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Review

Use of models to analyse land-use changes, forest/soil degradation and carbon sequestration with special reference to Himalayan region: A review and analysis

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Abstract

Land use-changes and forest/soil degradation affect emissions of green house gases (GHGs) rather strongly, thereby causing global warming. These processes have led to a deep concern among the policy makers, scientists and public alike. For analysing causes and impacts of this complex problem, modelling has become increasingly more important, as evidenced by a plethora of models developed particularly during the last decade. This study reviews and synthesises the available models relating to land-use changes, forest/soil degradation and C sequestration in developing countries in general and the Hindu Kush Himalayan (HKH) region in particular. The major findings of these models in terms of factors affecting land-use changes especially, deforestation or agricultural expansion, are agricultural and timber prices, wage rates, risks in agriculture, population density in the rural areas, access to forestland, and titling security in frontier areas, and some of the government policies of economic reforms in the developing world. These findings, however, are space and time specific, and hence suggest for different policy options. A number of modelling techniques have been used in the past, such as, conceptual, analytical, empirical regression, and programming/simulation models. Both static and dynamic models have been used at different scales from household to global levels. Most studies in the HKH region are based on qualitative/descriptive methods using conceptual modelling techniques. Integrated models for analysing C sequestration dynamics as a function of land-use changes and forest/soil degradation in a holistic approach are emerging. Based on the review and synthesis of different techniques, a conceptual modelling framework is presented. This consists of a dynamic bio-economic modelling framework capable of capturing both socio-economic behaviour and bio-physical processes combined with geographical information systems/remote sensing techniques. Such modelling efforts have the potential of assisting policy makers and planners to identify and implement sustainable agriculture and forestry practices, leading to mitigation of CO_2 emissions in developing countries in general and the HKH region in particular.

Keywords: C sequestration; Forest/soil degradation; Hindu Kush Himalayan region; Land-use changes; Models

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1. Introduction

Land use-changes in the recent past, especially deforestation and agricultural expansion in developing countries, have greatly affected the global warming process through emissions of greenhouse gases (GHGs), affecting thereby climate system, biodiversity, supply of forestry products, and soil degradation (Barbier, 2001; Brown and Pearce, 1994; Houghton, 1994, 1999; IPCC, 2000; Lambin et al., 2000; Turner, 1994; WCED, 1987). Policy makers, scientists and public have shown a deep concern about the challenges arising out of this phenomenon, which is caused by various factors interacting over time and space in complex ways. To analyse causes and impacts of these land-use changes, modelling is becoming increasingly more important as evidenced by the evolution of a plethora of models since the 1990s (e.g., Agarwal et al., 2002, Angelsen, 1999, 2001; Bajracyarya, 1983; Bluffstone, 1995; Brown and Pearce, 1994; Casse et al., 2004; Kaimowitz and Angelsen, 1998; Kant, 2000; Lambin, 1997; Sankhayan et al., 2003; Shively, 2001; Thapa and Weber, 1995; UNU/WIDER, 1999; Uitamo, 1999; Verburg et al., 2002; World Bank, 1991).

These studies have applied different kind of models, give diverse findings, and also are to a varying degree characterised by disciplinary bias. Rather a few of them include consideration of GHG-emissions, or are developed for use in the Hindu Kush Himalayan (HKH) region. Although they undoubtedly have added to the understanding of the factors and processes responsible for land-use change behaviour and their consequences, it is of considerable interest to assess these models and discuss possible future improvements in this research field.

The main objective of this paper is to review and evaluate the existing models relating to land-use changes, forest/soil degradation, and effects on C sequestration in the HKH region, and discuss which type of models seem most promising for future integrated analyses.

The focus is on the interactions between agriculture and forest lands. We found rather few models, which have been used in the HKH region, and, therefore, extended the scope of the study to include relevant models used in other developing countries or at global level. First, the main contents of past reviews of land-use models are presented. Secondly, because the behavioural assumptions underlying land-use analysis are important, we discuss (in Section 3) the theoretical underpinnings of farm household models and von Thünen's celebrated land-use model. Thirdly, we evaluate more recent and relevant models relating to these issues, and classify the various models according to modelling techniques used, major variables included, scale of studies, their origin, and main findings. Finally, pros and cons of different models are discussed, and recommendations given for future work.

The underlying purpose of this study is to establish a theoretical and empirical basis for developing a dynamic bio-economic model capable of analysing land-use changes and C sequestration dynamics in its entirety in areas in the HKH region following systems approach. This effort constitutes a part of the research project 'Land-use changes and forest/soil degradation effects on C sequestration at the watershed level in Nepal: an interdisciplinary systems analysis using bio-economic modeling'. This project aims at improving the decision basis for formulating appropriate policies relating to land-use changes and forest/soil degradation under an agrarian dominated rural economy conducive to reduction of forest/soil degradation, and enhancing C sequestration potential at the end in the developing countries in general and the HKH region in particular.

2. Earlier reviews

A number of reviews are available relating to modelling of land-use changes and their effects on forest and soil degradation. The issue of C sequestration impacts due to land-use changes and forest/soil degradation, however, is missing in all these reviews. The reviewers are primarily guided by their own disciplines like economics, geography, natural sciences. The scope of the reviews varies from a single discipline like economics (Barbier, 2001; Kaimowitz and Angelsen, 1998; Brown and Pearce, 1994) to multidisciplines including combinations of geography, ecology and economics/social sciences (Agarwal et al., 2002; Brown and Pearce, 1994; Lambin, 1994, 1997; Lambin et al., 2000; Verburg et al., 2004). These reviews mainly focus on methodologies, data sets and findings.

2.1. Economic models

Kaimowitz and Angelsen (1998) reviewed about 150 economic models for deforestation used in different parts of the globe. The reviewed models were basically related to individual choices on decision making with simplification of complex multidimensional processes, and highlight only a few of many variables and causal relations involved in land-use change giving answers to why, where, when and how much land has been converted from one use to other. The framework used for analysing the variables affecting deforestation is as shown in Fig. 1. The variables affecting deforestation are linked with scale and size of the unit of analysis under study. The authors have first classified the whole range of models into three levels, namely, household and firm level (micro), regional level (meso), and national level (macro). Further, under each level the models are grouped according to the techniques used—i.e. analytical, simulation (including mathematical programming) and regression. These classifications are then used for evaluating the models in terms of their structure, function, strengths and weaknesses.

In these models, the links between underlying variables, decision parameters, and choice variables work through markets, institutions, infrastructure and technology in a given time and space (Fig. 1). However, CGE (Computable General Equilibrium) and international trade models confine themselves to market linkages alone.

The study concludes that increase in deforestation is mainly due to easy access to forest; higher agricultural and timber prices; low rural wages; and more opportunities for long distance trade. Population and migration both affect deforestation rates in a complex fashion. The effect of population growth on deforestation is always not positive. The relationships between deforestation and productivity growth, input prices, land markets, land and forest tenure security, and household income (poverty) vary over space and time. Generally, it is hard to find any clear-cut relationship between macroeconomic variables/policies and deforestation, but this review argues that a number of policy reforms included in current economic liberalisation and adjustment efforts might have increased the pressure on forests.

The review criticises multi-country regression models, mainly due to rather poor forest data quality they use. National studies applying general equilibrium models are evaluated as useful in principle, but they should more strongly take into account regional diversity, distinguish between sub-sectors of agriculture, and modify conventional perfect competition assumptions. The poor data quality in these models is emphasized. One main recommendation is that the

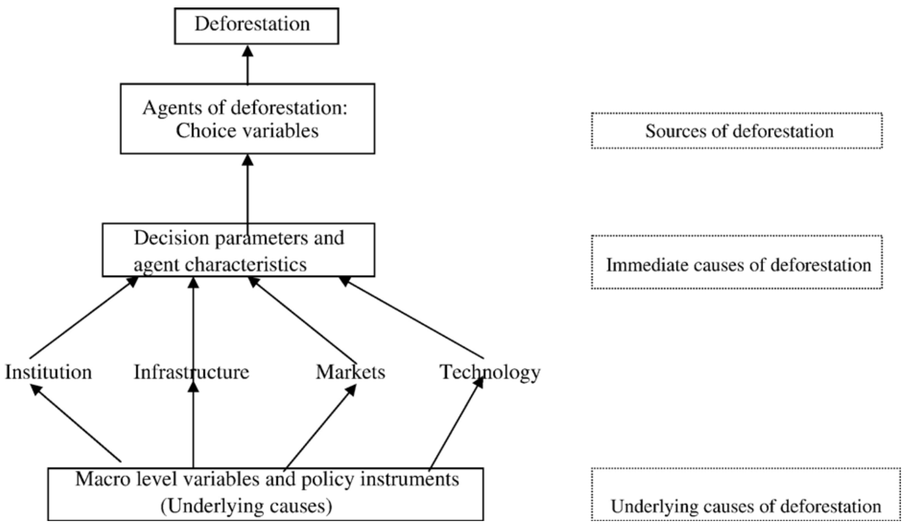

Fig. 1. A conceptual framework of different types of variables affecting deforestation (Source: Kaimowitz and Angelsen (1998)).

future research can probably be made more productive by concentrating on household and regional-level studies, instead of national and global studies.

Barbier (2001), in another attempt to reviewing economic models on deforestation, categorised the models of deforestation and land-use as 'first wave' and 'second wave' models. The models that fall under the 'first wave' group are cross-country analyses of deforestation using four types of models. These models usually employ poor data quality and the cross-country averages are sometimes problematic to interpret. The results of Environmental Kuznets Curve (EKC) (inverted U shape regression models using change in forest area as dependent variable and per capita GDP and other macroeconomic variables as explanatory variables) analyses are mixed. The EKC holds for Latin American and African countries whereas it is inconclusive when applied to both temperate and tropical countries.

The second type of models are competing land-use models that usually include some measure of price or opportunity cost of agricultural conversion and deforestation in terms of the foregone benefits of timber production and environmental benefits from forestland. The main findings are that increased population density increases forest clearance, whereas rising income per capita and agricultural yields reduce the demand for forest conversion. The third type of models are forest land conversion models based on farm household's decision in allocating the available labour for forest conversion or buying labour from markets given the profitability of the activities. In these models, the aggregate equilibrium level of cleared land across all households is usually hypothesised to be a function of product and factor prices and other household characteristics. The major findings are that agricultural conversion is positively related to agriculture product prices and other way round with rural wage rates. The fourth type of models are institutional models dealing with institutional factors such as conflict on land-use, property rights, political stability, degree of corruption, etc. These models are based on multivariate regression techniques where change in forestland is assumed to be affected by indices of institutional as well as the economic factors. The main difficulty with these models, besides the data quality, is to give a proper weight for each of the institutional variables considered in the model. Ownership security is in several of the studies found statistically significant, indicating that greater security reduces forest loss.

Barbier (2001) later developed a synthesis model based on the 'first wave' models and applied it for empirical tests. The change in forest area was transformed into change in agriculture area, i.e., agricultural expansion. The model specification is as below:

$$A_{it} - A_{it-1} = A\left(Y_{it}, Y_{it}^2, s_{it}, z_{it}; q_i\right)$$

where,

$A_{it} - A_{it-1}$ = change in agricultural area between two consecutive years in country i,
Y_{it} = GDP per capita (EKC variable) in year t for country i,
s_{it} = set of structural variables (such as crop yields, crop share of land area, agricultural export share, etc) in year t for country i,
z_{it} = other exogenous variables (such as population, GDP growth, migration, etc.) in year t for country i,
q_i = set of time invariant institutional factors for country i.

With this functional specification of the synthesis model a panel data analyses tool, both with random and fixed effect models, was used to test different hypotheses. The results were mixed. Structural variables were found to be more important explanatory factors across all tropical countries. Squared GDP per capita had a negative sign, though very small in magnitude, indicating EKC effect.

At the end of the review, 'second wave' models are explored that deal with micro or meso level analyses with different statistical and analytical tools incorporating spatial as well as locational variables. These models are useful in analysing the economic behaviour of agricultural households, timber concessionaires, and other agents (proximate or primary causes of deforestation) who are supposed to be responsible for deforestation in developing countries (Barbier, 2001). The discussed models employ bivariate probit, multinomial logit, household spatial model with probit and sample selection procedure, vector autoregression, farm household models linking upland lowland labour movement and CGE modelling techniques. Analytical models using game theoretic approaches to investigate state and local community interactions for the land-use issue are also reviewed. These models incorporate more detailed input data and have resulted in new findings at micro levels as compared to that of 'first wave models'. The major findings are that the variables, such as, accessibility or locational variables relating to forestland and forest products, changes in regional and national agricultural prices, changes in technology, increased employment opportunities in low land areas, and strategic state-community interactions, are statistically significant in affecting land-use decisions of local people.

A compilation of deforestation models by Brown and Pearce (1994) looked mainly at regression models (cross-country and regional) with descriptions of inherent mechanisms of land-use changes and their consequences. They highlighted two main factors namely, competition for space and economic failure, as well as the importance of misdirected past policies by bilateral and multilateral aid agencies, corruption, the indifference of much big business to environmental concerns, the results of foreign debts and poverty as causes of deforestation in the developing countries.

2.2. Multidisciplinary models

Use of land-use change models is equally popular with geographers and natural scientists (for detailed review see Agarwal et al. (2002); Lambin (1994, 1997)). These models are primarily developed for taking space and/or ecological interactions into account. Spatially explicit land-use change models with integration of socio-economic and bio-physical variables are considered important for the projection of alternative future pathways and for conducting experiments to enhance understanding of key processes in land-use changes (Veldkamp and Lambin, 2001).

Reviewing different approaches for monitoring and modelling of deforestation and dry-land degradation in tropical regions, Lambin (1997) emphasised the importance of specific models for investigating into specific research question of interest. Descriptive models designed to project future land-use changes, empirical models to explain land-cover changes, spatial statistical models for projecting the future spatial patterns of changes, dynamic ecosystem models to test the scenarios on future changes in land-cover, and economic models to design policy interventions were reviewed under different scales of time and space. The most fundamental obstacle to progress in the understanding and predicting of human impacts on terrestrial ecosystems was identified as the lack of a comprehensive theory of land-use changes. It was recommended that the future research should focus on new theoretical and empirical studies aimed at building a theory of land-use changes at regional to global scales with the help of Geographical Information System/Remote Sensing (GIS/RS) technologies.

Agarwal et al. (2002) reviewed and assessed 19 representative multidisciplinary models related to land-use changes with a focus on dynamics of space, time and human choices that demand the use of scale and complexity in modelling process. The reviewed models have a greater focus on ecological or bio-physical interaction perspectives as compared to that on economic aspects of land-use changes. From the point of view of process based modelling paradigm, the review gives comparisons and analysis of different approaches in land-use change modelling that can form a good basis for system analysis of C sequestration dynamics.

The three dimensions of land-use change models, namely, space, time and human decision; along with two distinct attributes of each, i.e., scale and complexity, provide the foundation for comparing and reviewing land-use change models. The reviewed models are compared across several attributes, such as, the model type, dependent and explanatory variables, if any, modules as well as their strengths and weaknesses in explaining the complexities. Some of the models in this review also cover the C sequestration issues (e.g., Adams et al., 1996).

3. Basic economic theories explaining land-use behaviour

The agricultural household and agrarian change literature (e.g., Ellis, 2000; Sadoulet and de Janvry, 1995; Singh et al., 1986) provide useful theoretical framework for analysing land use and land-use change behaviour of peasant/farm households. Models derived from a theoretical framework of micro-level choice allow investigation of how different combinations of bio-physical and socio-economic variables combine to drive operational sequences of land use evolution (e.g., timber extraction to agriculture), thereby providing the basis for generating various scenarios of land-use changes (Kaimowitz and Angelsen 1998; Stomph et al., 1994). Farm household models have mostly been used for analysing the response of market supply to changes in prices and other exogenous variables with the implicit linkages between the response and land use patterns. These models address the choice among competing land uses, that still remains to be fully exploited. It is, thus, imperative to have a theory for linking the production and consumption decisions of the farmers to the implications for land use changes. For this, there are two types of farm household models, namely, separable (recursive) and non-separable (non-recursive). In addition, von Thünen's land-use model incorporating explicitly the spatial context is of considerable interest. These three theories are discussed briefly in the following sub-sections.

3.1. Separable household model

Barnum and Squire (1979) developed the full version of the recursive model. With utility function maximized subject to constraints on cash income, total time of family labour, and technology, it can be shown that the optimal household production is independent of leisure and consumption choices (Singh et al., 1986). The intuition behind this result is illustrated by the positive effect of income in contributing to total household utility. Since income is a function of exogenously given prices for output and labour, the household will attempt to maximize its net income like a profit maximizing firm by equating the marginal value product to wage rate (the marginal factor cost). Whether the household is a net buyer or seller of labour or output has no effect on the result, since, as a price taker, its valuation for both is determined exogenously. This point can be illustrated by deriving the household's demand for labour (Singh et al., 1986).

Let us assume that the household maximizes the following utility function U (being concave and twice differentiable function):

Maximize $U = U(X_a, X_m, X_l)$

subject to

$$p_m X_m + p_a X_a + w X_l = w(X_l + F) + p_a Q(L, A) - wL$$

where X_a, X_m, and X_l are the quantities of the agricultural staple, the market purchased good, and leisure respectively; p_m and p_a are the corresponding prices of the commodities, w is the wage rate or cost of leisure, $Q(\ )$ is the production function for the staple, L is total labor input, F is family labor input, and A is the fixed quantity of land. Collapsing the family's income, time, and technological constraints into a single equation derives the constraint. The left hand side of the constraint shows the total household expenditure on the market purchased commodity as well as the opportunity costs associated with consuming its own output and time in the form of leisure. The right hand side represents the household's full income. Maximizing the utility function with respect to the choice variable labour (L) through first order condition yields:

$$p_a Q_L = w$$

indicating that the household equates the value of marginal product of labour to the market wage and the household's utility function is independent of total labour input decision-indicates separability of the model.

The consumption side of the model is, however, dependent on production. This is because the household behaves as if its consumption decisions are made based on prices and income, the latter of which is determined by the solution to the profit maximization problem. Specifically, it can be shown that the effect of an increase in the price of the agricultural staple can be decomposed into two components, a substitution effect and a profit effect:

$$\mathrm{d}X_a/\mathrm{d}p_a = \partial X_a/\partial p_a + (\partial X_a/\partial Y^*)\cdot(\partial Y^*/\partial p_a).$$

The first term on the right hand side of the above equation is unambiguously negative for a normal good; as a consumer of the staple, the farmer responds to an increase in its price by decreasing demand. The second term captures the farmer's response as a producer of the staple. It shows the effect of an increase in the profit maximizing income, Y^*, via an increase in the price of the staple, p_a, on the amount of the staple demanded. Since this term is unambiguously positive for a normal good, the net effect on the quantity demanded from a price increase is indeterminate and depends on the income elasticity of food consumption. The presence of Y^* in the above equation is evidence of the model's recursive property; with prices exogenously given, the consumption decision is seen to be related to the production decision through the level of income obtained from profit maximization.

3.2. Non-separable household model

Non-separability affects farm household modelling in two ways: theoretically, it changes the comparative statics, and empirically it renders statistically inconsistent parameter estimates for the demand and supply functions (Singh et al., 1986). How non-separability affects the choice of land use depends on the source of the market failure and the goods or factors that are affected by it. Labour market imperfections, for example, may influence land use by limiting the number of crops that can be grown, or, given a surplus of family labour, by inducing farmers to cultivate their land more extensively in response to insufficient off-farm employment opportunities (Benjamin, 1992; Sadoulet et al., 1996). Alternatively, missing markets for insurance may lead risk-averse farmers to allocate a greater share of their land to a staple crop despite greater expected profitability of cash crop production (Hammer, 1986; Monela, 1995). Thus, while modelling land use changes, the pervasiveness of material and behavioural conditions (Binswanger and McIntire, 1987) of the rural economies needs to be taken into account.

Incorporating financial assets opens a possible avenue for exploring the effects of family remittances in decision-making. In this regard, it might be hypothesized that those families with a greater stock of wealth are more likely to engage in riskier but more profitable commercialized farming activities, given the existence of a fallback in cases of crop failure or adverse market fluctuations. Likewise, stock variable could play a role similar to an asset by providing a carry-over buffer that relaxes the farmer's constraint of meeting subsistence requirements. Hence, everything else equal, acreage in commercial as opposed to subsistence crops could be hypothesized to be greater for those farms with access to storage facilities. An alternative insurance may be derived from cattle ownership. Not only cattle can survive from vegetation produced by precipitation that are insufficient for crop production, but they can also be easily shifted to different locations depending on climatic conditions (Binswanger and McIntire, 1987).

3.3. von Thünen's spatial model

von Thünen's model for analysing the land use is a core concept in all the spatial analysis (see Fig. 2). This model considers a featureless plain surrounding a central market. Let us assume two types of crops, namely vegetables with higher price '*a*' but faster perishability and grains with lower price '*b*' but slower perishability. All locations have identical production characteristics including profit-maximizing firms, but transport costs to the market, with exogenously determined prices, differ by crops. Due to higher costs of transportation for vegetables, price of vegetables falls faster than that of grains along the distance to the central market. Beyond point '*c*', the price for grains is higher than vegetables and that gives rise to another concentric circle of land use for grain crops. Thus, there develops a chain of concentric circles of land uses with the natural forests/shrub lands beyond the point '*d*' due to zero profitability of agricultural activities beyond that distance. In summary, crops that are costlier to transport and more perishable tend to be produced closer to the market.

This is rather a simplified version of the model and with the introduction of differences in land productivity, prices, transport costs and multiple markets; the analysis becomes more complex, *albeit*, the basic insights of the importance of location and transport cost in determining land use remain intact.

This model has been used in different empirical studies while analysing deforestation in tropical areas

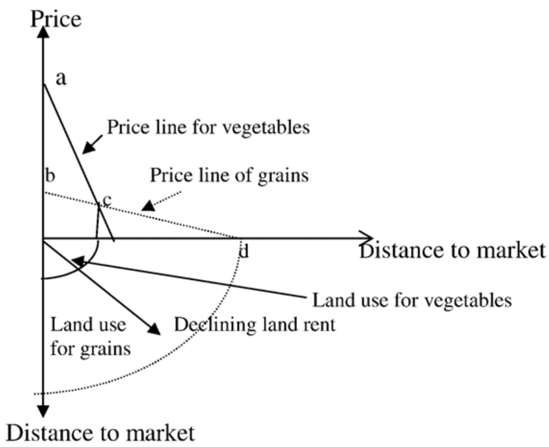

Fig. 2. von Thünen's model (Source: Nelson (2002)).

(e.g., Cline-Cole et al., 1990; Guyer and Lambin, 1993; Nelson and Hellerstein, 1995). The relevance of such type of models demands certain conditions, viz., (i) agricultural activities in nearby urban areas; (ii) most of the production tied with central markets; (iii) significant transportation costs; and (iv) demand for agricultural and forest products exceeds the supply (Lambin, 1994).

4. Land-use changes, forest/soil degradation and C sequestration models—our own review and evaluation of recent models

4.1. Land use, land-use changes and forest/soil degradation models

This section reviews different models that are used for analysing land use and land-use change behaviour in relation to forests and soil degradation in developing countries, especially in the HKH region, and are not included in the reviews thus far. The term "land use" refers to the uses of a given land area, e.g., forestland for timber, fuelwood, fodder or recreation uses and agricultural land for cultivation of different crops. Forest degradation implies both quantitative and qualitative loss of attributes in the forest areas. Soil degradation is a broader ecological and economic problem, which refers to soil erosion, loss of soil organic matter and soil fertility, and damage of its structure (Hediger, 2003). In the context of this review, however, it mainly relates to soil loss due to erosion processes. The reviewed models are grouped according to the modelling techniques and the *scales* of studies. The models reviewed in different subsections are not exhaustive, but only indicative of modelling frameworks and their major findings on land-use changes and forest/soil degradation issues.

4.1.1. Conceptual models

Before embarking on the review of actual quantitative models of land-use change, it is relevant to discuss the use of conceptual models. Based on certain explicit assumptions, these models consist of flow or causal loop diagrams of the various variables included, and thus constitute the first step in any modelling exercise (Lambin, 1994). These conceptual models are important in the context of HKH region where more studies are based on such models than those using quantitative techniques. These type of models represented with boxes and arrows (Lambin, 1997) are useful to explain the complex human and biophysical dimensions that need to be integrated into land-use change models. They are of considerable importance in building the analytical and empirical basis for further analysis of C sequestration processes using quantitative models.

Thapa and Weber (1995) used a flow diagram[1] to depict the processes and consequences of change in natural resource under different land-use dynamics at watershed level in Nepal. This model is useful to understand the complexities of modelling for land-use changes and their effects in an agrarian subsistence economy like the HKH region (see Fig. 3). At the first place, the existing forestland is converted into scrubland (degraded forest) either by heavy extraction or by grazing then into *pakho* (dry terraced cropland in steep slopes). Depending upon the availability of labour and prospect of irrigation some of the *pakho* land is further converted into *khet* (paddy fields). In the past, shifting cultivation was severe problem that used to convert either forests or scrubland into *khoriya* (land under swidden practice). While some of these lands were converted into permanent agricultural land, remaining lands went back to scrub again. The environmental and socio-economic effects of these processes of change are depicted in Fig. 3.

Similarly, Silwal (1995) used a conceptual framework to study the land-use pattern, especially agricultural land due to population dynamics in Nepal. The study concludes that increased population led to increase in agriculture land and production but in a varying proportion in different ecological regions.

Some examples of other relevant studies using this technique for analysing land-use changes and forest soil degradation issues in the HKH region are Baskota and Sharma (1995); Gilmour and Fisher (1991); HMG/ADB/FINIDA (1988); Saxena et al. (1997). In these studies, authors have first invariably tried to sketch the analytical framework based on the underlying or proximate causes of land-use changes and their impacts, and then analysed the issues either

[1] This conceptual diagram can be taken as a representative model used for analysing the land-use changes and their effects in the HKH region, and hence presented here in detail.

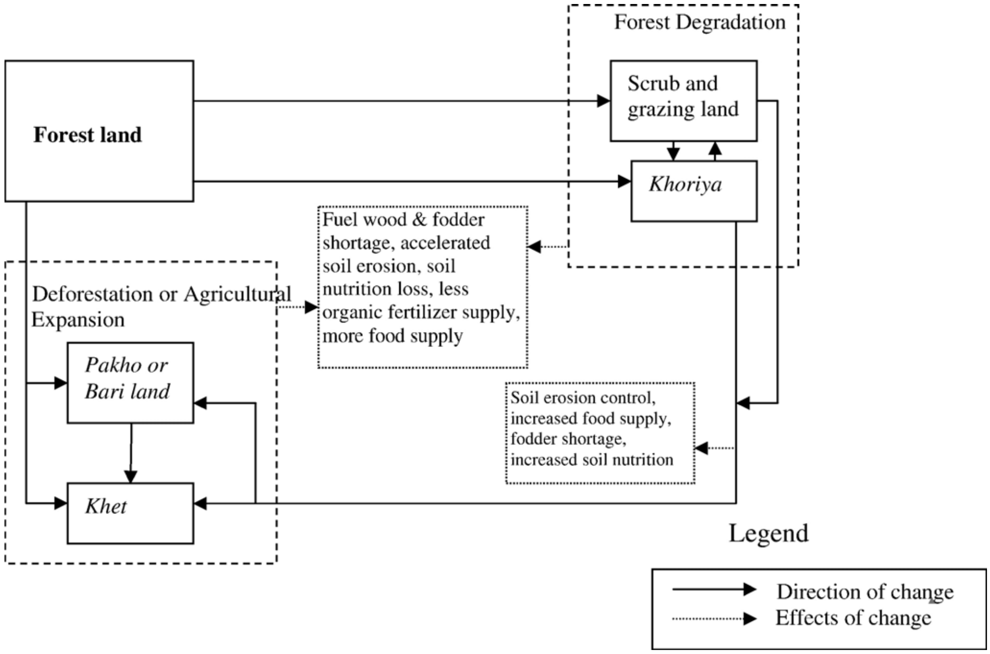

Fig. 3. Flow diagram of land-use changes and their effects in a mountain watershed (Source: Thapa and Weber (1995)).

qualitatively (descriptive statistics) or with the help of some quantitative techniques such as regression and programming/simulation models.

4.1.2. Analytical models

Contrary to empirical models, analytical models do not use data set, but represent given theories in a rigorous framework allowing researchers to conclude with logical implications of their assumptions (Kaimowitz and Angelsen, 1998). The models are most often based on a general programming problem framework with a single objective function (usually second differentiable concave form) of either maximizing profit or utility (discounted if dynamic model) subject to several exogenously given technological, infrastructural or institutional constraints.

Angelsen (1999) used an analytical model to diagnose the deforestation processes under four different market assumptions, namely the ‘full belly’ economy, the Chayanovian economy, the small open economy with private property and the small economy with open access. He argues that deforestation should be seen as an investment decision as a title establishment strategy rather than a conventional framework of resource use decision, which emphasise the trade off between different forest services, and the intertemporal aspect of these, and frame deforestation as a disinvestment. In contrast to conventional views on deforestation, well-intentioned programs for intensification, land titling or credit expansion may actually boost deforestation. The focus was mainly on three factors, namely, household’s preferences, labour market integration, and the property rights regimes. The study concludes that anything that increases the current and/or expected future rent will boost deforestation. These factors are mainly improved technology, higher output prices, lower transport costs, lower opportunity costs of labour, more secure claims to cleared forestland, or lower discount rates.

Bluffstone (1995) and Amacher et al. (1996) used household level models to analyse fuelwood consumption behaviour leading to deforestation in Nepal. Using simulation analysis based on analytical models, where labour is the only input in the production function optimally allocated among four activities—animal raising, agricultural production, fuelwood collection and off-farm work. Bluffstone (1995) concluded that there would be a stable agro-forestry system given the off-farm job opportunity under an open access regime of forest land. The model predicted a mixed fuel regime, i.e., fuelwood and purchased alternative fuelwood from off-farm income if the incentives structures are perfect. Amacher et al. (1996) used non-separable model with maximization of utility of a household based on consumption of goods or services where fuelwood enters as an intermediate input subject to budget constraint. Later on, the model developed structural equations to estimate the production and consumption of forest products. Inelastic fuelwood prices, the impacts of improved stoves and low fuelwood collection elasticity with respect to private land ownership indicated greater fuelwood scarcity and higher fuelwood prices. Policies targeting labour opportunities and physical resources are more important in regions where "collecting households" predominate in contrast to policies targeting the fuelwood market in regions where "purchasing household" predominate.

Southgate (1990) used an analytical model with Kuhn–Tucker conditions to analyse the land clearing behaviour of agricultural colonists in developing countries. The model used labour as an input to agriculture, soil conservation and land clearing; and primarily focused on institutional crisis, i.e., land titling and tenure issues as causes for tropical deforestation. To be able to acquire property rights in 'idle' land by converting it to agriculture use induces the new settlers to deforest more and discourage them from conserving existing farmland. Strengthening the property rights of settlers, of those adversely affected by deforestation and erosion, or of both groups, rather than technological innovation or price deregulation were emphasised to decelerate the deforestation along the agricultural frontier. The reader should refer to Kaimowitz and Angelsen (1998) for further detailed synthesis and review relating to analytical models used for analyses of deforestation processes.

More recently, game theoretic models have also been used to analyse deforestation issues by capturing externality effects that are ignored by the household models. Angelsen (2001) gives example from Indonesia and Brazil of this technique for analysing the strategic interactions between the state and local community in common property resource uses arising due to loosely defined or lack of property rights in frontier forest areas. Three typical cases related to scenario development over time of increased resource competition and market integration were discussed. The future scenarios include either conversion of forestland (i) to agricultural land by local community and (ii) to plantations, logging or other large-scale projects by the state; or (iii) natural forest remaining unchanged. The increased deforestation, as the model suggests, is due either to the local community or to the state acting as a leader in a Stackelberg game to squeeze out the other agent in a situation of a strong scarcity of and competition for forestland. However, the local response to more state deforestation depends on the costs, market, and behavioural assumptions, and less on the structure of the game, either Cournot or Stakelberg. The state fuels local deforestation by providing infrastructure like roads and hydropower that reduces the net costs for agricultural expansion. Imperfect markets and local behaviour determined by survival needs may also lead to similar results. Another study shows that some predictions can be made based on the theory of repeated games that are more likely to yield cooperative solutions than what can be drawn from a single-period "prisoners' dilemma game" (Balland and Platteau, 1996).

4.1.3. Empirical regression models

Empirical statistical models aim at identifying explicitly the causes of land-cover changes and forest/soil degradation through multivariate analytical techniques for understanding the contributions of exogenous variables under different socio-economic conditions. Multiple regression methods that include ordinary least square (OLS), logit (binomial and multinomial) probit, tobit, instrumental variables with two stage (2SLS) or three stage (3SLS), system estimation and panel or pooled data analysis techniques are generally used for this purpose. The regression models at the farm level are more useful for analysing the relationship between farmers' land use pattern and their previous experience, cultural attributes, household characteristics and other relevant economic characteristics. These models, however, demand large volume of relevant data set-cross-section, time series or panel; depending on the situation and the research question at hand. Recently, spatial considerations like location of forests or agricultural land relative to roads or market places, size, topography, soil conditions, etc., have also been taken into account while studying the land-use change

Table 1
Summary of empirical regression models—main characteristics and findings

References/techniques/ country/scale	Dependent variables	Explanatory variables[a]	Remarks
Silwal (1995); OLS Nepal; Regional level, Time Series data for 21 years	Crop areas and crop production at regions and country levels	+agricultural labour force; +rainfall (for food production)	For crop production relations rainfall variable is added which is found to be insignificant in some regions.
Amacher et al. (1996); 2SLS, Tobit; Nepal; Household level (Comparing Hills and Terai Activities), Cross-section data	Household fuelwood production	+collection time; +livestock; +forest area+family size; +fuelwood price	Consumption and production of fuelwood are distinguished between 'collecting' and 'purchasing' households. Suggest different policies for hills and Terai region.
Sah (1996); OLS; Nepal; Watershed level, Land-use changes data for three different years	Soil degradation	+sensitivity; − socioeconomic status	The indexes for sensitivity and socioeconomic status are based on watershed conditions and land based activities
Zhang et al. (2000); Generalised least square method; China (Hainan); Regional level, Panel data set for 13 counties over 17 years period.	Rain forest cover and plantation forest	− timber prices; − population growth; +agricultural prices; − share of forest land	Shows interaction between natural forest cover and plantation forests. Effects of the explanatory variables on forest cover are inverse in two cases. i.e., for plantation forest all of these variables are positive.
Köhlin and Parks (2001); Probit and sample selection; India (Orissa); Household level spatial model 742 household samples	Fuelwood collection	− distance to woodlots; − distance to plantation forest	A spatial model dealing with fuelwood collection from natural forest or village woodlots.
Foster et al. (2002); Fixed effect and instrumental variable FE regression; India; Village level 250 villages for the period of 29 years, 1971–1999 (panel data set)	Forest areas (land and labour were two inputs to be allocated across agriculture, industry and forestry)	− population growth; − income growth; − roads; − electricity; − wages	Measures magnitude and signs of consequences of agricultural technical change, population growth and rural industrial growth
Coxhead et al. (2002); OLS; Philippines; Household level 85 samples of farm households	Agricultural areas	+relative crop prices; +yields; +land holding size; +labour;	Initially induces increase in farm area but later smoothen the yield risk by switching to less risky crops and crops intensification leading to less deforestation.
Kant and Redantz (1997); Two stage maximum likelihood estimate; Global level 65 countries (35 African, 13 Asian and 17 Latin American) cross-section data	Deforestation	+round wood consumption; +forest product export; +change in crop land; +change in pasture land (first level); +GDP; +population; +debt, terms of trade (second level)	The level of effects is different in different continents of Asia, Africa and Latin America. The causal mechanism is through two stages process.
Mahapatra and Kant (2005); Multinomial logistic model; Global level cross country, Includes 117 countries in different years	Deforestation	+population growth; +forest areas; +agriculture; +road to agriculture; +road; +debt service	A theoretical deforestation model is proposed by incorporating two-way effects of all explanatory variables and hypothesised that the net effect of variable may vary across regions.

[a] Symbols '+' and '−' before the explanatory variables indicate positive and negative effect on dependent variables.

and forest soil degradation problems. These efforts add to the understanding as to 'where' (location question) the change occurs making the model more pragmatic (Barbier, 2001; Cropper et al., 2001; Kaimowitz and Angelsen, 1998; Nelson, 2002; Nelson and Geoghegan, 2002). Many forestland conversion models incorporate the 'accessibility' factor as an explicit determinant of the equilibrium level of land converted to agriculture, along with location specific input and output prices, to explain the influence of construction of roads on forest conversion. Different levels of analysis and a wide coverage of review for deforestation models in tropical countries can be found in Barbier (2001); Kaimowitz and Angelsen (1998); Saxena et al. (1997); and in a special issue of '*Agricultural Economics Vol 27*(*2002*)'.

In some empirical exercises, the first step has invariably been to elucidate the analytical model of land expansion and allocation under different assumptions like, risk-averse behaviour of farmers, market imperfections, subsistence rural economy, etc., followed by derivation of reduced form equations for econometric estimation (Amacher et al., 1996; Coxhead et al., 2002; Foster et al., 2002). Table 1 presents a summary of studies using regression models, their findings, and information on location and scale.

4.1.4. Linear/non-linear programming and simulation models

Programming models are useful tools to analyse different activities involved in land use, land-use changes, forest and soil degradation and the related environmental decisions. These models have proved very effective tools for modelling a large number of interacting socio-economic and biophysical variables by providing an interface between human behavior and biophysical processes in terms of resource extraction and stock changes (e.g., Holden and Shiferaw, 2004; Sankhayan et al., 2003). Such models most often apply Leontief-type production functions with zero elasticity of substitution among inputs in the same activity and constant returns to scale. They can either be used with goal programming or compromise goal programming or some goals can be set under constraints and the optimization takes place by fulfilling the hierarchies of objectives given as hard or soft constraints (e.g., Kaoneka 1993; Kaoneka and Solberg 1997; Monela 1995; Monela and Solberg 2000; Sankhayan et al., 2003; Sankhayan and Hofstad, 2001).

These models, however, demand voluminous data and finding true parameters is often a daunting task. Input–output data, factor and product prices and other parameters for production or consumption requirements are generally drawn from farm household surveys. Programming models can be used for simulation of various (optimal) scenarios. However, the term 'simulation model' is most often used for models without optimization subroutines, and for clarity we will use the term "pure simulation model" for this kind of models (e.g., Saxena et al., 1997; Bluffstone, 1995; Baskota and Sharma, 1995).

The time dimension is crucial in the land-use change processes and their impacts. It is hence important to develop dynamic bio-economic models that capture properly the inter-temporal behaviour of both ecology and economics. In conventional terminology 'dynamic programming" refers to a situation where the final (end period) state is known and it is therefore possible through backward induction to arrive at an optimal pathway. But, our interest in dynamic model is different as we do not know the terminal conditions and optimal decisions at any point in time are based on current knowledge and expectations about the future. In dealing with bio-economic cases, we observe two types of dynamic mathematical programming models. First, a time recursive model in which the current optimal values of variables and parameters depend on their optimal values in the past one or more periods. The advantage of such models lies in making simulations for longer periods as well as incorporation of periodic stochasticity for changes in exogenous variables such as prices (e.g., Barbier and Bergeron, 2001; Barbier, 1998). The other category of dynamic models are those that perform simultaneous optimization over the entire planning horizon while allocating the resources optimally over each period of time based on global optima (e.g., Sankhayan et al., 2003; Sankhayan and Hofstad, 2001). These models represent efforts at handling the true dynamics in contrast to the time recursive models that deal with static optimization in each period over the planning horizon.

Table 2 summarizes some of the relevant programming models used for analyzing land-use changes and forest/soil degradation issues.

Saxena et al. (1997) use a pure simulation model applying systems dynamics to capture the complexities in analysing tropical deforestation in India with the help of parameter values of consumption and production of forest and agriculture tied with socio-economic variables like population, livestock population and other goods and services. This system model considers agriculture, livestock, energy and socio-economic sectors, competing for forestland use or products interacting dynamically in a complex re-

Table 2
Summary of programming/simulation models—main characteristics and findings

Reference/technique/country/scale of study	Objective functions	Exogenous/endogenous variables	Main findings
Shakya (1987); Multi-objective linear programming; Nepal; Watershed level	Five objectives: maximize food, fodder and fuelwood production and minimize soil loss and cost.	Population, livestock, yield growth due to technology (10% increase is assumed).	Weighting of objectives gives different land-use scenario under subsistence farming economy. The demand for different products links the use of land in the model.
Sankhayan et al. (2003); Dynamic, non-linear bio-economic model; Nepal; Watershed level, The model runs over a 25 years horizon.	Maximize discounted net present value of cash flows from production and leisure values.	Population, prices, technology for high yielding varieties.	Increase in prices and yields increase cropped area while decrease in population growth rate decreases the cropped area.
Bluffstone (1995); Simulation; Nepal; Household level, The simulations are carried over 50 years period.	Linkage of fuelwood use and increase in off-farm income are analysed that cause a switch to alternate fuel.	Wage rates, off-farm employment, biomass growth.	Increase in wage rate reduces fodder collection but increase fuelwood consumption. Increase off-farm income causes switching to alternate fuel and stabilizing the agro-forestry system.
Banskota and Sharma (1995); Adaptive simulation model; Nepal; District level	The simulation is based on food, natural resource, environment, other and exogenous variables	Population, livestock, factor and product prices, land, agricultural technology.	Populating and livestock are major drivers for forest and agri-products extraction and hence increase deforestation.
Sankhayan (1996); Compromise/linear programming (Static); Tanzania; Household level	Separately maximize the goals and the differences in the goals are later minimized.	Factor and product prices.	The prices are positively related to the level of deforestation It assumes no labour market.
Kaoneka (1993) and Kaoneka and Solberg (1997); Linear programming (Static); Tanzania; Household level	Maximise net cash income.	Population, factor and input prices, yields. The consumption requirements are included as constraints.	Population growth leads to expansion of farm land through forest clearing.
Barbier (1998); Recursive, dynamic programming bio-economic model; Burkina Faso; Village level, the model runs for 32 years	Maximize discounted income and leisure.	Population, migration, prices, technology (labor and land saving).	Population pressure leads to intensification and investment on conservation but not necessarily to more farm income. Market opportunities of products may increase productivity The conclusion of the model is land intensification in Sahel is still more expensive than the fallow system.
Monela (1995), Monela and Solberg (2000); Compromise/quadratic programming (Static); Tanzania; Household level	Maximize net annual income, minimize income and labor supply risks.	Factor and product prices, population, credit access and risk. The consumption requirements are included as constraints.	Product and fertilizer prices are positively related to the level of deforestation whereas increase in other input prices has opposite effect. Declining crop productivity, income risks and growing food demand are main drivers of deforestation.
Barbier and Bergeron (2001); Time-recursive dynamic bio-economic model with five years planning horizon as single year decisions; Honduras; Village level, the model run is 100 years	Maximizes additive discounted utility of two household groups (ranchers and small farmers).	Population, livestock, soil depth, type of ploughs, crop choices, presence or absence of conservation new technologies, market access, road construction, and land reform.	Technology enhances the labor productivity even in increased population situation, population increase slightly increase the cropped area due to intensification giving rise to U shape relations between population and natural resource base. Increased market access increased per capita income but not necessarily investment on land conservation.

(continued on next page)

Table 2 (*continued*)

Reference/technique/country/scale of study	Objective functions	Exogenous/endogenous variables	Main findings
Sankhayan and Hofstad (2001); Dynamic, bio-economic model; Senegal; Village level, model runs for 21 years	Maximize discounted net present value of cash flows from production and leisure values.	Population, agricultural prices, wages, charcoal price, agricultural technology.	Population degrades more forest in terms of biomass extraction whereas other variables retard the degradation process. Land clearing, grazing and extraction of biomass as woodland degradation measures were used in the model.
Okumu et al. (2002); Static goal programming and dynamic non-linear programming model; Ethiopia; Watershed level	Maximize cash income and leisure; and basic food requirement comes as a constraint.	Fertilizer, crop rotation based on changing land suitability, secure land tenure.	Use of fertilizer from farm income increases the net income with increase in soil loss. In the long run soil loss would decline and unable to counteract the effect causing decline in yield. The best strategy suggested by the model is to combine fertilizer application with crop rotation based on land suitability and provide secure land tenure to minimize the soil loss.

source use system. First, a conceptual model is depicted for the interactions and then the model is run through different levels of stocks and flows with the relationships assigned among the variables. The relations may be linear or non-linear and derived from empirical observation. Through a sensitivity analysis of deforestation in India the model was used to show that no forest will be left in 2–3 decades if the current land use and production/consumption policies continue. The main problem with this kind of simulation models is their assumptions regarding agents' behaviour, because when no optimization is involved one cannot be sure of behavioural consistency over time.

4.2. Models to analyse C sequestration due to land-use change and forests/soil degradation

A detailed review of different relevant studies by Upadhyay et al. (2005) have revealed the lack of integrated models for analysing land-use changes, forests/soil degradation and C sequestration impacts in the HKH region. However, such models in other regions of developing world are emerging in the recent past (e.g., Pfaff et al., 2000; Kerr et al., 2003). A few models used at the global or country level for analysing C sequestration (e.g., Adams et al., 1996; Sands and Leimbach, 2003) have a high degree of aggregation and rather shaky theoretical underpinnings.

An important prerequisite for developing an integrated model of C sequestration dynamics is to understand the underlying bio-physical processes and socio-economic behaviour affecting vegetation and soil characteristics in different land uses. Fig. 4 depicts a simplified flow diagram of C pools and fluxes. The C fluxes enter into biomass through the photosynthesis, after which the biomass components go into either soil or to biomass extraction (socio-economic interactions) or remain as standing biomass in the vegetation. C emissions are then emitted back into the atmosphere through the extracted biomass (e.g., fuelwood, timber, fodder, animal beds, poles, paper and pulp, etc.). Some part of biomass component enters into the soil as soil organic matter (SOM) thereby enhancing the soil organic C (SOC) in soil profiles, or get decomposed contributing to the emissions. There are different levels of biomass and SOC under different land-use categories. Once the changes in land use or extraction of biomass take place, C stocks in biomass and soil are affected with significant implications for C sequestration. At a given point of time, any C pool in Fig. 4 acts as a sink or source depending on whether the net result of sequestration and emission is positive or negative.

Models integrating land use changes and associated C fluxes seem to have received very little attention in spatially explicit models, mainly due to their inability in studying the complexity of human impacts

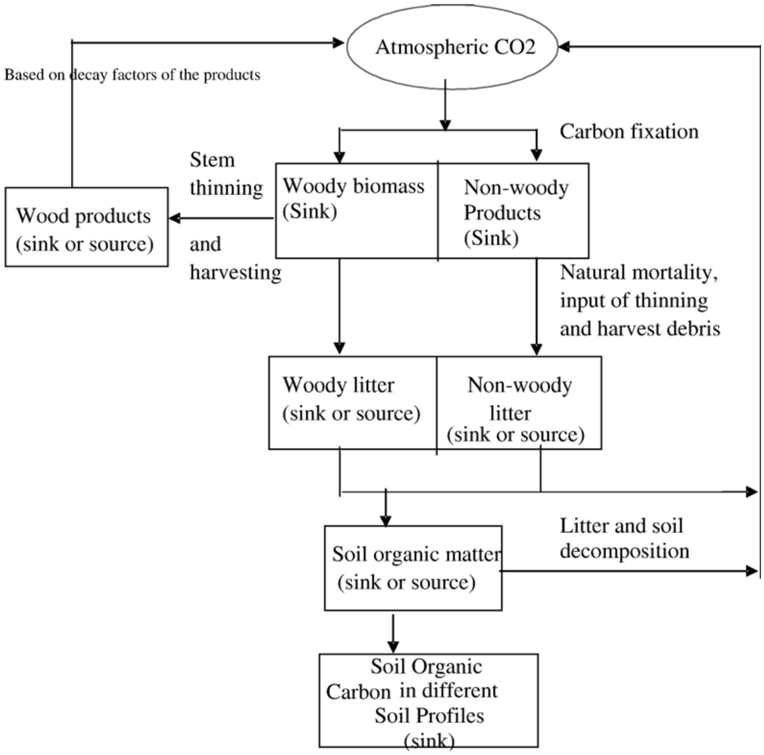

Fig. 4. C pools (rectangles) and fluxes (arrows) in a land based ecosystem (Source: Cannel (1995)).

by using the current data. Markov model can play an important role in this context (Miles et al., 1996, Prasad et al., 2003). Prasad et al. (2003) have used Markov model for simulation of C sequestration from land use changes affecting C pools in forests and soils at the national level in India. Markov chains are computed by converting the land-use changes and forestry data of India from 1997 to 1999 into a matrix of conditional probabilities that show changes in one class at time $t+1$ due to changes in another class at time t. The simulation results showed that with an increase in dense forest area and decrease of open and scrub forest areas, the forests work as a potential sink in the beginning if the land-use changes occur like those observed for 1997–1999. The analysis of results for transition probabilities for different years till 2050 showed, however, that this sink potential of Indian forests would be changed to a source due to increasing human pressure on open and scrub forests. Protecting degraded and scrub forests, plantation forest, social or joint forest management with proper planning and management, efficiency improvement in biomass fuel use, bio-energy initiatives, wild fire management and reform in present forest administration setup are some of the major policy measures suggested for reducing the C emissions.

Recently in the discourse of integrated modelling for C-sequestration analysis, Pfaff et al. (2000) presented a general method combining bio-physical and economic models to generate a future scenario of C-sequestration supply to carbon-offset markets and its optimal rules under clean development machnism (CDM). Taking Costa Rica as a case study, CENTURY model is used for process based ecological modelling to estimate C fluxes under different land-uses and dynamic panel data analysis for economic modelling of land-use change behaviour. The models highlighted the need of base line estimates of various parameters. The prediction of C sequestration is based on monetary incentive or reward for extra unit C-sequestration that affects the land-use patterns rather than impacts of land-use changes due to their driving forces. Based on this general modelling framework later, Kerr et al. (2003) supplemented ecological, geographical and economic empirical data to analyse C dynamics and land-use choices in spatially explicit way in Costa Rica. They sketch a comprehensive conceptual diagram in a dynamic framework to depict the ecological and economic interactions/feedbacks over time and space and proceed further by using data set of land-use changes spanning over 50 years. Plot-level CENTURY model has been scaled up over national level, by using a General Ensemble bio-egeochemical Modeling System (GEMS). Economic model uses multinomial logit technique on crop choices based on their returns. Spatial autocorrelation problem has been corrected and the prediction of this model is used to form transition probabilities of land-uses. The integrated ecology and economics model predicts land use and its impacts on C-sequestration by taking different driving factors over space and time into consideration. These integrated modelling efforts though represent significant development, they still lack complete system approach to integrate socio-economic behaviour and bio-physical processes. The blowing up of estimates of different ecological units and economic agents from plot or individual levels to national level raises the issue of scale in the context of interdisciplinary studies. Moreover, with the availability of powerful computer programs on mathematical programming techniques this type of complex problems can be better analysed by using optimization techniques that are capable of handling several objectives and constraints to approximate bio-economic system's behaviour.

Adams et al. (1996) described a model for analysing the process of C sequestration due to land use changes at state level in the US. This model uses dynamic, non-linear mathematical programming technique to analyse the optimal land allocation between agriculture and forestry by maximizing discounted economic welfare of both producers and consumers with 10-year time step over a 100 years' planning horizon. The prices of products and land are endogenous in the model and those in the proceeding decade influence the changes in land use in the following decade. The net effect on C sequestration is then computed based on the magnitude of land use changes. The broader scales and the inability of taking into account the land capability variations within regions are some of the major weaknesses of the model. The model having been developed in the context of a developed market economy, does not take into account proximate or direct interactions of agents' behaviour to land use changes, does not have a detailed description of the various agriculture production alternative possibilities, and the time steps of 10 years are too long to capture realistically the various socio-economic and biophysical processes involved. Although it provides useful insights into modelling techniques and system analysis for the complex interactions of socio-economic and land-use changes, the model seems to have a limited use for analysing C sequestration in the context of the Himalayan Region.

Mauldin and Plantiga (1998) used a multinomial logit model to analyse the costs of afforestation program for enhancing C sequestration in USA. This study approximated the foregone agricultural returns by prevailing agricultural rents in the region. A potential shortcoming of this approach is that it does not recognize some important behavioural aspects of land use decisions. They used share of agricultural, forestry and urban land uses as qualitative dependent variables. The choices of land use are based on the respective land rents and population density (used as explanatory variables). Based on land-use theory, higher forest rents should shift the extensive margin between forestry and agriculture in favour of forestry. The results of this study confirmed the hypotheses that while the higher returns to forestry may prevent conversion to urban land use, higher population density leads to just the opposite results. The land allocations at different payment levels under different scenario are simulated for C sequestration program used for 60-year time horizon. This model shows a significantly higher cost estimates for C sequestration due to the model's capability of capturing influences of option values, non-market benefits and other behavioural aspects of land use decisions.

More recently, an integrated land use model dealing with C sequestration at a global scale has been developed by Sand and Leimbach (2003). This is a top-down recursive economic model with a multiple structure to simulate global land-use changes and the resulting C emissions over one century. The model divides the world into 11 regions with production of composite crop, animal product, forest product and commercial biomass. These products are assumed to have international markets with prices that bring the market into equilibrium. Forward price for forest product is used due to time lag between plantation and harvest. The resulting effect on land-use based on demand and supply forces, produce an impact on C emissions. The model results show that an increase in C price creates incentives for production of commercial biomass that affect the distribution of other land use types. Commercial biomass provides a link between the agriculture and energy systems. Each major land-use type is assigned an average C density to calculate a total C stock. The C emissions from land-use changes are based on those in the reference scenario.

5. Discussions

Quantitative modelling exercises dealing with land use changes, forest soil degradation and C sequestration help in policy analysis bridging the gap between pure theory, which lacks in dealing with these issues in a holistic manner, and the real world situation. In order to improve the policy debate for pragmatic solutions to the complex problems of optimal and sustainable use of biomass and soils, quantifications of the various variables stated in the underlying theories are required. Hence, in most cases, only qualitative insight and conceptual models are not sufficient and quantitative modelling can help reveal important direct and indirect effects of a policy, which are easily lost when only discussing the policy issues. Quantitative analysis allows running sensitivity tests to clarify the role of key behavioural assumptions and important parameters (Sadoulet and de Janvry, 1995). Thus, with the help of different modelling techniques, the C sequestration dynamics can be more thoroughly analysed in the case of HKH region. Review of literature like this can stimulate discussion on focus and locus of the subject matter, informational and intellectual outcome, and their effects on land-use changes related subjects in relation to C sequestration dynamics. This can also encourage constructive debate and discussion, facilitating identification of neglected research topics and opportunities for applying more appropriate research techniques.

Land-use change models are useful tools for understanding the causes and consequences of land-use dynamics under complex socio-economic and biophysical conditions. With the help of scenario analysis, these models can identify near-future critical locations in the face of environmental change and hence prove to be an effective tool for integrated environmental management (Verburg et al., 2002). The main challenges in modelling land-use and its changes are level of analysis, cross scale dynamics, driving forces, spatial interaction and neighbourhood effects, temporal dynamics and level of integration (Verburg et al., 2004), and the quality of socioeconomic and biophysical data. Predictions depend, among other things, on the assumptions, specification and theoretical grounding of the models themselves as well as on the scenarios of change from which they borrow the values of the exogenous variables driving the predictions. Faced with a situation of an extremely complex and unpredictable future, use of simulation models might be justified even if their theoretical soundness is questionable (Briassoulis, 2000).

The emphasis of geographers and natural scientists has been on developing spatially explicit models of land-use changes (Irwin and Geoghegan, 2001). These models, however, give relatively less attention to understanding the economic processes and human behaviour components that underlie the land-use changes. The importance of economic theories, including choice of functional forms and explanatory variables indicating the preferences for land-use change decisions, in explaining the causal relationships between individual choices and land-use change outcomes and their magnitudes needs to be incorporated in modelling exercises in a holistic way (Barbier, 2001; Irwin and Geoghegan, 2001; Kaimowitz and Angelsen, 1998).

To understand the C sequestration dynamics by land based anthropogenic activities, it is imperative first to understand the causal linkages and systems behaviour of land-use changes and forest soil degradation under varying market, behavioural and material conditions characteristic of the third world. Then, in the next stage, C sequestration processes can be analysed as effects of human induced activities using appropriate existing or newly developing modelling tools incorporating the main complexities inherent in the systems. This implies that at least the following two (interconnected) issues have to be emphasized: (i) selection of modelling techniques which appropriately include both socio-economic and bio-physical factors, and (ii) deciding on the appropriate scale at which the modelling exercise should be undertaken.

The importance of scale of time, space and socio-economic sectors are indeed crucial in modelling exercises. Distinction among different scales or levels of agents, space or times, decides to a large degree which research and policy questions are possible to be addressed. At broad scales, the high level of aggregation of data obscures the variability of situations and relationships, and may in many cases produce meaningless averages (Lambin, 1994). At lower scales, it may be impossible, however, to capture fully the processes occurring at higher levels of aggregation. Whether different variables are endogenous or exogenous is likely to depend upon the scale. 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. However, Chayanovian and subsistence models of land-use do not use exogenous prices (Kaimowitz and Angelsen, 1998). At the regional level-with a distinct ecology, agrarian structure, political history, local institutions, established trade networks, pattern of settlement, infrastructure and land use-some prices, institutions, demographic trends and technological changes are endogenous (Lambin, 1994).

Spatial aspects are important in nearly all analyses of land-use changes (Mertens and Lambin, 1997). It is a challenging task to incorporate appropriately space as explanatory variable in land use modelling. A key element in this regard relates to the interdependencies between aggregate patterns of land use and the individual choices that give rise to these patterns. A given land use conversion at a location is determined by the economic returns or utility generated by a given use. These returns are, in turn, largely determined by the existing spatial distribution of surrounding land uses (Geoghegan and Bockstael, 1996). This would cause autocorrelation problem in the spatial regression models. While the linkages between the spatial arrangement of land use and land-use change are receiving increased attention within the economics literature, a few existing empirical studies investigate these linkages using individual decision-maker data (Barbier, 2001; Irwin and Geoghegan, 2001).

With the latest innovation on geographical information system (GIS) and remote sensing (RS), it has been easier and more cost effective to acquire spatial data, analyse land-use changes and forest/soil degradation, especially in a rugged terrain like that of the HKH region. Recent studies at the watershed level using GIS techniques have produced useful information about the detailed land use classifications with their biophysical attributes (Awasthi et al., 2002; Thapa and Weber, 1995). These studies have estimated temporal changes in major land uses in a representative watershed of middle mountain of Nepal. Information generated by using GIS coupled with accounting of socio-economic behaviour and good databases for detailed land-use changes over time seems promising indeed for developing more comprehensive and useful models to analyse C sequestration dynamics based on system analysis.

Both macro and micro government policies influence incentives for expansion and intensification of the utilization of marginal lands throughout the developing countries, with a significant bearing on forests and soil degradation affecting C sequestration. Subsidies in developing countries have been found to encourage extensification of agriculture into forest-land. On the contrary, subsides in the developed world have lead to intensification making it very difficult for the developing world to compete in the international markets for agri-products, thereby locking them into primitive agricultural practices (Brown and Pearce, 1994).

The local-level processes causing soil and forest degradation are greatly influenced by the fact that forest land is not being privately owned (Dasgupta, 1995). The U shape relations between population growth and forest cover are found in many cases and this may give a challenge to conventional thinking of the Himalayan environmental crisis. In some mid hills of Nepal, the forest cover is returning back, probably due to institutional interventions or availability of off-farm income. Jodha (1985) asserts that in spite of rapid population growth, many commons in the Himalayan region were well managed, mediated by institutional factors and hence highlight the vital role of local institutions in managing the commons. Factors like better access to forestland, low wage rate, high prices for forest products, and input subsidies are generally found to be positively correlated with deforestation. However, the factors affecting land-use changes, the interactions between them and the magnitude of their effects all vary significantly over space and time.

Several of the reviewed studies support the hypothesis that farmers appear to take risk (both yield and price) into account while making decisions for choosing annual and perennial crops, and when undertaking investments in soil conservation. Under risk neutrality, land allocation can be expected to be invariant among crops to their own price and yield variability (Coxhead et al., 2002). Infrastructure improvements lowers marketing risks resulting in reduced trade margins, with some benefits presumably returning to farmers in the form of higher and more stable prices. On the other hand, abundance of low-skilled labour because of high population growth has resulted in agricultural expansion. Frontier land has long served as the employer of last resort for underemployed, unskilled labour. Contrary to this, land shortages associated with rising rural population have encouraged more intensive land-use methods. In the Sahelian case, shifting cultivation is still a desirable option due to relative abundance of land (Barbier, 1998).

6. Synthesis of available models

A number of models have been found dealing with land-use changes, forest and soil degradation issues in developing countries using different types of modelling techniques. Except for a few aggregated country and global level models, models suitable for the analysis of C sequestration dynamics in its entirety in developing countries' perspective are still lacking. Conceptual models and programming models appear to be of direct relevance for developing bio-economic dynamic model for analysing C sequestration in the HKH context. However, analytical and empirical regression models may also be useful particularly for understanding the land-use change and forest/soil degradation processes, and identifying main drivers of change in the third world.

While developing and implementing improved models for natural resource analyses, attention needs to be paid to a protocol for model disclosures proposed by Beres et al. (2001). The protocol consists of statement of purpose; list of assumptions; structural or design information; list of variables, parameters, and relationships; decisions, features, uniqueness, weaknesses; sensitivity analysis; validation; scenarios; outcomes, interpretation; and real world consequences.

Under diverse ecological and human settlement, situations like those found in the HKH region, the nature of mountain forests as well as the management challenges is multifunctional. Therefore, to provide meaningful analyses of C sequestration aspects connected to land-use changes, it is important to integrate site and landscape levels, short and long term time dimensions, and ecological, economic and social considerations. For this, we propose an interdisciplinary systems analysis approach as outlined in Fig. 5, where existing land-use models of various types (upper left), biophysical models emphasizing C sequestration aspects (upper right), and GIS/RS techniques and data bases (down) are interfaced to develop a new and improved modelling system. The interactions or feedbacks between the socio economic and bio-physical system are handled by the proposed dynamic bio-economic model depicted in the centre of the diagram (rectangle at the centre with thick dark lines), which is the central theme of the research project and will be dealt in detail in the forthcoming work. This approach is complemented through the general conceptual framework developed by Upadhyay et al. (2005) which contains detailed background and issues to be addressed for the HKH region in this regard.

The time horizon of the model can range from 30–40 years, a typical forest rotation period used in the HKH region, in order to capture the economic and ecological characteristics of the system. Regarding the appropriate geographical level at which the model should be used, we are of the opinion that the watershed level is most relevant. The proximate and underlying causes of land-use changes and forest/soil degradation can be handled more effectively at this level, and the aggregation and externality problems arising due to resource use can be internalized by maximizing the aggregate utility function. The externalities may sometimes be very important in collective action problems at the watershed level, for example upstream farmers may encroach on forests

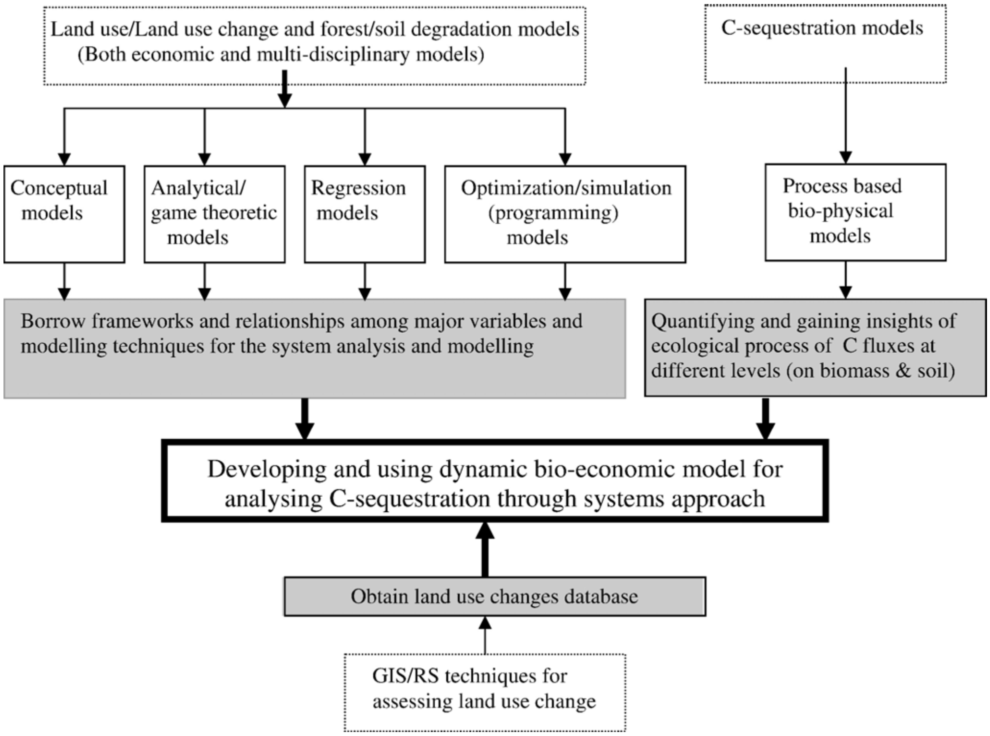

Fig. 5. A systems analysis framework for improved modelling of land-use changes and C sequestration dynamics in the HKH region.

causing negative external effects on households living downstream.

7. Conclusions

This study has highlighted the availability and use of a number of approaches in modelling the complexities of land-use changes and forest soil degradation. The literature on modelling approaches of C sequestration due to land use changes and forest/soil degradation was, however, scanty in the context of developing countries in general and the HKH region in particular. Most efforts in the HKH region have relied only on descriptive statistics and qualitative analysis by using conceptual models.

In summary, it can be concluded that land-use changes and forests/soil degradation are mostly affected by complex interactions of ecological, biophysical, socioeconomic and institutional factors. It is not possible to find unambiguous cause-effect linkages that would have a universal application. This calls for studying specific situations in detail and learn from such studies.

Owing to the fact that land-use changes and forest/soil degradation significantly affect the emissions of GHGs, especially CO_2, there is a strong need for developing integrated models that capture the entire dynamics related to this issue following an interdisciplinary systems approach. Based on the review of models, therefore, a modelling framework is proposed, representing probably a first attempt of its kind for the HKH region. Properly used, results of such models could assist policy makers and planners to identify and implement sustainable agriculture and forestry practices, leading to mitigation of CO_2 emissions in developing countries in general and the Himalayan region in particular.

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References

Adams, D.M., Alig, R.J., Callawya, J.M., McCarl, B.A., Winnet, S.M., 1996. The forest and agricultural sector optimization model (FASOM): model structure and policy applications. USDA Forest Service Pacific Northwest Research Station. Research Paper-ISSN: 0882-5165, No. 495.

Agarwal, C., Glen M. G., Morgan, J.G., Tom P. E., Charles, M.S., 2002. A Review and Assessment of Land-Use Change Models: Dynamics of Space, Time, and Human Choice. CIPEC Collaborative Report No. 1. USFS Publication GTR-NE-297. Joint publication by the Center for the Study of Institutions, Population, and Environmental Change at Indiana University—Bloomington and the USDA Forest Service. Burlington, Vt.: USDA Forest Service Northeastern Forest Research Station.

Amacher, G.S., Hyde, W.F., Kanel, K.R., 1996. Household fuelwood demand and supply in Nepal's Terai and Mid-hills: choice between cash outlays and labor opportunity. World Development 24, 1725–1736.

Angelsen, A., 1999. Agricultural expansion and deforestation: modelling the impact of population, market forces and property rights. Journal of Development Economics 58, 185–218.

Angelsen, A., 2001. Playing games in the forest: state-local conflicts of land appropriation. Land Economics 77, 285–299.

Awasthi, K.D., Sitaula, B.K., Singh, B.R., Bajracharya, R.M., 2002. Land use changes and morphometric analysis using GIS for two mountain watersheds of Western Nepal. Land Degradation and Development 13, 1–19.

Bajracyarya, D., 1983. Fuel, food or forest? Dilemma in a Nepali village. World Development 11, 1057–1073.

Balland, J.M., Platteau, J.P., 1996. Halting Degradation of Natural Resources: Is There a Role for Rural Communities? Clarendon Press, Oxford.

Barbier, E.B., 1998. Induced innovation and land degradation: results from bio-economic model of a village in West Africa. Agricultural Economics 19, 15–25.

Barbier, E.B., 2001. The economics of tropical deforestation and land use: an introduction to the special issue. Land Economics 77 (2), 155–171.

Barbier, B., Bergeron, G., 2001. Natural resource management in the hillsides of Honduras. Bioeconomic Modeling at the Microwatershed Level. IFPRI Research Report No. 123. IFPRI, Washington, D.C.

Barnum, H., Squire, L., 1979. A Model of an Agricultural Household. World Bank, Washington D.C.

Baskota, K., Sharma, B., 1995. Economic and natural resource conditions in the districts of Bagmati zone and their implications for the environment: an adaptive simulation model. MEI. ICIMOD, Nepal. Series No. 95/9.

Benjamin, D., 1992. Household composition, labor markets, and labor demand: testing for separation in agricultural household models. Econometrica 60, 287–322.

Beres, D., Gordon, S., Colin, C., Anthony, S., 2001. Research notes—truth in modeling. Natural Resource Modeling 14, 457–464.

Binswanger, H., McIntire, J., 1987. Behavioural and material determinants of production relations in land-abundant tropical agriculture. Economic Development and Cultural Change 36, 73–99.

Bluffstone, R.A., 1995. The effect of labor market performance on deforestation in developing countries under open access: an example from rural Nepal. Journal of Environmental Economics and Management 29, 42–63.

Briassoulis, H., 2000. Analysis of land use change: theoretical and modeling approaches. In: Loveridge, Scott (Ed.), The Web Book of Regional Science (www.rri.wvu.edu/regscweb.htm). Regional Research Institute, West Virginia University, Morgantown, WV, USA.

Brown, K., Pearce, D.W. (Eds.), 1994. The Causes of Tropical Deforestation: The Economic and Statistical Analysis of Factors Giving Rise to the Loss of the Tropical Forests. University College London Press, London.

Cannel, M.G.R., 1995. Forest and the global carbon cycle in the past, present and future. European Forest Research Institute. Research Report 2. Finnland.

Casse, T., Milhøj, A., Ranaivoson, S., Randriamanarivo, J.R., 2004. Causes of deforestation in southwestern Madagascar: what do we know? Forest Policy and Economics 6, 33–48.

Cline-Cole, R.A., Main, A.C., Nichol, J.E., 1990. On fuelwood consumption, population dynamics and deforestation in Africa. World Development 18, 513–527.

Coxhead, I., Shively, G., Shuai, X., 2002. Development policies, resource constraints, and agricultural expansion on the Philippine land frontier. Environment and Development Economics 7, 341–363.

Cropper, M., Puri, J., Griffiths, C., 2001. Predicting the location of deforestation: the role of roads and protected areas in North Thailand. Land Economics 77, 172–186.

Dasgupta, P., 1995. An enquiry into well being and destitution. Clarendon Press, Oxford.

Ellis, F., 2000. Peasant Economics: Farm Households and Agrarian Development, 2nd edition. Cambridge University Press, Cambridge.

Foster, A.D., Rosenzweig, M.R., Behrman, J.R., 2002. Population, income and forest growth: management of village common land in India. Brown University, Rhode Island and University of Pennsylvania, Philadelphia. Mimeo.

Geoghegan, J., Bockstael, N., 1996. Ecological Economics, Geographic Information Systems and Spatial Econometrics: Hedonic Models of the Patuxent Watershed. Department of Agricultural and Resource Economics. University of Maryland, College Park.

Gilmour, D.A., Fisher, R.J., 1991. Villagers, Farmers and Foresters: The Philosophy, Process and Practice of Community Forestry in Nepal. Sahayogi Press, Kathmandu, Nepal.

Guyer, J., Lambin, E., 1993. Land use in urban hinterland: ethnography and remote sensing in study of African intensification. American Anthropologist 95, 17–37.

Hammer, J., 1986. Subsistence First: Farm Allocation Decisions in Senegal. Journal of Development Economics 23, 355–369.

Hediger, W., 2003. Sustainable farm income in the presence of soil erosion: an agricultural Hartwick rule. Ecological Economics 45, 221–236.

HMG/ADB/FINIDA, 1988. Master plan for the forestry sector Nepal, Main report. Ministry of forests and soil conservation, Kathmandu, Nepal.

Holden, S.T., Shiferaw, B., 2004. Land degradation, drought and food security in a less-favored area in the Ethiopian highlands: a bio-economic model with market imperfections. Agricultural Economics 30 (1), 31–49.

Houghton, R.A., 1994. The worldwide extent of land-use change. BioScience 44, 305–313.

Houghton, R.A., 1999. The annual net flux of carbon to the atmosphere from changes in land use 1850–1990. Tellus 50B, 298–313.

IPCC, 2000. The Intergovernmental Panel on Climate Change, Special Report on Land Use, Land-Use Change, and Forestry. Cambridge University Press, Cambridge, United Kingdom.

Irwin, E.G., Geoghegan, J., 2001. Theory, data, methods: developing spatially explicit economic models of land use change. Agriculture, Ecosystems and Environment 85, 7–23.

Jodha, N.S., 1985. Population growth and the decline of common property resources in India. Population and Development Review, 247–264.

Kaimowitz, D., Angelsen, A., 1998. Economic Models of Tropical Deforestation: A Review. Centre for International Forestry Research, Jakarta, Indonesia.

Kant, S., Redantz, A., 1997. An econometric model of tropical deforestation. Journal of Forest Economics 3, 51–86.

Kant, S., 2000. A dynamic approach to forest regimes in developing economies. Ecological Economics 32, 287–300.

Kaoneka, A.R.S., 1993. Application of economic analyses and mathematical programming in land use planning at the village level in the West Usambara Mountains. PhD Rep. No. 4. Department of Forestry, Agricultural University of Norway.

Kaoneka, A.R.S., Solberg, B., 1997. Analysis of deforestation and economically sustainable farming systems under pressure of population growth and income constraints at the village level in Tanzania. Agriculture, Ecosystems and Environment 62, 59–70.

Kerr, S., Liu, S., Pfaff, A.S.P., Hughes, R.F., 2003. Carbon dynamics and land-use choices: building a regional-scale multidisciplinary model. Journal of Environmental Management 69, 25–37.

Köhlin, G., Parks, P.J., 2001. Spatial variability and disincentives to harvest: deforestation and fuelwood collection in South Asia. Land Economics 27, 206–218.

Lambin, E. F., 1994. Modelling deforestation processes. Trees Series B: Research Report No. 1. Brussels, Luxembourg: ECSC-EC-EAEC.

Lambin, E.F., 1997. Modelling and monitoring land-cover change processes in tropical regions. Progress in Physical Geography 21, 375–393.

Lambin, E.F., Rounsevell, D.A., Geist, H.J., 2000. Are agricultural land-use models able to predict changes in land-use intensity? Agric. Ecosyst. Environ. 82, 321–331.

Mahapatra, K., Kant, S., 2005. Tropical deforestation: a multinomial logistic model and some country-specific policy prescriptions. Forest Policy and Economics 7, 1–24.

Mauldin, T., Plantinga, A., 1998. An econometric analysis of the costs of reducing atmospheric carbon dioxide concentrations through afforestation. Department of Resource Economics and Policy, University of Maine. Mimeo.

Mertens, B., Lambin, E.F., 1997. Spatial modelling of deforestation in southern Cameroon. Applied Geography 17, 143–162.

Miles, G.L., Bell, E.J., Westerlund, F.V., 1996. Probability mapping of land use change—a GIS interface for visualizing transition probabilities. Computer, Environment and Urban Systems 20, 389–398.

Monela, G.C., 1995. Tropical rainforest deforestation, biodiversity benefits and sustainable land use: analysis of economic and ecological aspects related to the Nguru mountains, Tanzania. Doctor Scientiarum thesis 1995:27. Agricultural University of Norway.

Moneal, G.C., Solberg, B., 2000. Deforestation and agricultural expansion in Mhonda area, Tanzania. In: Palo, M., Vanhanen, H. (Eds.), World Forests from Deforestation to Transition? Kluwer Academic Publishers, Dordrecht, pp. 183–194.

Nelson, G. C., Hellerstein, D., 1995. Do roads cause deforestation? Using satellite images in econometric analysis of land use. Staff Paper 95 E-448, Department of Agricultural Economics. University of Illinois, Urbana-Champaign.

Nelson, G.C., 2002. Introduction to the special issue on spatial analysis for agricultural economists. Agricultural Economics 27, 197–200.

Nelson, G.C., Geoghegan, J., 2002. Deforestation and land use change: sparse data environment. Agricultural Economics 27, 201–216.

Okumu, B.N., Jabbar, M.A., Colman, D., Russell, N., 2002. A bio-economic model of integrated crop-livestock farming systems: the case of Ginchi watershed in Ethiopia. In: Barrett, C.B., Place, F.M., Aboud, A.A. (Eds.), Natural Resources Management in African Agriculture: Understanding and Improving Current Practices. CAB International, Wallingford, U.K.

Pfaff, A.S.P., Kerr, S., Hughes, R.F., Liu, S., Sanchez-Azofeifa, G.A., Schimel, D., Tosi, J., Watson, V., 2000. The Kyoto protocol and payments for tropical forest: an interdisciplinary method for estimating carbon-offset supply and increasing the feasibility of a carbon market under the CDM. Ecological Economics 35, 203–221.

Prasad, V.K., Badrinath, K.V.S., Tsuruta, H., Sudo, S., Yonemura, S., Cardina, J., Stinner, B., Moore, R., Stinner, D., Hoy, C., 2003. Implications of land use changes on carbon dynamics and sequestration–evaluation from forestry datasets, India. The Environementalist 23, 175–187.

Sadoulet, E., de Janvry, A., Benjamin, C., 1996. Household Behavior with Imperfect Labor Markets. Working Paper #786. Department of Agricultural and Resource Economics, Division of Agriculture and Natural Resources, University of California at Berkeley.

Sadoulet, E., de Janvry, A., 1995. Quantitative Development Policy Analysis. The Johns Hopkins University Press, Baltimore and London.

Sah, B.P., 1996. Watershed degradation and its socio-economic impacts using RS and GIS: A case study of Trijuga watershed, Nepal. Dissertation (M.Sc.) NR 96-20. AIT, Bangkok, Thailand.

Sands, R., Leimbach, M., 2003. Modelling agriculture and land use in an integrated assessment framework. Climatic Change 56, 185–210.

Sankhayan, P.L., 1996. Effects of structural adjustment programmes on cropping pattern and environment: a study on the southern highlands of Tanzania. Structural adjustment policies and environmental degradation in Tanzania, Zambia and Ethiopia. Preliminary Seminar Report, 9–10 January, Agricultural University of Norway.

Sankhayan, P.L., Gurung, N., Sitaula, B.K., Hofstad, O., 2003. Bio-economic modelling of and use and forest degradation at watershed level in Nepal. Agriculture, Ecosystems and Environment 94, 105–116.

Sankhayan, P.L., Hofstad, O., 2001. A village-level economic model of land clearing, grazing, and wood harvesting for Sub-Saharan Africa: with a case study in southern Senegal. Ecological Economics 38, 423–440.

Saxena, A.K., Nautiyal, J.C., Foot, D.K., 1997. Analyzing deforestation and exploring policies for its amelioration: a case study of India. Journal of Forest Economics 3, 253–289.

Shakya, K.M., 1987. Land use planning with multiobjective programming: a model for forest development in the hills of Nepal. PhD dissertation. Virginia Polytechnic Institute and State University, Virginia, USA.

Shively, G., 2001. Agricultural change, rural labor markets, and forest clearing: an illustrative case from Philippines. Land Economics 77, 268–284.

Silwal, U.K., 1995. Population growth and agricultural change in Nepal. Vikas Publishing House Pvt. Ltd., New Delhi, India.

Singh, I., Squire, L., Strauss, J. (Eds.), 1986. Agricultural Household Models: Extensions, Applications, and Policy. The World Bank. The Johns Hopkins University Press, Baltimore.

Stomph, T.J., Fresco, L.O., van Keulen, H., 1994. Land use system evaluation: concepts and methodology. Agricultural Systems 44, 243–255.

Southgate, D., 1990. The causes of land degradation along 'spontaneously' expanding agricultural frontiers in the third world. Land Economics 66, 93–101.

Thapa, G.B., Weber, K.E., 1995. Status and management of Watersheds in the upper Pokhara valley, Nepal. Environmental Management 19, 497–513.

Turner, B.L., 1994. Local faces, global flows: the role of land use and land cover in global environmental change. Land Degradation and Rehabilitation 5, 71–78.

Uitamo, E., 1999. Modelling deforestation caused by the expansion of subsistence farming in the Philippines. Journal of Forest Economics 5, 99–122.

UNU/WIDER (United Nations University/World Institute for Development Economics Research), 1999. In: Palo, M. (Ed.), Forest Transitions and Carbon Fluxes: Global Scenarios and Policies. UNU/WIDER, Helsinki.

Upadhyay, T.P., Sankhayan, P.L., Solberg, B., 2005. A review of carbon sequestration dynamics in the Himalayan region as a function of land use change and forest/soil degradation with special reference to Nepal. Agriculture, Ecosystems and Environment 105, 449–465.

Veldkamp, A., Lambin, E.F., 2001. Predicting land-use change: editorial. Agriculture, Ecosystems and Environment 85, 1–6.

Verburg, P.H., Veldkamp, A., Espaldon, V., 2002. Modeling the spatial dynamics of regional land use: the CLUE-S model. Environmental Management 30, 391–405.

Verburg, P.H., Schot, P., Dijst, M., Veldkamp, A., 2004. Land use change modelling: current practices and research priorities. GeoJournal 61, 309–324.

WCED (World Commission on Environment and Development), 1987. Our Common Future. Oxford University Press, Washington D.C.

World Bank, 1991. The Forestry Sector: A World Bank Policy Paper. World Bank, Washington D.C.

Zhang, Y., Uusivuori, J., Kuuluvainen, J., 2000. Econometric Analysis of the Causes of Forest Land Use Changes in Hainan, China. Department of Forest Economics, University of Helsinki, Finland.