table 15 continued

Study	Per capita income	Debt	Timber export prices	Devalu-ation	Roads	Political factors
Palo and Lehto (1996b)	Level: increase	NA	NA	NA	NA	NA
Palo *et al*. (1996)	Level and growth: reduce	NA	NA	NA	NA	NA
Palo *et al.* (1987)	Level: increase	NA	NA	NA	NA	NA
Panayotou (1993)	Level: Kuznets	NA	NA	NA	NA	NA
Rock (1996)	Level: Kuznets	NA	NA	NA	NA	NA
Rudel and Roper (1997a)	No effect	No effect	NA	NA	NA	NA
Rudel and Roper (1997b)	Mixed	Mixed	NA	NA	Mixed	NA
Rudel and Roper (1996)	NA	Increase	NA	NA	Increase	NA
Rudel (1989)	Mixed	NA	NA	NA	NA	NA
Shafik (1994a,b)	No effect	No effect	NA	Increase	NA	Rights: increase
Southgate (1994)	NA	NA	NA	NA	NA	NA

* Kuznets: Increases for low per capita income levels, but reduces for high levels
NA = Not applicable

The models show no similar consensus when it comes to economic growth. A few studies conclude growth and deforestation are generally positively related (Inman 1993; Kant and Redantz 1997; Palo *et al.* 1996); one concludes the opposite (Palo and Lehto 1996b); while several others perceive no relationship (Allen and Barnes 1985; Deacon 1994).

Results relating to the relationship between greater external indebtedness and deforestation are also decidedly mixed. While no study argues more debt leads to less forest clearing, a number find no correlation between the two, or get contradictory results depending on the indicator of debt used and the region involved. Sometimes different studies by the same authors have even come to opposite conclusions on this issue (Rudel and Roper 1996, 1997a,b).

The few models which have included price variables, such as agricultural and timber export prices and real exchange rates, have all found higher export prices and devaluation to be positively correlated with deforestation (Binswanger *et al.* 1987; Capistrano 1990; Gullison and Losos 1993; Cropper and Griffiths 1994; Shafik 1994a; Mainardi 1996; Kant and Redantz 1997).

Positive associations have also been found between deforestation rates and access (Binswanger *et al*. 1987; Enroth 1996; Mainardi 1996; Rudel and Roper 1996, 1997b; Palo and Lehto 1996a). Road construction is especially important in countries with large forests, which would otherwise be quite inaccessible, and coastal countries with more accessible forests have higher deforestation (Rudel and Roper 1996).

With regard to political factors, the studies come to diametrically opposed conclusions. Deacon (1994) claims that politically unstable countries deforest less, while Mainardi (1996) asserts the contrary. Similarly, Didia (1997) says democracies have less deforestation, but Shafik (1994a) says authoritarian regimes do.

Deforestation is also said to be higher in places with more-unequal land tenure (Rock 1996), technologically stagnant agricultural sectors (Southgate 1994), lower fertiliser prices (Binswanger *et al.* 1987) and drier climates (Palo and Lehto 1996a).

Strengths and limitations

The data limitations affecting most of these models are so great that ‘any statistical results derived from them can be dismissed as not being based on a strong enough database’ (Kummer and Sham 1994: 151). As noted previously, the models also have problems arising from limited degrees of freedom, multicollinearity, heteroscedasticity, outliers, incorrect specification of causal relationships, and missing variables. Many authors overstate the statistical significance of their results, because they only present those equations which provided the best fit, after experimenting with numerous independent variables and functional forms.

In synthesis, one can question the validity of most available global regression models on three major issues:

- *Reliability of data:* As noted, most models use deforestation data from either FAO’s Forest Resources Assessment (1993) or FAO’s Production Yearbooks. We agree with Rudel and Roper (1997b: 54) that neither is ‘acceptable for empirical analysis of the causes of deforestation’. In particular, one should note the tautology in using the Assessment estimates, which, in most cases, were created using formulae that include population density, to evaluate population’s effect on forests. In effect, ‘a variable which FAO used to construct the dependent variable is now being used to predict the value of that variable!' (page 54).

The data limitations may be partially overcome in the future, as more accurate global land-use data become available, particularly using remote sensing. In the meantime, one possible alternative would be to supplement or substitute the FAO data with deforestation estimates based on local data and case studies, as Rudel and Roper (1996, 1997b) have done, although this also has problems. They use a dichotomous deforestation variable (high/low, with one per cent as the cut-off point).

Another possible way to overcome this problem would be to use proxies of deforestation for which more reliable data exist, such as wood production (Capistrano 1990; Gullison and Losos 1993) or agricultural land expansion (Southgate 1994). Again, however, as noted in Section 5.3, these variables have their own limitations.[47]

- *Mixing direct and indirect causes:* Earlier we have noted the potential dangers of mixing independent variables with varying degrees of directness in their causal relationships with deforestation. Most global regression studies suffer from this problem, in part because many studies lack an explicit theoretical framework.

  There are exceptions to this general picture. Kant and Redantz (1997) distinguish between first-level (direct) causes (roundwood consumption, export of forest products, changes in cropland and change in pasture area), and second-level (indirect) causes (e.g., prices, terms of trade, debt). It then uses a two-step regression method: first, the paper establishes the link between first-order explanations and deforestation; next, it analyses the links between first- and second-order causes. Such two-step procedures and the use of instrumental variables appear to be more-sound methodologies than conventional approaches.

- *Regional variation:* To produce meaningful results, the use of cross-national regression analysis requires that the variables included affect deforestation in roughly the same manner across countries. This is obvi-

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[47] Kant and Redantz (1997) raise additional doubts about whether the expansion of pasture and cropland is a good proxy for deforestation. He finds that, in Africa, one hectare of cropland expansion results in 2.8 hectares of deforestation, whereas the figure for Asia and Latin America is 0.5 hectares; although since his study is based on FAO's 1990 Forest Resources Assessment, these results could also be questioned.

> ously a strong assumption. Studies indicate that the effect of economic growth, foreign debt, population, and other variables may differ greatly between countries since, among other things, the explanatory variables interact with each other, and the state of each partially determines the effects of the others.
>
> In principle, this problem could be overcome by adding interaction terms among the independent variables, but often the degrees of freedom are too small to do that. Many studies include regional dummies, but this only allows point intercepts to vary across regions, rather than the slopes (coefficients). This problem can be solved by multiplying regional dummy variables by the global variables to create separate explanatory variables, but only at the expense of considerable degrees of freedom (Mainardi 1996; Kant and Redantz 1997). In the extreme case (dummies introduced for all variables), this would imply making separate regressions for the different regions.
>
> One possible alternative that may be able to address the issue of regional variation better than regression analysis is the use of Boolean algebraic methods (Rudel and Roper 1996). These techniques permit researchers to take into account factors that are locally important, even if they are not particularly common between countries, and to assess each factor within its own context.

In summary, at present, the large majority of global regression models cannot seriously presume to estimate the size of the effect of each independent on forest clearing, which is indicated by the very diverging results of these studies. Data quality and modelling techniques may improve in the future, although limited degrees of freedom will continue to be a problem. Until better data are available and more appropriate models are used, the principal contributions of the global regression modelling literature is more likely to come from its qualitative discussions of factors influencing deforestation than from a model's quantitative results.

Section Six

Summary: What Drives Deforestation?

This guide has reviewed some 150 economic models of deforestation. This section synthesises what these models tell us (and do not tell us) about the sources and causes of deforestation, and discusses policy implications. To the extent possible, we distinguish between points on which relative consensus exists and those where significant controversy persists.

It is worth emphasising again, that our approach has led us towards synthesising the most universal lessons regarding tropical deforestation, which may or may not apply to any specific case. Even though we have tried to make reference to the circumstances under which the conclusions are likely to apply, each country and region is unique and should be analysed individually.

6.1 The Sources of Deforestation

A broad consensus exists that expansion of cropped area and pasture constitutes a major source of deforestation. Pasture expansion is especially important in Latin America.

There is no similar consensus with regard to logging, although it seems to be a direct source of deforestation in some contexts and to play an indirect role in others. Southeast Asia has been identified as one region where logging contributes to deforestation.

Evidence regarding both fuelwood and open pit mining is weak, although it points to they being occasional sources of deforestation, particularly for fuelwood in Africa.

6.2 The Agents of Deforestation

Surprisingly little is known about how the characteristics of deforestation agents affect their behaviour. We know households that exhibit ‘full-belly’ or subsistence type behaviour are less responsive to market signals, but existing models tell us little about how common such behaviour is. No significant generalisation can be made about the roles of farm size, farmer background or timber company characteristics.

Analytical models suggest both time preferences and risk aversion are important. But their practical effect depends on assumptions about the relevant investment decisions, and there is little empirical evidence on which to base such assumptions. High discount rates and risk aversion both reduce investment, but that investment could be either forest clearing or forest conservation.

Some authors argue poorer families deforest more because they have shorter time horizons (higher discount rates), while others say they deforest less because they lack the necessary capital to put additional land into production. One (Godoy) has also suggested that a Kuznets curve may exist at the household level, implying that poor families initially clear more forest as their incomes rise but this tendency levels off or is reversed as they begin to seek more leisure. Existing models provide rather weak and conflicting evidence on these issues.

6.3 Agents’ Decision Parameters

Physical environment

The physical environment strongly influences where agents deforest. Many models provide evidence that forests in drier, flatter, higher-fertility areas, with adequate drainage – and thus more suitable for agriculture – are more likely to be cleared.

Agricultural prices

Substantial evidence supports the assertion that higher agricultural prices stimulate forest clearing. They make agriculture more profitable and help finance putting additional land into production.

An argument which may modify this conclusion is that over the long-run higher agricultural prices may facilitate a country’s transition to a more industrialised economy, which relies less on agriculture (Vicent, personal communication 1997). That implies deforestation would increase in the short term but later fall. Unfortunately, none of the models reviewed addresses this issue.

Since different crops and livestock products use distinct technologies and each has its own characteristic land intensity, changes in relative prices between agricultural products may affect forest clearing as much or more than changes in the general profitability of agriculture. This makes it impossible to predict how specific policies will affect forest clearing without analysing their impact on prices for specific products and the pressure each product places on forests.

The expenditure effect of higher agricultural prices (and changes in wages and other input prices) may have a profound impact on resource use, but is ignored in most models (Ruben, personal communication, 1997). It may, for example, lead to a shift from fuelwood to commercial energy sources (gas, electricity) which has positive impacts on the forests. But it could also lead to increased demand for forest products and land, and provide more capital for investments in forest conversion.

Timber prices

The evidence regarding timber prices is less definitive but suggests a similar conclusion, although the effect of higher timber prices remains particularly controversial. Higher prices may promote deforestation by making logging more profitable. Particularly in situations where producers do not have secure rights over forest resources, higher timber values only increase the net benefits of land clearing (presuming landholders sell the timber from cleared forest) and would definitely encourage deforestation.

Using a traditional supply-demand framework, trade restrictions (e.g., log export taxes and bans) will reduce total demand for timber, and therefore the log prices and the production of logs (deforestation due to logging), even if domestic demand may increase due to lower prices.

Other authors suggest that in the medium-term low timber prices discourage efficient harvesting and processing techniques, and that, in turn, leads to logging more rather than less timber. As evidence for this, they point to the fact that processing efficiency in developing countries where trade restrictions exist is often well below levels found in other countries, but the models reviewed cannot directly evaluate that hypothesis.

Low timber prices may also discourage investment in guarding against encroachment of logging areas by farmers. Logging companies will not avoid encroachment on forests that have already been logged unless they expect to log the entire concession area and the discounted value of future timber harvests is greater than the cost of managing the forest (Walker 1987). Under most typical situations in tropical countries, these conditions are unlikely to apply. Modelling logging and agriculture as complementary (logging-shifting cultivation tandem) rather than competing activities, makes it much more likely that higher timber prices will lead to greater overall deforestation.

The empirical evidence on the impact of higher timber prices comes largely from trade models and multi-country regression models and is not very strong. However, it points to the conclusion that higher prices lead to more logging.

Wages and off-farm employment

Micro-level, analytical, simulation and empirical models strongly suggest that higher rural wages reduce deforestation by making it less profitable to engage in agricultural and forestry activities associated with deforestation. They also suggest that, at the individual household level, greater off-farm employment opportunities produce a similar effect by competing with such activities for labour.

Regional and national analytical and simulation models also support the conclusions of micro-level models, although these hypotheses have yet to be successfully validated in macro-level empirical models, because of limited data on wages and off-farm labour. There are strong reasons, therefore, to believe that policies that favour rural wage increases and generate off-farm employment opportunities for rural people should reduce deforestation. Such policies should simultaneously conserve forests and diminish poverty.

Agricultural input prices

The evidence on how increased agricultural input prices may affect forest clearing is mixed, particularly as regards fertilisers. Analytical models point to two conflicting effects: the first involves the substitution of fertiliser by land in response to the change in relative prices; the second a reduction in the amount of land devoted to crops because farming becomes less profitable.

Attempts to resolve the issue empirically have met with only partial success. Linear programming and regression models suggest fertiliser price increases in Southern Africa may provoke greater deforestation or have little impact, while in some Latin American contexts they may reduce deforestation. It appears higher fertiliser prices are most likely to induce greater forest clearing when farmers are wavering between sedentary agriculture and more extensive shifting cultivation systems (assuming forest clearing for shifting cultivation is considered deforestation). This adds a cautionary note about the possible negative impact of current policies aimed at reducing fertiliser subsidies in Sub-Saharan Africa. The limited available evidence suggests that increasing pesticide and farm implement prices may lower deforestation.

In tropical Latin America, greater agricultural credit availability, particularly for cattle, is positively correlated with deforestation. This issue has largely been ignored in other regions.

Technological change in agriculture

The direct effect of technological change on individual farmer behaviour depends on the characteristics both of the technology and labour and output markets. Changes such as new crop varieties, which increase yields without significantly altering the demand for labour or capital, increase the amount of forest cleared by each farmer, in a similar manner as an agricultural price increase. If, however, higher yields subsequently depress agricultural prices, the ultimate outcome becomes indeterminate.

If the new technology is more labour intensive, its direct effect on deforestation is also indeterminate, particularly if farmers find it difficult, expensive or inconvenient to hire wage labour. Labour-intensive technologies stimulate land expansion by improving the profitability of agriculture, but will tend to limit the amount of land cultivated because each farmer will be able to cultivate less land with available household labour. Technologies that are especially suited for land already under cultivation, such as irrigation technologies that cannot be applied in the type of land that is still under forest cover, are especially likely to restrain forest clearing. Methods that improve the relative profitability of more intensive production systems are more likely to reduce deforestation than those that favour extensive systems.

These findings imply that agricultural research and extension policies designed to limit deforestation should focus on promoting profitable technologies that are more easily applicable to areas that have already been deforested, and intensive in labour and capital requirements.[48]

Accessibility

Numerous models from diverse contexts show that greater access to forests and markets generally leads to more deforestation. Roads, rivers and railroads all facilitate access, as do lower gasoline prices. Forest fragments are more accessible than large compact forests, and forests in coastal countries and islands are more accessible than in continental countries. Roads seem to have a stronger impact in regions dominated by commercial agriculture and areas with better soils, than in marginal lands inhabited mostly by small farmers that practice slash and burn cultivation.

The simple correlation between roads and deforestation, however, overstates the causal link from the first to the second, because roads are partly endogenous. Some roads are built precisely *because* an area has been cleared and settled, rather than vice versa, or both variables can be simultaneously

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[48] For the reasons explained previously, these types of technological change may also promote greater deforestation, but are less likely to do so than other types.

influenced by a third set of factors, such as soil quality or population density. Nevertheless, no policy intended to influence deforestation can be considered comprehensive unless it includes clear guidelines with respect to investments in transportation infrastructure.

Property regime and strategic behaviour

In analytical models, deforestation is greater under open access regimes – in particular when forest clearing gives claims to the land (homesteading) – compared to situations with well-defined and secure property rights. Open access situations where forest clearing becomes a means to obtain property rights creates incentives for strategic behaviour and 'land races'. It may be useful to distinguish between different types of strategic behaviour resulting from a homesteading context. Forests may be cleared *beyond* the point where the current net benefits are zero (the private property solution) for at least three different reasons (Angelsen 1997). (1) Forest is cleared up to the point where the *net present* value of land is zero. Even if the profit is negative the first years, technological progress, new roads, etc. will make it profitable in the future. (2) Forest is cleared to capture an expected profit through later *sale*, a situation that has similarities to phenomena in stock markets ('rational bubbles'). (3) In situations with few actors competing for forest land (*games*), and deforestation by one agent is costly to the other, certain groups may have an incentive to 'squeeze the others' by clearing more themselves (Angelsen 1997).

Broadly speaking, the first type of strategic behaviour can be found throughout the tropics. The second appears to be especially relevant in tropical Latin America, where several models from Brazil suggest that land speculation has stimulated forest clearing. The third kind of strategic behaviour, for example, in the form of conflicts between local communities and the state, seems to be particularly relevant to Southeast Asia and perhaps parts of Africa.

Some authors suggest that improving land tenure security in contexts where farmers obtain property rights by clearing forests encourages them to clear larger areas, and there is empirical evidence of such 'land grabbing' behaviour. This does not necessarily contradict the findings of several regression models from Latin America that show that deforestation is lower in areas with high land tenure security. Nevertheless, at this stage it is difficult to draw any general conclusion, and further empirical research is clearly needed.

Theoretically, high land costs resulting from land taxes or one-time price increases should discourage deforestation. However, constantly rising land prices encourage deforestation for speculative purposes in contexts where farmers obtain (more-secure) property rights by clearing land.

6.4 Underlying Factors of Deforestation

It is more difficult to establish clear links between underlying factors and deforestation than between immediate causes (decision parameters) and deforestation. The causal relationships are less direct and to empirically examine the role of underlying factors typically requires data from multiple countries and time periods, which often do not exist or are of poor quality.

Population

One of the most consistently cited, and controversial, underlying factors in deforestation in population pressure. Theoretically, population can affect deforestation through (1) changes in the number of rural families seeking land to cultivate, fuelwood or timber; (2) population's indirect effects on labour markets; (3) demand for agricultural and forest products; and (4) induced technological or institutional change.[49]

Population density and the percentage of land in forest are negatively correlated at the national level. However, this correlation often disappears when the models incorporate additional variables, implying that rather than population density determining forest cover a third set of factors may simultaneously affect both. In addition, only weak evidence links national population variables and recent deforestation. Moreover, models which use FAO forest resources assessment data to examine the relationship between population and forest cover, as many of them do, give spurious results since the FAO deforestation estimates themselves are to a large extent based on population data. Thus, the models provide few firm conclusions regarding the correlation between national population density and growth and recent deforestation.

At the local and regional levels, population is partly endogenous and determined by infrastructure availability, soil quality, distance to markets, and other factors. Government policies that affect migration (and hence population) at these levels include road construction, colonisation policies, agricultural subsidies and tax incentives, gasoline prices and macroeconomic policies. Since people migrate to forested areas because it is economically attractive to clear forest for agriculture, population levels in those areas cannot be considered an independent variable with regard to deforestation.

Greater population increases labour supply, which tends to lower wages and make forest clearing for agriculture more profitable. However, many factors can intervene at each step of this chain that may keep this from occur-

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[49] If technology becomes more labor and less land intensive as population density increases, deforestation should increase less than proportionally to rural population growth.

ring. Some studies at the subnational level show population density and growth to be positively correlated with recent deforestation, but others find no significant relationship between the two once variables such as market access and soil quality are incorporated.

Some evidence supports the hypothesis that rural population density has a greater effect on deforestation in places with less-developed markets, few off-farm employment opportunities, and more equally distributed landholdings. This implies that in the future this variable's importance may decline.

Few models focus specifically on the relationship between population and the demand for agricultural and forest products. However, it is worth noting that this aspect should be relatively less important in contexts where per capita income is changing rapidly or where agricultural and forestry products are strongly tradable. Globalisation is likely to make the population-demand relationship become less important at the national and regional levels. New agricultural and forestry export prospects may lead to rapid deforestation in low-population countries where small domestic markets previously limited deforestation.

Income

Many models associate higher national per capita income in developing countries with greater deforestation. They are less clear about whether deforestation later declines as countries become richer. It cannot be concluded from this, however, that rapid economic growth promotes deforestation, as there is no strong short- or medium-term relationship between economic growth rates and average per capita incomes.

Models that have attempted to evaluate the effect of high growth have obtained contradictory results. In the short-run, economic growth can be expected to reduce pressure on forests by improving off-farm employment opportunities, but increase it by stimulating demand for agricultural and forest products and improving access to markets.[50] Most conclusions regarding the correlation between per capita income or economic growth and deforestation come from global regression models with poor forest cover data, and thus must be assessed with caution.

External debt, trade and structural adjustment

The studies reach no consistent conclusion about the relationship between external indebtedness and deforestation. Some studies find the two to be pos-

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[50] Forest mining may also lead to economic growth, implying a causal relationship in the opposite direction.

itively correlated, while others find no connection. They are all based on global regression analyses that use poor-quality data.

According to analytical macro-models, policies that seek to improve the terms of trade for agriculture, such as exchange rate devaluation, trade liberalisation, reductions in agricultural export taxes, agricultural price subsidies and reduced fiscal spending on non-agricultural sectors, tend to raise prices received by farmers, and hence increase deforestation. Thus, structural adjustment policies (SAPs) that improve the terms of trade for agriculture can increase pressure on forests, and policies such as over-valued exchange rates, industrial protectionism, and urban biases in spending may be good for forests.

Despite the rhetoric of their supporters, not all SAPs have led to improved terms of trade for agriculture (J. Smith, personal communication, 1997). In particular, many adjustment programmes in Latin America have prompted real exchange rates to appreciate by promoting large capital inflows, rather than to be devalued, as might have been expected *a priori*.

Market characteristics and general equilibrium effects can either strengthen or dampen the effects of different policies on forest clearing. Agricultural and timber price increases and productivity improvements will tend to generate more deforestation when both output and labour supplies are more elastic. The initial effect of price increases or technological change on deforestation will be partially dampened as rural wages rise in response to greater demand, and this effect will be stronger when labour supply is more inelastic.[51] On the other hand, higher rural wages could potentially generate more demand for agricultural and forest products.

Structural adjustment and trade liberalisation policies may have short- or medium-term recessionary consequences that reduce urban food demand and this could potentially lead to lower, rather than higher, agricultural prices. But they might also lower urban employment, putting downward pressure on rural wages, and consequently having the opposite effect.

Pro-export policies designed to increase agricultural and forest product exports are likely to affect deforestation more than policies that promote production for the domestic market. This is because increased supplies of agricultural exports are less likely to put downward pressure on prices and dampen the initial effects of the policies. Similarly, pro-agricultural policies can be expected to have stronger deforestation effects in the contexts of global agricultural markets and trade liberalisation.

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[51] Local labor supply is likely to be much more elastic in the long run due to the possibility of migration.

Computable General Equilibrium and global regression models tend to show that foreign currency devaluations, trade liberalisation and subsidies for agriculture increase deforestation. It should be remembered, however, that the results of the former depend heavily on rather arbitrary assumptions about price elasticities, and both generally use poor-quality data. Finally, all of these macro-models tend to look at the agricultural and forestry sectors at a very aggregate level. Changes in relative prices within these sectors may have a greater impact on deforestation than the overall sectoral terms of trade and to date these models have shed little light on this aspect.

Political factors

Little can be said based on existing economic models about the impact of political factors on deforestation. The empirical studies have significant methodological and data problems and are evenly divided in their results.

Section Seven

Priority Areas for Future Research

> '*All models are wrong, but some are useful*.'
> (George Box, quoted in Kennedy 1992: 73).

Even though there has been a boom in the production of economic models attempting to explain deforestation, many issues remain unexplored and major research challenges persist. The availability of more and better data in the coming years, particularly from remote sensing sources, should permit better empirical analysis and hypothesis testing. In this final section, we discuss some promising research topics and methodologies.

7.1 Micro-level Models

Analytical household and firm-level models help explore the logical implications of different assumptions, and ensure consistency in the arguments. The current weakness of available data further strengthens the need for explicit analytical frameworks to be able to fully take advantage of the data that do exist.

There is also no substitute for careful, quantitative micro-level empirical research, and the volume of such studies is not impressive. Plausible theoretical mechanisms are often found to be of little empirical relevance. Such studies are, however, time and resource consuming, and the conclusions are – strictly speaking – limited to the geographical area being studied.

Important issues that require further analytical clarification and empirical investigation include:

- Under what circumstances will policies designed to improve agricultural productivity and make agriculture more labour and capital intensive reduce pressure on forests and when are they likely to increase it? This issue has strong policy relevance, since intensification programmes are a commonly suggested means to reduce the pressure on virgin forest, and the existing theory and empirical evidence about their impact is still weak and contradictory.

- As shown, many model conclusions depend on assumptions made regarding labour markets. Existing open economy and subsistence/Chayanovian models generally make extreme assumptions regarding labour markets – either they do not exist or they are perfect – and intermediate cases need to be explored further. Fortunately, a relatively rich literature on agricultural household models exists that could be applied to analysing this issue. The labour market assumption is closely related to another key area for further investigation, namely *migration.*

- The popular and professional literature often refers to a link between poverty and environmental degradation, yet poverty is rarely integrated into economic models in general, and deforestation models in particular. On the consumption side, poverty could be directly related to the strength of the income effect relative to the substitution effect (Angelsen 1996). However, poverty is also associated with limited ability to invest on the production side, and may have other, less obvious, relationships with deforestation (Reardon and Vosti 1995).

- When forest clearing establishes property rights (homesteading), deforestation becomes an investment in the future for the farmer. Conventional economic theory portrays environmental degradation as a form of disinvestment, but in homesteading situations the logic is reversed. This can lead to unexpected results such as lower discount rates and higher tenure security actually increasing deforestation. If land race effects are present, they ought to be incorporated into future models since this can be crucial for the results. Moreover, it may be useful to consider *both* deforestation and forest management to be long-term investments, and generate analytical conclusions about the conditions under which landholders chose one or the other or a combination. More empirical work on the relative importance of different effects is also clearly needed.

- Most household models assume one representative household or a homogeneous farm group. This ignores crucial aspects of social differentiation. Households have different initial resource endowments and face different constraints and prices in labour, credit, land and product markets. This has fundamental implications for the dynamic aspects of deforestation processes, interactions between deforestation agents, and the implications of policies that affect the distribution of wealth and other assets. Including such aspects could yield new and innovative results, but has yet to be carried out in a rigorous manner. Both purely analytical and simulation models could be very useful for this purpose. Research in the area should be able to draw on both the empirical literature, as well as the more recent 'economics of rural organisation', which focuses on the issues such as moral hazard, adverse selection, unequal distribution of assets and power (e.g., Hoff *et al.* 1993).

- Another recent branch of rural and agricultural economics is village-level Computable General Equilibrium (CGE) models. Taylor and Adelman (1996: 5-6), the standard reference on this subject, note that 'it is entirely possible that the most important impacts of a policy change on production, marketed surplus, or income will not be found within the households seemingly most affected by the policy, but in the ways that one household transfers the impacts of policy changes to another'. Village CGE models attempt to capture such economic linkages between households, in particular the price effects. The application of this modelling approach to deforestation is still in its infancy. (See, for example, Holden *et al.* 1997.)[52]

7.2 Meso-level Models

Non-spatial regression models, using provincial or municipal data, appear to be more useful and conceptually more sound than global regression models. Such regression models should be based on an explicit theoretical framework. This is necessary to ensure consistency in the interpretation of results, and to avoid mixing variables at different levels (see Figure 1). Two-step procedures and the use of instrumental variables can be a useful approach in this respect (Deininger and Minton 1996; Kant and Redantz 1997).

Spatial models appear to be most useful at the meso level. As available GIS data expand, many new possibilities will develop for useful modelling. It should soon be possible in some cases to use panel data for spatial regres-

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[52] At present, economists from the International Food Policy Research Institute (IFPRI) and Wageningen Agricultural University are engaged in research of this type, but little has been published to date (R. Ruben, personal communication, 1997).

sion models, as Foster *et al.* (1997) and a Wageningen Agricultural University project in Costa Rica have begun to do (R. Ruben, personal communication, 1997). This will greatly facilitate the incorporation of price variables into the models. It should also be possible to incorporate agricultural census and survey data into a GIS framework, allowing modellers to take into account many additional variables related to deforestation agents and land use.

A major challenge is to incorporate a realistic description of economic behaviour into spatial models. Decisions affecting the rate of deforestation are taken at the household level, whereas the most interesting consequences are often at the district or regional level. Regional, spatial models that integrate a realistic description of agricultural household decision making would therefore be very useful.

In the future, spatial models will have particular merit in answering the ‘where’ question. They can help decision makers answer questions such as: Which forest areas are likely to face the heavy pressure in the future, and therefore preventive actions will be needed to avoid deforestation? What are the implications of building new roads in a particular area? How is the establishment of a protected forest area likely to affect the surrounding forests?

7.3 Macro-level Models

General equilibrium models

General equilibrium models can fill an important gap left by household and firm models, by exploring the effects of government policies and of aggregate supply and demand for products and factors on the behaviour of economic agents. Such models therefore have an important role in economic studies of deforestation. The models, however, tend to make fairly conventional assumptions and they often uncritically adopt features taken from previous attempts to address other issues.

Future work with these models might productively focus on two broad areas: first, disaggregating the models into sectors, subsectors of agriculture and regions; and second, more realistic descriptions of the underlying behaviour of economic agents and the way the economy operates.

- Deforestation is often concentrated in a few regions that represent only a small proportion of the national economy. It is, therefore, essential to disaggregate economic processes by region. Where data limitations make this impossible, the value of CGE modelling is significantly reduced.

- Another relevant disaggregation is between different subsectors of agriculture, for example, based on location (frontier and non-frontier), production systems (shifting cultivation and sedentary cultivation), or groups of crops (e.g., based on land intensity). This will enable a more detailed policy analysis, taking into account switching between crops and/or production systems. One particularly important aspect is how different types of technological progress affect various subsectors, thereby identifying policies which can boost agricultural production and rural income without making forest conversion more attractive.

- Most CGE models that include both the agricultural and forestry sectors assume they compete for land. Many empirical studies suggest that the two sectors complement each other and work in tandem in forest encroachment. This issue of competing *versus* complementing sectors is important. Modifying assumptions of previous models on this point is likely to alter some of the model results.

- More realistic and complete assumptions should be incorporated regarding agricultural household and firm level behaviour. Generally, the micro-behaviour posited in these models assumes the simplest version of the open economy approach, which implies that important aspects related to poverty and self-sufficiency are not included. 'Land race' effects (property rights obtained by forest clearing) and other issues related to property rights and land markets that are central to deforestation in many countries might also be included.

- Current CGE models assume that markets are friction free and ignore issues of transaction costs. Thus, changes in tax rates, world market prices and other variables are expected to pass through to the farm gate fully and immediately. Although recent policies designed to liberalise markets may have increased market integration, the persistence of high transport costs, monopoly power and other market imperfections imply this assumption should be critically examined.

- As mentioned earlier, attempts are now under way to nest farm-level linear programming models within macro-level CGE models. This approach, while expensive and still largely experimental, has the potential to generate more realistic approximations of how farmers might respond to policy changes at the macro-level and allow those responses to feed back into the macroeconomy.

Global regression models

Global regression models comprise the single largest group of deforestation models. This reflects the greater availability of data appropriate for this type of model, the analytical and computational simplicity of the approach, and a desire to produce conclusions that are universally valid, rather than the models' superior capacity to assist in understanding and explaining deforestation.

We have strong doubts about the value of producing more global regression models. The main reasons for this are:

- the poor quality of available data;
- the limited degrees of freedom that force model makers to attempt to explain all deforestation based on a small number of explanatory variables and to assume each variable affects all countries similarly;
- their weak capacity to distinguish between correlation and causality or to determine the direction of causality;
- their often inappropriate assumptions regarding the normality of the dependent variables and the residuals, as well as the independence of the explanatory variables and the residuals; and
- their tendency to lose sight of strong micro-level relations, which evaporate in the process of aggregating data.

Certain steps can be taken to overcome some of these limitations, and some recent global regression models are substantially better than the earlier models. These tend to have a clearer theoretical framework and more appropriate dependent variables. Typically, they use higher-quality data and two- or three-step regressions or systems of equations, rather than simple Ordinary Least Squares (OLS), and test and correct for normality, multicollinearity, heteroscedasticity and autocorrelation (if time series or panel data). The quality of global forest cover data may also significantly improve over the next 10 years. Nevertheless, we believe that other modelling strategies hold more promise for offering significant new insights and conclusions about deforestation than global regression models.

7.4 Some Largely Non-researched Modelling Approaches

Given the large variety of economic modelling approaches that are available, there are many new and innovative economic approaches to studying the causes of deforestation that might be fruitfully applied in the future. Here are some examples.

- *Institutions* are generally recognised to be important in shaping the incentives for the deforestation agents, and the large qualitative and descriptive literature has generated useful insights about how they operate. Yet, there are few modelling exercises that explicitly take institutions into account, and the little work to date has been confined almost exclusively to looking the effect of different property regimes. Making institutions endogenous in the models is even more difficult. A general tenet is that institutions develop as resource scarcity increases (e.g., Eggertson 1990). If correct in the deforestation context, this could dampen the effect of higher resource pressure on the rate of deforestation.

- *Strategic interaction (games)* between different agents involved in the use of forest resources is a topic which has received little attention in the deforestation literature. Such games could be important. For example, they may in some cases result in 'land races' where an agent wants to squeeze the others by clearing more forest (Angelsen 1997).

- *Empirical economic models of logging company behaviour* are almost non-existent. This is surprising given the prominence logging receives in the deforestation debate. One explanation is, of course, the difficulty of obtaining reliable data. Given the inconclusive nature of some of the theoretical models, empirical research to test opposing hypotheses and to measure the strength of different effects is clearly needed.

7.5 Final Remarks on Models and Muddles

This review has assessed the relative merits of different economic modelling approaches, and we have summarised our judgements in Table 16. Our assessment of policy relevance and priority in future research is made in relation to what we consider the main purpose of the models reviewed, namely to gain insight into the causes behind deforestation.

We are sceptical of the value of the global regression modelling work done so far, and of some of the highly stylised general equilibrium models, based on rather artificial assumptions about economic behaviour and how the economy functions. We would like to see more studies that combine a realistic description of household behaviour and the regional/national dynamics, both in terms of general equilibrium effects (endogenous prices) and migration, as well as the spatial dimension. Micro-level models should attempt to better include aspects of poverty, social differentiation and institutions. Spatial models at the meso-level could fruitfully include a better description of economic behaviour and the role of economic incentives. Macro-level general equilibrium models should be disaggregated to capture regional differences and the interaction between different crops and agricultural production systems.

Finally, as noted earlier, this review's exclusive focus on quantitative models may have left some with the mistaken impression that we consider

Table 16: A summary assessment of different modelling categories.

Model category	Theoretical soundness	Data quality	Policy relevance	Research priority	Suggested redirection; new topics
Analytical household/ firm models (3.1, 3.2)	High	NA	Medium	Medium	Social differentiation; poverty; institutions
Empirical household/ firm models (3.3)	Medium	High	High	High	As above; income *vs.* substitution effects; crop choice
Regional, spatial models (4.1, 4.2)	Medium	High	High	High	Economic incentives: migration, village-level CGE models
Regional, non-spatial regression models (4.3)	Low/ Medium	Medium	High	Medium	Distinguish between variables at various levels
Analytical macro-models (5.1)	Medium	NA	Medium	Low	
CGE models (5.2)	Medium	Low (medium)	Medium (potentially high)	Medium	Disaggregation (regions, agricultural sub-sectors, crops); micro-foundation
Trade and commodity models (5.3)	Medium	Medium	Medium	Medium	Relationship trade-deforestation
Global regression models (5.4)	Low	Low	Low (potentially medium)	Low	Better data; distinguish between variables at various levels

this approach is superior to others that have been used to understand deforestation. We believe qualitative analysis and studies using descriptive statistics are complementary to formal models. Qualitative studies provide important insights that are difficult to capture in quantitative models and can inspire model builders to include new variables and causal relationship in their models.[53] They are also particularly useful for adding a historical dimension to studies of deforestation and for highlighting institutional issues that have

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[53] As Lambin (1997: 18) notes, ‘there is a striking contrast between the complexity of descriptions of land-cover change processes for specific case studies, and the relative simplicity of the mechanisms represented in models’.

proved difficult to model. Quantitative models, on the other hand, are useful to check the internal logic of the arguments: What are the implications of a given set of assumptions, or what are the assumptions necessary for certain policies to work? Empirical quantitative models may also be useful to test hypotheses about causes of deforestation, and the relative importance of different factors.

After all, all models are wrong, but some may hopefully be useful to understand the process of deforestation, and help in addressing the problem.

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Appendix 1

Variables Which Have Been Included in Economic Deforestation Models

1. Magnitude of deforestation

- Forest cover
- Estimated biomass
- Decline in forest cover (absolute and percentage)
- Wood production
- Forest reserve area
- Increase in crop and pasture area

2. Characteristics of deforestation agents

Utility function

- Discount rates
- Time preferences
- Risk preferences
- Desire for leisure
- Basic needs
- Desire for stable employment
- Consumption preferences

Background

- Place of origin
- Duration of residence
- Ethnic group
- Education
- Parent's occupation
- Number of previous moves
- Previous farming experience

Initial resources

- Household size
- Number of adults
- Number of children
- Initial capital
- Initial value of livestock
- Initial irrigation investment
- Initial landholding
- Initial forest resources
- Wealth
- Farmer's age
- Nutritional status
- Health: time lost due to illness

3. Choice variables

Land allocation

- Area cleared
- Area logged
- Product mix
- Fallow and cropping length
- Clearing of primary or secondary forest

Labour allocation

- Between work and leisure
- Between on- and off-farm labour

- Between intensification and forest clearing
- To logging
- To forest management
- To property rights enforcement
- To fuelwood and fodder collection
- Migration

Capital allocation

- Land purchase
- Forest rights purchase
- Land title/tenure security investments
- Input purchase
- Hired labour purchase
- Other capital purchases

Consumption purchases

- Fuelwood purchase

Disembodied technology

4. Decision parameters

Output prices (current and expected)

- Agricultural prices
- Timber prices
- Fuelwood prices
- Price of cleared land

Labour costs

- Rural wages
- Returns to alternative investments
- Implicit land rents
- Forest resource rents
- Time spent walking to fields
- Probability of unemployment

Other factor prices (current and expected)

- Land titling/enforcement costs
- Input prices
- Transportation costs to market
- Interest rates
- Wages for hired labour
- Land rents and concession payments

Risk

- Physical security/violence
- Market fluctuations
- Climatic/biological risks
- Policy fluctuation risks
- Land and forest tenure risks

Property regimes

- Land tenure (full private property, homesteading, open access, control over land but not forest)
- Forest tenure (terms of concessions, including duration, under what conditions revoked)

Available technology

- Technical assistance
- Type of technology
- Whether appropriate only for already cleared land or also for still forested land
- Availability of chainsaws
- Effectiveness of conservation measures
- Effectiveness of malaria control efforts

Factor constraints

- Labour (available supply of hired labour, quality of hired labour)
- Capital (availability of credit)

Government restrictions

- Protected areas
- Minimum logging diameters
- Concession conditions – with regard to type of management

Environmental factors

- Soils
- Topography
- Forest size
- Climate
- Island/coastal/river
- Physical tree growth
- Incidence of malaria

Family Income

5. Underlying Variables

Demographics

- Population growth (rural, urban and total)
- Population density (rural, urban and total)
- Dependency ratios
- Labour supply/economically active population (total and rural)

Government policies

- *Ad valorem* taxes
- Export taxes
- Tariffs
- Land taxes
- Income taxes
- Land tenure and concession policies
- Timber trade restrictions
- Minimum wages
- Agricultural processing subsides
- Subsidies to manufacturing / urban areas

- Input subsidies
- Credit subsidies
- Urban and rural public infrastructure investments
- Pan-territorial pricing
- Total public expenditure
- Exchange rate policies
- Monetary policy
- Public debt
- Foreign assistance capital flows

World market prices

- Agricultural prices
- Timber prices
- Manufacturing or mineral prices

Macroeconomic variables

- National income (level and growth rate)
- Exchange rates
- Interest rates
- Private capital flows

Technology

Asset and income distribution

Appendix 2

Deforestation Models for Specific Countries

Africa:

Botswana

Unemo (1995)	computable general equilibrium

Burundi

Bosquet *et al*. (1997)	spatial regional simulation

Cameroon

Gockowski (1997)	trade and commodity
Mamingi *et al*. (1996)	spatial regression
Mertens and Lambin (1997)	spatial regression
Thiele and Wiebelt (1993a)	computable general equilibrium
van Soest (1998)	regional regression

Chad

Chomitz and Griffiths (1997)	spatial regional simulation

Ghana

López (1993)	computable general equilibrium

Tanzania

Angelsen *et al*. (1996)	regional regression
Aune *et al*. (1996)	computable general equilibrium
Monela (1995)	linear programming
Sankhayan (1996)	linear programming

Sudan

Dufournaud *et al*. (1992)	computable general equilibrium
Elnagheeb and Bromley (1994)	trade and commodity

Zaire

Mamingi *et al*. (1996)	spatial regression

Zambia

Holden (1991, 1993a,b, 1997)	linear programming
Holden *et al*. (1997)	household regression
Holden *et al*. (1996)	village level computable general equilibrium
Mwanawina and Sankhayan (1996)	computable general equilibrium

Asia:

India

Chakraborty (1994)	national regression
Foster *et al*. (1997)	household regression

Indonesia

Angelsen (1996)	household simulation
Barbier *et al*. (1995)	trade and commodity
Gastellu-Etchegorry and Sinulingga (1988)	spatial regression
Holden and Simanjuntak (1995)	linear programming

Osgood (1994)	regional regression
Thiele (1995)	computable general equilibrium
Walker and Smith (1993)	household simulation

Malaysia

Brown *et al*. (1993)	spatial regression

Nepal

Bluffstone (1993 and 1995)	household simulation

Philippines

Coxhead and Shively (1995)	computable general equilibrium
Cruz and Repetto (1992)	computable general equilibrium
Kummer and Sham (1994)	regional regression
Kummer (1992)	regional regression
Liu *et al*. (1993)	spatial regression

Sri Lanka

Bandara and Coxhead (1995)	computable general equilibrium

Thailand

Cropper *et al*. (1997)	regional regression
Katila (1995)	regional regression
Lombardini (1994)	regional regression
Panayotou and Sungsuwan (1989)	regional regression
Panayotou and Sussengkarn (1992)	computable general equilibrium

Latin America:

Belize

Chomitz and Gray (1996)	spatial regression

Bolivia

Godoy *et al*. (1996)	household regression
Godoy (1997)	household regression

Brazil

Andersen (1996, 1997)	regional regression
Dale *et al*. (1993a,b, 1994)	spatial simulation
Jones *et al*. (1995)	household regression
Nghiep (1986)	linear programming
Ozório de Almeida and Campari (1995)	household regression
Pérez-García (1991)	household regression
Pfaff (1997)	regional regression
Reis and Guzmán (1994)	regional regression
Reis and Margulis (1991)	regional regression
Southworth *et al*. (1991a and b)	spatial simulation
Wiebelt (1994)	computable general equilibrium

Costa Rica

Harrison (1984)	regional regression
Persson and Munasinghe (1995)	computable general equilibrium
Persson (1995)	computable general equilibrium
Rosero-Bixby and Palloni (1996)	spatial regression
Ruben *et al*. (1994)	linear programming
Sader and Joyce (1988)	spatial regression
Sader (1987)	spatial regression

Ecuador

DeShazo (1993)	household regression
Hoogeveen (1994)	computable general equilibrium
Pichón *et al*. (1994)	household regression
Pichón (1997)	household regression
Pichón (1993)	household regression
Southgate *et al*. (1991)	regional regression

Honduras

Godoy *et al*. (1997)	household regression
Ludeke *et al*. (1990)	spatial regression
Ludeke (1987)	spatial regression

Mexico

Barbier and Burgess (1996)	regional regression
Boyd (1994)	computable general equilibrium
Deininger and Minten (1997)	spatial regression
Deininger and Minten (1996)	regional regression
Muñoz (1992)	household regression
Nelson and Hellerstein (1997)	spatial regression

As international concern over tropical deforestation has grown over the last ten years, researchers have sought to understand the causes of deforestation and possible solutions using quantitative economic models. This book reviews the results and methodology of over 150 of these models and synthesizes the main lessons that can be learned from them.

Higher agricultural prices, lower wages, less off-farm employment, and more roads generally lead to more deforestation. Major doubts remain on the impact of technological change, agricultural input prices, household incomes, and tenure security. The role of macro level factors such as population growth, poverty reduction, national income levels, economic growth and foreign debt is still largely uncertain.

While the boom in deforestation modeling has yielded new insights, many model results should be regarded with caution because of poor data quality and methodological weaknesses. In particular, the book finds most multi-country regression models to be of limited value. It recommends a shift in future research towards household and regional level studies, instead of the current emphasis on national and multi-country studies.

The Center for International Forestry Research (CIFOR) was established in 1993 under the Consultative Group on International Agricultural Research (CGIAR) system in response to global concerns about the social, environmental and economic consequences of loss and degradation of forests. CIFOR's Mission is to contribute to the sustained well-being of people in developing countries, particularly in the tropics, through collaborative strategic and applied research and related activities in forest systems and forestry, and by promoting the transfer of appropriate new technologies and the adoption of new methods of social organisation, for national development.

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