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Rautiainen, A.

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Interim Report **IR-11-036**

Accounting for forest degradation in the Global Biospere Management Model (GLOBIOM)

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Approved by

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Abstract

Reducing Emissions from Deforestation and Forest Degradation in Developing Countries (REDD) is a hot political and scientific topic. Deforestation is largely driven by the competition for land. Forest degradation is often attributable to the way forest resources are managed and utilized. The Global Biospere Management Model (GLOBIOM), developed at IIASA, is a tool for assessing the carbon impacts of the land use competition of major land-based production sectors and different policy options influencing it. Currently the model can identify deforestation risks, but cannot account for degradation processes within forests. Here, I propose a solution to how forest degradation could be integrated into the GLOBIOM, especially in the context of the Congo Basin region where the economic activities of the informal sector are an important driver of forest degradation. The solution is based on two interacting modules that simulate the processes of forest degradation. The Informal Sector Module (ISM) simulates the procurement of fuel wood and timber by the informal sector, and the allocation of its harvests into forests based on a cost-minimization principle. The Forest Structure Module (FSM) simulates the development of forest structure over time in unsustainably managed forests and accounts for the impacts of the Informal Sectors harvests and rotating subsistence agriculture.

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About the Author

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Accounting for forest degradation in the Global Biospere Management Model (GLOBIOM)

1. Introduction

Forest degradation is considered a serious environmental, social and economic problem affecting many developing countries (1, 2).By reducing the forests' capacity to provide ecosystem services, forest degradation has an adverse impact on the livelihoods of local population where it occurs. Broad scale forest degradation can also have global impacts. If the forests' capacity to store carbon is hampered by degradation, the amount of carbon sequestered in forest biomass will be reduced. This carbon is released into the atmosphere, thus contributing to climate change.

In recent years the potential of Reducing Emissions from Deforestation and Forest Degradation in Developing Countries (REDD) has received both political and scientific attention (3-5). Politicians seeking to turn REDD into reality require scientific advice on the carbon impacts of different policy options. The Global Biospere Management Model (GLOBIOM), developed by Dr. PetrHavlík at IIASA, is one tool that can be used to assess such impacts in terms of land use competition of major land-based production sectors (6). However, out of the two Ds, only deforestation is currently accounted for in the GLOBIOM. In this paper, I present a blueprint for including forest degradation into the model. The patterns and processes of forest degradation in the Congo Basin region have been used as point of reference in the development of the proposed model enhancement. The economic processes driving forest degradation in other parts of the world may differ and hence, the proposed way of modeling the economics of forest degradation may not be directly applicable to other regions. However, components of the proposed solution, such as the Forest Structure Module for unsustainably exploitable forests (Chapter 2.4), maybe also useful in modeling forest degradation processes elsewhere.

The introductory chapter at hand provides the basic background information and the definitions of concepts used in later chapters. First, we look at the concept of forest degradation, which, despite increased political and scientific interest towards the phenomenon (3, 4), has not been unambiguously defined (2). As the different scientific backgrounds of the readers may influence their interpretation of the concept, it is necessary to clarify its definition in the context that it is used in this paper. Second, we focus on the economic aspects of forest degradation, and highlight how the forest utilization practices that lead to forest degradation differ from economically optimal sustainable forestry. Third, we look at the specific patterns and characteristics of forest degradation in the Congo Basin region. These observations have been used as background information in modeling process, and help understand why, for instance, the markets for informal sector products and the harvesting patterns of the informal sector are modeled the way they are. Lastly, I review the model framework for which I propose my enhancements. This framework includes the GLOBIOM, for which the enhancements are proposed, but also the Global Forest Model (G4M), which is the source of the input data for forests in the GLOBIOM, and is also the source of the input data for the forest structure model proposed in this paper.

The review of the models is not intended to be exhaustive, but to provide the necessary details of their functioning and resolution that are needed in the later chapters. The description of the models is supplemented by additions in further chapters, where necessary.

1.1 Forest degradation and recovery

Despite increased political and scientific interest towards the phenomenon (3, 4), it is not always clear what is meant by forest degradation(2). According to its most generic definition, forest degradation refers to the reduction of the capacity of forests to provide goods and services (2, 7). Yet, as forests are valued for the wide variety of ecosystem services they provide ranging from biodiversity and soil conservation to the production of fuelwood and timber, the interpretation of the definition tends to vary depending on the context. In this the focus is on biomass carbon, and forest degradation is defined accordingly. Readers interested in the differences between definitions of forest degradation are referred to (2).

Here, the term *forest degradation* is used to refer to the process of structural change within forests that, on the landscape level, has a negative impact on the carbon stock in forest biomass. The opposite of forest degradation is called recovery of forest biomass, or simply recovery. The process of forest degradation and recovery is influenced by human societies, that manage and utilize their forest resources. The intensity at which forest resources are used influences the species composition, size distribution, and number of trees in forests (8, 9), which in turn determine the amount of biomass and carbon per hectare. Young or heavily degraded forests are sparse and contain little biomass (8, 10). The amount of biomass, averaged on the landscape level, is greater in forest that are managed for maximum sustainable yield or maximum profit (8, 11), but not as high as in pristine old-growth forests (12).

Forest degradation can be divided into two components: landscape level degradation and class level degradation. Landscape level degradation (or recovery) can only occur as a result of changes in the landscape shares of different forest use classes. For example, the final felling of a commercially managed forest stand is not considered forest degradation, although the stand's biomass stock is temporarily depleted. In a *normal forest*, with an uniform age distribution of stands, the regional biomass stock will remain unchanged despite the felling, as the equal share of stands in each age class is sustained by a constant annual harvests (11). However, forest degradation does occur if commercial forest management is expanded into pristine natural forests, as the change in forest use class involves a shift from a from higher steady-state level of biomass (12) to a lower one (11) on the landscape level. Nevertheless, the introduction of commercial forestry does not always cause forest degradation. If forests that are over-exploited and thus, highly degraded, are brought under commercial management, the biomass stock can recover, if it is profitable to lengthen rotations to produce a greater yield (8).

In order to determine class level degradation, the biomass stock on the stand level is compared to the corresponding maximum potential biomass stock, conditional to the forest use class, natural growing conditions, successional stage, etc. The degree of class level degradation can be assessed by comparing the total amount of biomass observed in all stands belonging to the class to the respective sum of the their conditional maximum biomass potentials. To grasp the definition, suppose that there are two forest stands that together form a class called managed forests. Both stands are the same age and have similar growing conditions. The first stand has been optimally managed and its stocking degree, given its age and natural growing conditions, corresponds to its maximum potential. The second stand has been managed suboptimally and its stocking degree is only half of that observed in the first stand. The first stand is not considered degraded. The second stand is considered 50 % degraded. On the class level, the forests classified as managed forests are considered 75 % degraded. The conditionalization to age and natural growing conditions makes our definition of class level degradation insensitive to changes in the age distribution of forests. *(The earlier examples illustrating landscape level degradation rely on a normal forest assumption, which implies uniform age structure. Yet, the age-structure of forests within a forest use class is usually uneven and changes over time.)* As the amount of biomass in forest stands strongly depends on age and successional stage, gradual changes in the age distribution of forests cause fluctuations in biomass stocks. According to our definition, these fluctuations do not count as forest degradation or recovery, as the characteristics of each stand are compared to the theirconditionalized maximum potential, which implies that the effect of the changing age distribution is controlled for.

Neither landscape level degradation nor class level degradation, as they are here defined, are irreversible. Depleted regional biomass stocks can always be recovered by increasing the landscape share of biomass-rich forest use classes, or improving class-specific forest management practices. The possibility of irreversible degradation or a permanent loss in productivity, due to e.g. soil erosion or the loss of nutrients, is not included in the presented module. Accounting for these impacts is left to further research.

1.2 A note on the economics of forest utilization

Traditionally, economic questions of forest utilization are considered from the perspective of a sole-owner (or a group of users acting as one (13)) in a context in which land rights are well-defined and respected. A classical set of questions from a rational forest owner's point-of-view is *how to maximize the net present value of profits from forestry on a single stand? What is the optimal rotation length? Should the forest be thinned, fertilized, etc.?*(14). If we have reason to believe that property rights are defined and respected and that the land owners are well-informed, and pursue their best economic interests, we can model the regional development of growing stock volume, biomass and carbon in secondary forests based on the expected behavior of the land owners. Moreover, also land use decisions can also be modeled based on the economic considerations of land owners (15, 16). If, in a given location, farming is more profitable than forestry it is rational to clear forests for agricultural use. Or, if forestry is more profitable than agriculture, it makes economic sense to abandon farming and plant trees. Although, land use patterns in the GLOBIOM are not modeled as the result of the individual land owners optimization, the adopted welfare maximization approach produces fairly similar patterns of land use change.

Relaxing the assumptions of property rights and perfect information gives rise to a wide array of forest utilization patterns, that are economically logical, but deviate from the conventional behavior of the well-informed rational land owners. If land rights are well defined, but the forest users are not informed of economically optimal forest management practices, continuous harvesting of fuelwood and timber may lead to forest degradation and low yields (8). On the other hand, a lack of property rights or respect for them can erode economic incentives for sustainable forest management. If the users of the forest resources cannot secure the future profits for themselves, their behavior is guided by more immediate economic incentives rather than the maximization of net present value. For instance, the patterns of peri-urban deforestation around several African cities (17-19), suggest that the harvests are guided by a principle of minimizing harvesting and transport costs, rather than a principle of maximizing sustained profits.

In order to understand and model forest degradation it is necessary to give up some of the assumptions of rational profit-maximizing forestry. For instance, if all secondary forests are modeled based on the assumption that they are managed in a sustainable and economically optimal way, forest degradation can only occur on the landscape level (if pristine natural forests are converted to secondary forests). Forest degradation cannot occur at the class level, since all secondary forests are assumed to be managed in the same sustainable way that keeps the forest structure unchanged. However, many of the activities that promote forest degradation strongly influence forest structure at the class level. For instance, intensive fuel wood collection in the Congo Basin primarily affects secondary forests near urban centers (19). The harvesting pressures are first directed to the nearest forests, where the stock of biomass is depleted and productivity plummets. Then, due to a shortage of wood sources nearby, the wave of degradation spreads outward to secondary forests further away (17, 19). As long as the wood is harvested from secondary forests, the degradation occurs at the class level and cannot be modeled without accounting for structural change within forests.

1.3 Forest degradation in the Congo Basin

The main causes of forest degradation in the Congo Basin are fuel wood collection, slash-and-burn subsistence agriculture, and illegal logging. The impacts of fuel wood collection and slash-and-burn agriculture are greater than the impact of illegal logging. According to official statistics, the annual wood energy harvests in Central Africa total approximately 104 M m^3, while only 13 M m^3 are harvested for industrial timber (18). The official statistics for industrial timber harvests do not account for the informal sector (i.e. illegal logging) but it has been estimated that fuel wood collection is accountable for a significantly higher level of harvesting than logging by the formal and informal sectors combined (18, 19). The patterns of forest degradation caused by fuel wood collection, slash-and-burn subsistence agriculture, and illegal logging are briefly described in more detail in later sections, where the impacts of these practices are modeled.

1.4 Modeling framework

1.4.1 GLOBIOM and G4M models

The purpose of the module proposed in this paper is to act as an interface between two existing models: the Global Biospere Management Model (GLOBIOM) and the Global Forest Model (G4M). "GLOBIOM is a global recursive dynamic partial equilibrium model integrating the agricultural, bioenergy and forestry sectors with the aim to provide policy analysis on global issues concerning land use competition between the major land-based production sectors" (6, 20). The global market equilibria for agricultural and forest products are calculated by optimizing land use and processing activities so that the sum of consumer and producer surplus is maximized, subject to a set of resource, technological and political constraints (20). The optimization problem is formulated into a welfare maximization problem that is then solved at ten year intervals, as the state of the world changes according to exogenous scenarios depicting social and environmental conditions. The G4M provides spatially explicit estimates of annual aboveground wood increment and the development of aboveground biomass (21). It also provides information on the costs of different forest management options (21). The wood increment, biomass and cost estimates produced by the G4M are used as inputs for modeling forests in the GLOBIOM (20, 22).

The models are not reviewed here in detail. Only some technical details that are crucial to understanding how the 4DM works are briefly reviewed in this section. My interpretation of the models based on entries in the IIASA FOR Wiki (20-22), two published articles(6, 23), unpublished documents (24-26), a presentation (27) and my personal communication with PetrHavlík, AlineMoisnier, HannesBöttcher, Georg Kindermann and MykolaGusti. Any misinterpretations are my own. Regarding the GLOBIOM, interested readers are referred to the currently most extensive publicly available description of the model (6) and advised to contact Dr. PetrHavlík, the developer of the model, for more details. Regarding the G4M, interested readers are referred the description of a predecessor of the current model (23) and advised to contact its developer, Dr. Georg Kindermann.

1.4.2 The Resolution of GLOBIOM

In the GLOBIOM, the physical environment is represented by dividing global land area into Simulation Units (SimU) by layering two maps on top of each other (6, 27). First, the world is divided into 175 Homogenous Response Units (HRUs) based on a classification of five altitude classes, seven slope classes and five soil classes, using data from the Geo-bene database (6, 28). The parameters used for this geographical clustering are fairly insensitive to changes in land use or climate (6). In the next step, the HRU map is intersected with global a 0,5 degree grid (28). Together the HRU map and the 0,5 degree grid delineate a set of roughly 200,000 SimUs(27). Each grid cell contains at least one SimU, but may contain more if the terrain is heterogeneous. For each SimU the climatic, land use and irrigation parameters are separately defined (6) and a number of management options are simulated using the Environmental Policy Integrated Climate Model (EPIC) (6, 29, 30). Forest data are simulated using the G4M (6, 23) Societal parameters, such as population, that are used to model the demand for goods are defined at the grid cell level.

1.4.3 Treatment of forests

In the G4M global forests are composed of a single representative tree species. The differences in the growth rate of the species in different growing conditions are described by a single variable, the optimum mean annual increment (MAI), and a set of exogenously defined parameters which define the shape of increment and mortality curves. Currently, changes in forest structure are not included in GLOBIOM simulations. All forests are modeled as if they were sustainably managed normal forests with a uniform age structure and a constant annual yield.

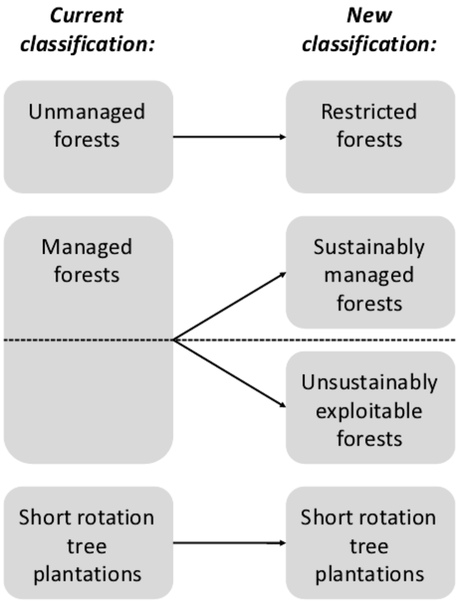
2. Enabling forest degradation in the GLOBIOM

There are two important amendments that must be made to the GLOBIOM in order to enable forest degradation to occur in simulations. Firstly, at least one category of forests must be made degradable. That is to say, that the age-structure of (at least some forests) must be allowed to change in response to harvesting rates that are greater or lesser than the maximum sustainable yield. In section 2.1, I propose introducing a separate category of forest (called *unsustainably exploitable forest*), for which management practices and harvests are not optimized and whose structure may change over time. The impacts of harvests and regrowth in unsustainably exploitable forests are simulated by the Forest Structure Module (FSM) described in section 2.3. Secondly, it is necessary to model the utilization of these degradable forests and the economic principles governing their use. In section 2.1, I propose introducing an informal sector that is responsible for the utilization of unsustainably exploitable forests. The working of the Informal sector is further described in Section 2.2. Harvests are allocated into unsustainably exploitable forests based on a principle of minimizing costs from harvesting and transport. To allow running this optimization process separately, these principles are coded into a distinct module, the Informal Sector Module (ISM). Lastly, after presenting the components of the blueprint separately, in Section 2.4 we look at the big picture and summarize the how the two modules interact with each other and the GLOBIOM.

2.1 Amendments to the GLOBIOM

2.1.1 Categories of forests

Currently, forests are presented by three categories in the GLOBIOM (Fig. X): unmanaged forests, managed forests and short rotation tree plantations. Unmanaged forests are set aside from the production chains of forest and bioenergy products. All harvests are directed to managed forests and short rotation tree plantations. Both exploited forests types are assumed to be normal forests with a uniform age structure and a constant mean annual increment (MAI), which is also used to present the sustainable annual yield.



The new classification presented in (Fig. X) consists of four classes. The category of short rotation tree plantations remains unaltered. The composition of the category of unmanaged forests also remains the same, but it is relabeled as restricted forests. The renaming is done to avoid possible confusion caused by the term *unmanaged.* The category of managed forests is split into to two classes: sustainably managed forests and unsustainably exploitable forests. The category of sustainably managed forests inherits the properties of the former category of managed forests. Sustainably managed forests are assumed to be optimally managed normal forests[1], with a constant MAI. However, the category's geographical coverage is more restricted. Only the forests that are officially managed for legal wood or bioenergy production (e.g. official logging

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[1] Even if forests are optimally managed from (an economic point-of-view) it does not imply that the age structure of the forests is uniform on the landscape level. However, the simplifying normal forest assumption makes the treatment of the forests and the calculation of MAI much easier. The assessment of the validity of this assumption in the regions included in the GLOBIOM is beyond the scope of this study.

concessions or forests with a forest management plan) are classified as sustainably managed forests. All other forests, that are not restricted or sustainably managed forests or short rotation tree plantations are classified as unsustainably exploitable forests. The characteristics of these forests are modeled using the forest structure module proposed in this paper. This is done to allow changes in forest structure to occur in response harvest volumes that are either above or below the forests' natural renewal capacity.

2.1.2 The formal sector and the informal sector:

Currently, the land use patterns in the GLOBIOM are entirely determined as the solution to a single welfare maximization problem, where the allocation of land resources (along with other inputs) is optimized to maximize the objective function (consumer and producer surplus). In order to allow for a part of the land resources (in this case forests) to be utilized according to a different logic (in this case suboptimally) it is necessary to exclude these land areas from the land use optimization problem. Also, it is necessary to determine the conditions under which these resources can be introduced into the realm of optimal land use.

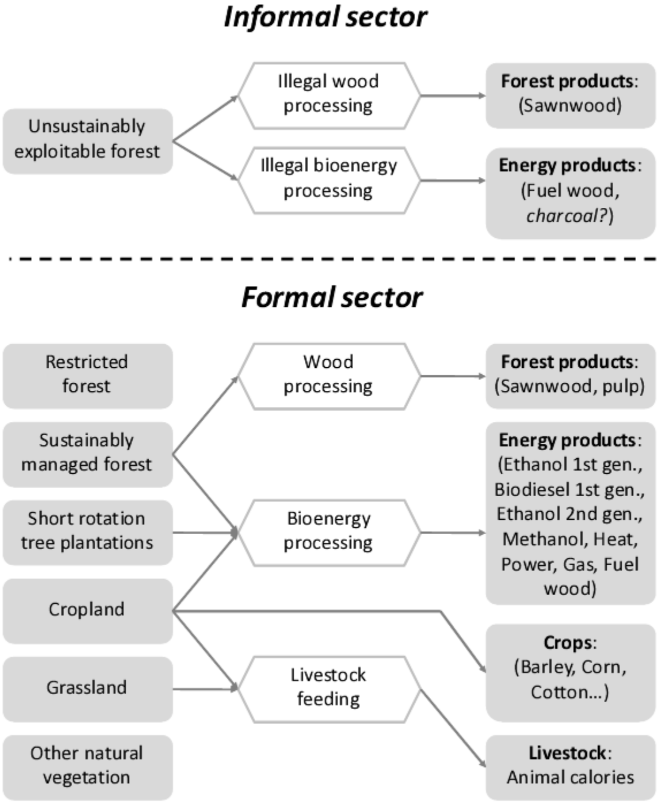

Fig. Y The production chains of the formal sector and the informal sector

To conceptualize the problem it is helpful to imagine that the land resources are used by two sectors: the formal sector and the informal sector. The social welfare allocation, as it is currently done in the GLOBIOM, is considered to represent economic activities in the formal sector (Fig. Y). In the proposed setting, the pool of land resources available to the formal sector covers three out of four categories of forest (restricted forests, sustainably managed forests and short rotation tree plantations) and all other land use classes (cropland, grassland and other natural vegetation). The informal sector is responsible for harvests in unsustainably exploitable forests (Fig. Y). The volume of these harvests is not determined as a part of the solution to the social welfare maximization problem. Instead, there are separate markets for informal sector products.

Technically, the separation of the two sectors can be achieved in the following manner: When the GLOBIOM is run for a given year, the model is first run for the formal sector. Social welfare is maximized by optimizing land use over a pool land resources that includes all other categories apart from unsustainably exploitable forests. Next, the the informal sectors activities in unsustainably exploitable forests are simulated using the Informal Sector Module, described in Section 2.3.

2.1.3 Transition of land resources to the formal sector

In the current set up of the GLOBIOM land use change is driven by welfare maximization: if welfare can be increased by substituting on form of land use for another in any given SimU, then land use is observed. However, in the proposed setting, this logic cannot be used to model land use between unsustainably exploitable and other land use classes. The reason is simple: if the unsustainably exploitable forests are excluded from the welfare maximization problem, then the land use cannot change as a result of welfare maximization. Here, I present two alternative ways to solve this problem of modeling land use conversions between unsustainably exploitable and other land use classes: Exogenous and Endogenous conversion patterns.

Before presenting the two alternatives useful to consider what kind of patterns of land use change could be expected. From the perspective of the formal sector, unsustainably managed forests form a pool of inefficiently used land resources that could be exploited to increase welfare. Thus, land resources can be generally expected to flow from unsustainably managed forests to other land use classes, managed by the formal sector, and not vice versa. The only reason for a flow of land resources in the opposite direction, from use by the formal sector into unsustainably managed forests, would be the complete loss of profitability of all forms of production. In this case the abandoned lands might revert to forest. However, if the property rights of the formal sector land resources are well-defined, the conversion of the land into the class of unsustainably exploitable forests would require (official or unofficial) renouncement of ownership in order to allow the forests to be exploited by the informal sector. Thus, for simplicity, it is reasonable to assume that land use change only occurs in the direction of the formal sector. The expansion of the formal sector pool of land resources can be thought of as a gradual process of securing property rights in the land areas formerly open to informal sector activities.

Exogenous conversion patterns. The simplest way to model the transition of land resources from unsustainably exploitable forests to formal sector use is to assume an exogenous rate of change. For instance, if we assume an annual rate of change of 1 %

and the GLOBIOM is run at a 10-year time-step, 10 % of the land pool in unsustainably managed forests will be brought into formal sector use between two consecutive GLOBIOM years, say 2010 and 2020. Different rules can be used to guide the patterns of land use change. For example, we may assume that the land areas incorporated into formal sector activities are selected based on accessibility. In the this case, the 10 % of the forests closest to roads and human habitations would be claimed first. Another possible rule is productivity. In this case, the unsustainably exploitable forest areas are incorporated into the formal sector in order of the profitability of alternative land uses. Property rights in areas with the highest production value in any other form of land use are secured first. Over time, property rights are also secured in less productive areas, but not until all more productive land has been transferred into the formal sector land resource pool.

Endogenous conversion patterns.Another approach is to endogenize the patterns of land use change into GLOBIOM simulation. One way to do this, is to introduce an (exogenously defined) conversion cost for unsustainably exploitable forests. This means, that all unsustainably exploitable forests can be brought into formal sector use, but at a cost that is separately defined for each SimU. However, the forests are only converted to other land use if the welfare generated in the new use is greater than the conversion cost. The conversion cost can be thought of as the expense of securing property rights by the new land owners. A drawback of this approach is that the conversion costs are not observable and would have to be determined rather arbitrarily in order to produce patterns of land use change that seem credible.

2.2 Informal Sector Module (ISM)

The Informal Sector Module is used to solve the market equilibrium for informal sector forest products in each grid cell and allocate harvests to unsustainably exploitable forests based on a principle of minimizing harvesting and transportation costs. As argued in Section 1.3, most of the economic activities promoting forest degradation in the Congo Basin are attributable to the informal sector, which is largely responsible for fuel wood and timber harvests. Also subsistence agriculture, the third major cause of forest degradation in the region, is an informal sector activity. However, subsistence agriculture is not included in the Informal Sector Module, as the module has been designed to depict the markets of traded goods. Unlike fuel wood and timber, the crops produced by subsistence farmers are generally not traded in the markets. The modeling of subsistence agriculture is considered later, as an integrated process in the Forest Structure Module.

In this section we first look at the justification for the separate modeling of the informal sector. We then turn to the economics of the informal sector (Sections 2.3.1 and 2.3.2), that form a theoretical basis for the module. The cost minimization procedure presented in section 2.3.2 forms the core of the Informal Sector Module. In section 2.3.3 we discuss why the Informal Sector Module needs to be run at a shorter time step (1 year) than the GLOBIOM (10 years).

2.2.1 Justification for the separation of the markets in the Congo region

On average, over 80 % of total domestic energy consumption in African countries is met by wood energy and fuel wood harvests account for more than 90 % of total harvests in forests and woodlands (18). According to official statistics, the annual wood energy harvests (104 M m^3) in Central Africa are eight-fold compared to legal industrial timber harvests (13 M m^3) (18). Currently the urban populations in Central Africa annually consume approximately 1 m^3 of wood fuel (including charcoal) per capita. The informal sector is responsible for almost all fuel wood harvests. Also timber is harvested by the informal sector, but the volume of timber produced by the informal sector is difficult to quantify. For instance in the DRC, while timber harvested by the formal sector is generally exported, the informal sector is the main source of domestic timber (19). The informal sector also exports to neighboring countries such as Angola, Zambia, Burundi, Rwanda, and Sudan (19).Annually, artisanal loggers are estimated to produce 1.5 to 2.4 million m^3 of timber, which is five to eight times the formal sector's production volume (19). Because the informal sector's domestic market share for fuel wood and timber is large, the importance of modeling the black market activities is justified.

2.2.2 Demand for informal sector forest products

As fuel wood and charcoal are used to meet the basic energy needs of households in the Congo region, the demand for them can be considered fairly inelastic; each person needs a certain amount of wood to subsist, less wood is too little, but having more wood will not significantly improve one's living conditions. The simplest way to model the demand for fuel wood is to assume that each inhabitant requires a fixed amount for fuel wood annually. For instance, the annual per capita consumption of fuel wood in the Congo region has been estimated to be 1 m^3. This information can be combined with the population data (Fig. Z) to estimate the demand for fuel wood at the grid cell resolution. Similarly, a rough population based estimate can be made of the demand for informal sector timber.

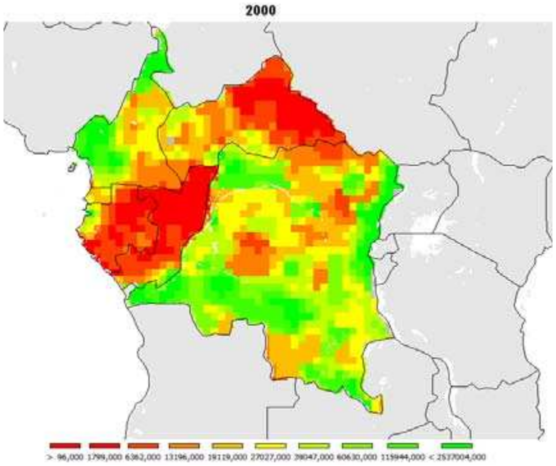

Fig Z. Population in the in the Congo basin region at grid cell resolution (Source: GLOBIOM / IIASA)

The per capita demand of informal sector forest products may change over time. For example, if cheap alternative sources of household energy, including legally produced charcoal and woodfuel, become available, the demand for the informal sector products may decline (in Fig. W this would imply a leftward shift of the demand curve, D). It is possible to model expected changes in household energy consumption using a different scenarios. One alternative is a business as usual scenario, where per capita wood consumption remains constant. Other alternatives are positive scenarios, where along with economic growth and development the demand for informal sector bioenergy declines, or negative scenarios, such as the substitution of wood fuel by charcoal which requires more wood to produce.

2.2.3 Supply and market equilibrium of informal sector forest products

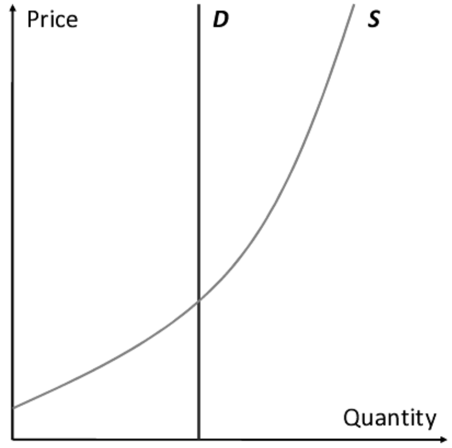

Fig. W Market equilibrium for informal sector forest products

The market equilibrium for informal sector forest products is shown in Fig. W. As the demand for informal sector forest products is assumed to be perfectly price-inelastic, the quantity traded at the market equilibrium is the same as the constant quantity of demand, regardless of the shape of the supply curve[2]. Thus, the markets for informal sector forest products are demand driven: whatever fixed quantity is demanded, is also supplied. Although the demand for e.g. fuel wood is considered to be insensitive to reasonable prices changes, the suppliers of informal sector forest products cannot charge any price they like for their goods. As the informal sector is composed of many small-scale entrepreneurs and the barriers of market entry are low, the competitive structure of

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[2] As long as the quantity demanded does not exceed the total amount of suitable wood in forests. Making this simplifying assumption does not affect our analysis as the amount of growing stock in forests grossly exceeds theannual harvests. For instance, the growing stock volume in DRC's forests alone is estimated at 35473 million m^3(1). This is approximately 200 times the volume of annual timber harvests (legal and illegal) and fuel wood collection in all of Central Africa, assuming that the consumption of fuel wood is 104 million m^3 , legal timber harvests are 13 million m^3, and that illegal timber production is at maximum 8-fold compared to legal harvests (18, 19).

the industry is very close to perfect competition. As a result, marginal profits in the industry are reduced to zero, and the unit price of the goods is determined by the marginal production costs at the market equilibrium. If marginal profits are temporarily greater than zero, new entrepreneurs can enter the markets and compete against incumbents by offering lower prices while still making a profit.

Because of the perfectly competitive industry structure, the supply curve is determined by production costs only. Production costs can be broken down into expenses accrued from harvesting and transport. If the demand for wood products in a grid cell is small, the cost of wood is low; small amounts of wood can be harvested in nearby forests, and the costs of transport remain minimal. However, if the demanded quantity increases, wood products will need to be imported from further away and transportation costs will cause its price to rise. Thus, the supply curve is upward sloping (Fig. W). The steepness of the supply curve depends on the availability of wood in the unsustainably exploitable forests nearby, since all of the informal sector's harvests are directed to these forests. The gradient of the supply curve in each grid cell may change over time. If unsustainably exploitable forests nearby are overexploited, the stock of available wood will be depleted and harvests will need to be redirected to forests further away. Consequentially, the price of wood products will rise as the transport distances are increased.

On the regional level, the harvesting patterns of the informal sector that match the described supply structure can be formally stated as a minimization problem, where the objective function is

$$\mathrm{Min} E_P = \sum_{\beta=1}^{l} \left(\sum_{\alpha=1}^{m} \sum_{\beta=1}^{n} E_{T^{\gamma}_{\alpha,\beta}} V_{H^{\gamma}_{\alpha,\beta}} + \sum_{\alpha=1}^{m} \left(E_{H^{\gamma}_{\alpha}} \sum_{\beta=1}^{n} V_{H^{\gamma}_{\alpha,\beta}} \right) \right),$$

where

E_P	are total production costs;
$E_{T^{\gamma}_{\alpha,\beta}}$	are transport costs of wood assortment γ, from SimUα to the markets in grid cell β;
$E_{H^{\gamma}_{\alpha}}$	are the harvesting costs of wood assortment γ, in SimUα;
$V_{H^{\gamma}_{\alpha,\beta}}$	is the volume of wood assortment γharvested in SimUα and sold in grid cell β; and
l, m, n	are the total number of assortments, SimU's and grid cells respectively

The minimization problem is subject to two sets of constraints. The first set of constraints is:

$$\sum_{\alpha=1}^{m} V_{H^{\bar{\gamma}}_{\alpha,\bar{\beta}}} = Q_{D^{\bar{\gamma}}_{\bar{\beta}}} \quad \forall \bar{\beta}, \bar{\gamma},$$

where

$V_{H^{\bar{\gamma}}_{\alpha,\bar{\beta}}}$	is the volume the fixed wood assortment$\bar{\gamma}$, transported from any SimUαi to the fixed grid cell $\bar{\beta}$, and
$Q_{D^{\bar{\gamma}}_{\bar{\beta}}}$	the demand of the fixed wood assortment $\bar{\gamma}$ in the fixed grid cell $\bar{\beta}$

The constraints state that the total sum of imports of each wood assortment from the forests in all SimUs to each particular grid cell must equal the demanded quantity of that assortment in that grid cell. More simply, this implies that in each grid cell, supply must meet demand.

The second set of constraints is:

$$\sum_{\beta=1}^{n} V_{H_{\bar{\alpha},\beta}^{\bar{\gamma}}} \leq V_{A_{\bar{\alpha}}^{\bar{\gamma}}} \quad \forall\, \bar{\alpha}, \bar{\gamma},$$

where

$V_{H_{\bar{\alpha},\beta}^{\bar{\gamma}}}$ is the volume the fixed wood assortment $\bar{\gamma}$, transported from the fixed SimU$\bar{\alpha}$ to any grid cell β, and

$V_{A_{\bar{\alpha}}^{\bar{\gamma}}}$ $is\ the\ maximum\ harvestable\ volume\ of\ the\ fixed$ wood assortment $\bar{\gamma} in\ the\ fixed$ SimU $\bar{\alpha}$

The constraints state that the amount of wood of each particular assortment cannot exceed the amount of wood of a suitable size class available in a given SimU. Simply put, you can only chop down as many trees as there are in the forest. The question of how the availability of wood is determined is explained further after the introduction of the forest structure model.

As a by-product of the solution to the informal sector production cost minimization problem we will also get geographically explicit data on the allocation of harvests into unsustainably exploitable forests. The optimal volume of harvests, $V_{H*_{\bar{\alpha}}^{\bar{\gamma}}}$, of assortment $\bar{\gamma}$directed to the unsustainably exploitable forests SimU$\bar{\alpha}$is:

$$V_{H*_{\bar{\alpha}}^{\bar{\gamma}}} = \sum_{\beta=1}^{n} V_{H*_{\bar{\alpha},\beta}^{\bar{\gamma}}},$$

where

$V_{H*_{\bar{\alpha},\beta}^{\bar{\gamma}}}$ is the volume wood assortment$\bar{\gamma}$, transported from SimU $\bar{\alpha}$ to grid cell βin the optimal solution.

2.2.4 Time-step of simulating informal sector activities

The GLOBIOM is usually solved for single years at a 10-year time step. Solving the model in a single year is suitable in the case of most forms of land use. It is suitable way of modeling agriculture, as agricultural lands produce one or more harvests per year and the crops can be changed yearly. It is also suitable for modeling managed normal forests that on average produce a constant yield per hectare (as long as the age distribution of the forest remains uniform, regardless of the patterns of land use change). However, it is not suitable for modeling unsustainable forestry, as the volume of harvests in one year affects the potential for harvests in the following years.

As the harvesting patterns of the informal sector vary from year to year depending on the availability of wood, it is necessary to simulate the informal sector activities in the years in between the GLOBIOM years, that are ten years apart. Fortunately, simulating the procurement of illegal forest products does not require solving the entire GLOBIOM every year. Instead, in the intervening years it is enough to run the production cost minimization procedure and account for the impact of harvests in unsustainably exploitable forests. The production cost minimization procedure can be programmed into a separate module (the Informal Sector Module, proposed in this section).

Likewise, changes in forest structure can be simulated using a another separate module (the Forest Structure Module, proposed in the next section). By separating these tasks into two distinct modules, the calculation procedures for the intervening years can be made substantially lighter than those required for the years for which the entire model is solved.

2.3 The Forest Structure Module (FSM)

The Forest Structure Module (FSM) is used to simulate the changes in the structure of unsustainably exploitable forests in response to growth and harvests at the SimU level. The FSM interacts with the ISM, for which the module provides input data on the availability of harvestable wood (by SimU and size-class).In return, it receives input data on the volume of harvests in each SimU (optimized by the ISM).

The first three subsections (2.3.1-2.3.3) introduce the structure and basic functions of the module. In the fourth subsection (2.3.4), we consider how the module could be initialized using existing data. The following three subsections (2.3.5-2.3.8), explain how informal sector activities (fuel wood and timber harvests, subsistence agriculture) interfere with the patterns of natural succession in forests and how these effects can be accounted for using the FSM.

Currently the FSM only includes the development of growing stock and living biomass. Other forest carbon pools, such as dead wood, litter and soil carbon have not been modeled. The inclusion of these pools in the module is left to future development work.

2.3.1 Setting up the forest structure model

The forest structure model consists of one scalar variable, forest area, $a(t) \in \mathbb{R}_{0+}$, and four matrices: the areal share matrix, the density matrix, the biomass expansion factor matrix and the carbon factor matrix denoted by $\mathrm{S}(t), \mathrm{D}(t), \mathrm{B}(t), \mathrm{C}(t) \in \mathbb{R}^{k \times l}$, respectively. The dimensions of the matrices, $k, l \in \mathbb{N}_{0+}$, are the number of density classes and age classes in the (discrete) joint stocking degree and age distribution, respectively. The extent of the forest area, $a(t)$, and values of the elements of the matrices $\mathrm{S}(t), \mathrm{D}(t), \mathrm{B}(t), \mathrm{C}(t)$, may change over time. Hence, the time index *t* is used to denote the time period for which these values are reported. The scalar variable and the matrices are defined at the same resolution as the G4M inputs to the GLOBIOM (i.e. simulation unit level for GLOBIOM, grid cell level for CongoBIOM). Similar to the G4M, in the presented model it is assumed that forests are composed of trees of one representative species only. The time step of the model is one year. The scalar variable and matrices are described in more detail below.

Forest area, $a(t)$, is measured in hectares. It is treated as a scalar. Thus, changes in forest area do not automatically affect the structure of forests. The impact of changes in forest area have to be separately accounted for by changes in the values of the elements of the area share matrix, $\mathrm{S}(t)$. For instance, the expansion of forest area accompanied by zero deforestation between periods *t* and *t+1*, would have two effects: (1) an increase in

a, so that $a(t+1) > a(t)$, and (2) an increase in relative area shares of the youngest age classes $[s_{1,1}(t) \quad \ldots \quad s_{k,1}(t)]'$ (compared to a case in which forest area would remain constant, and no additional land area would be introduced to the youngest age class).

The area share matrix, $\mathrm{S}(t)$, expresses the joint distribution of the relative areal shares of stands in each density and age class.The stocking degree of forests of a given age varies depending on the their utilization history. It is assumed that, at any given age, forests with no human impact have the highest stocking degree. Forests of a lower stocking degree are found in areas with greater human impact (i.e. uncontrolled fuel wood harvests, etc.): the greater the impact, the lower the stocking degree.

$$\mathrm{S}(t)=\begin{bmatrix} s_{1,1}(t) & \ldots & s_{1,l}(t) \\ \vdots & \ddots & \vdots \\ s_{k,1}(t) & \ldots & s_{k,l}(t) \end{bmatrix}, \qquad |s_{i,j}(t) \in \mathbb{R}_{0+};\ i \in \mathbb{N}_+ \leq k;\ j \in \mathbb{N}_+ \leq l$$

$$\text{and} \sum_{i=1}^{k} \sum_{j=1}^{l} s_{i,j}\,(t) = 1$$

The elements of $\mathrm{S}(t)$, $s_{i,j}(t)$, indicate the areal shares of each age-specific stocking degree class, where stocking degree and age classes are denoted by the subindices$i$ and j, respectively. For example, $s_{1,1}(t)$ is the areal share of stands in the lowest age-specific stocking degree class of forest stands in the youngest age class. (In the case of all age classes, the lowest stocking degree class is in fact a zero stocking degree class). Similarly, $s_{k,l}(t)$ is the areal share of stands in the highest age-specific stocking degree class of forest stands in the oldest age class. As all stands belong to some class (i,j), the areal shares $s_{1,1}(t), \ldots, s_{k,l}(t)$ cover all forest area (and, thus, the sum of the shares is 1).

The rows and the columns of the matrix express the conditional distributions with respect to age and stocking degree class. For example, the column vector $[s_{1,1}(t) \quad \ldots \quad s_{k,1}(t)]'$ is the age-class specific stocking degree distribution for stands in the youngest age class at time t. Similarly, the row vector $[s_{1,1}(t) \quad \ldots \quad s_{1,l}(t)]$ is the stocking degree class specific age distribution for stands in the lowest stocking degree class at time t.

The areal shares of the stands in each age and stocking degree class change over time in response to harvests, growth, and natural disturbances (e.g. forest fires). Hence, the time index, t, is used to mark the time period of the observed age and stocking degree distribution.

The density matrix, $\mathrm{D}(t)$, has the same dimensions as the area share matrix $\mathrm{S}(t)$ and expresses the average densities (m^3 of growing stock / ha) of all classes (i,j).

$$\mathrm{D}(t)=\begin{bmatrix} d_{1,1}(t) & \ldots & d_{1,l}(t) \\ \vdots & \ddots & \vdots \\ d_{k,1}(t) & \ldots & d_{k,l}(t) \end{bmatrix}, \qquad |d_{i,j}(t) \in \mathbb{R}_{0+};\ i \in \mathbb{N}_+ \leq k;\ j \in \mathbb{N}_+ \leq l$$

For example, $d_{1,1}(t)$ is the average density of stands in the lowest age-specific stocking degree class of the youngest forest stands and, similarly, $d_{k,l}(t)$ is the average density of stands in the higherst age-specific density class of the oldest forest stands. In theory the average densities of stands in each class (i,j) may change over time in response to changes in growing conditions (e.g. soil degradation or climate change). In the presented model, however, the average densities in each class (i,j) are assumed to be time invariant. Hence, the time indices of the matrix and its elements are dropped.

The biomass factor matrix, $\mathrm{B}(t)$ has the dimensions as the density matrix, D. For every element, $d_{i,j}$, in D, the biomass factor matrix contains a specific stand-level biomass factor, $b_{i,j}$ that expresses the ratio of living above-ground biomass to growing stock volume (tons of biomass / m^3 of growing stock).

$$\mathrm{B}(t)=\begin{bmatrix} b_{1,1}(t) & \dots & b_{1,l}(t) \\ \vdots & \ddots & \vdots \\ b_{k,1}(t) & \dots & b_{k,l}(t) \end{bmatrix}, \qquad |b_{i,j}(t) \in \mathbb{R}_{0+};\ i \in \mathbb{N}_{+} \leq k;\ j \in \mathbb{N}_{+} \leq l$$

For example, $b_{1,1}(t)$ is ratio of above-ground biomass to growing stock volume in stands in the lowest age-specific stocking degree class of the youngest forest stands and, similarly, $b_{k,l}(t)$ is the respective ratio in stands in the highest age-specific stocking degree class of the oldest forest stands. Similar to average density, the biomass to growing stock ratio of stands in each class (i,j) may change over time in response to changes in growing conditions. In the presented model, however, these ratios are assumed to be constant for each class (i,j). Hence, the time indices of the matrix and its elements are dropped.

Based on the values of the elements in matrices D and B, the average concentration of biomass per hectare for each class (i,j), $m_{i,j}$, can be expressed as a product of the average density and biomass concentration of growing stock, $m_{i,j} = d_{i,j} \times b_{i,j}$.

The carbon factor matrix, $\mathrm{C}(t)$ is used to convert biomass to carbon. For each class (i,j), the carbon factor matrix contains an element, $c_{i,j}$, which expresses the carbon content of biomass (tons of carbon / ton of biomass).

$$\mathrm{C}(t)=\begin{bmatrix} c_{1,1}(t) & \dots & c_{1,l}(t) \\ \vdots & \ddots & \vdots \\ c_{k,1}(t) & \dots & c_{k,l}(t) \end{bmatrix}, \qquad |c_{i,j}(t) \in \mathbb{R}_{0+};\ i \in \mathbb{N}_{+} \leq k;\ j \in \mathbb{N}_{+} \leq l$$

For example, $c_{1,1}(t)$ is the carbon concentration of biomass in stands in the lowest age-specific stocking degree class of forest stands in the youngest age class and, similarly, $c_{k,l}(t)$ is the respective ratio in stands in the highest age-specific stocking class of forest stands in the oldest age class. The carbon concentration in each class (i,j) may change over time (e.g. in response to a change in the species composition of the forests, which is not accounted for in the model). Nevertheless, in the model the carbon concentration of biomass in each class (i,j) is assumed to be time-invariant and, hence, the time indices of the matrix and its elements are dropped.

Based on the values of the elements in matrices D, B and C, the average concentration of carbon per hectare for each class (i,j), $q_{i,j}$, can be expressed as a product of the corresponding elements in the three matrices, $q_{i,j} = d_{i,j} \times b_{i,j} \times c_{i,j}$.

2.3.2 Stocks, average concentrations and annual rates of change:

Based on information of forest area and the areal shares and average densities of all classes (i, j), the average density of forests in the entire region (e.g. simulation unit or grid cell), $\bar{v}(t)$, can be calculated by the formula:

$$\bar{v}(t) = a(t)\mathbf{1}_k'(\mathrm{S}(t), \circ\mathrm{D})\mathbf{1}_l,$$

where$\mathbf{1}_k$ and $\mathbf{1}_l$ are column vectors with the dimensions $k \times 1$ and $l \times 1$, respectively. All elements of the vectors $\mathbf{1}_k$ and $\mathbf{1}_l$ are ones. In the formulae, $\circ$ denotes the Hadamard product of two matrices. The total growing stock volume in the region, $v(t)$, is the product of total forest area and average density:

$$v(t) = a(t)\bar{v}(t) = a(t)\mathbf{1}_k'(\mathrm{S}(t) \circ\mathrm{D})\mathbf{1}_l.$$

Similarly, the average biomass concentration per hectare,$\bar{m}(t)$, the total biomass stock, $m(t)$, the average carbon concentration per hectare,$\bar{q}(t)$, and the total carbon stock, $q(t)$, in unsustainably exploitable forests are received using the formulae:

$$\bar{m}(t) = a(t)\mathbf{1}_k'(\mathrm{S}(t)\circ\mathrm{D}\circ\mathrm{B})\mathbf{1}_l,$$

$$m(t) = a(t)\bar{m}(t) = a(t)\mathbf{1}_k'(\mathrm{S}(t)\circ\mathrm{D}\circ\mathrm{B})\mathbf{1}_l,$$

$$\bar{q}(t) = a(t)\mathbf{1}_k'(\mathrm{S}(t)\circ\mathrm{D}\circ\mathrm{B}\circ\mathrm{C})\mathbf{1}_l \text{and}$$

$$q(t) = a(t)\bar{c}(t) = a(t)\mathbf{1}_k'(\mathrm{S}(t)\circ\mathrm{D}\circ\mathrm{B}\circ\mathrm{C})\mathbf{1}_l.$$

The absolute annual changes in growing stock volume (between periods t and $t+1$)and average density can expressed as

$\Delta_{t,t+1}v = v(t+1) - v(t)$, and

$\Delta_{t,t+1}\bar{v} = \bar{v}(t+1) - \bar{v}(t)$, respectively.

Similarly, the log-percent approximations for the relative changes in total growing stock volumeand average densitycan be expressed as

$\Delta_{t,t+1}^{log\%}v = ln(v_{t+1}) - ln(v_t)$, and

$\Delta_{t,t+1}^{log\%}\bar{v} = ln(\bar{v}_{t+1}) - ln(\bar{v}_t)$, respectively.

The absolute and relative changes for total biomass and carbon stocks and the average biomass and carbon concentrations per hectare can be solved in a similar manner.

2.3.3 The transition matrices

For each specific age and density class $(\hat{\imath}, \hat{\jmath})$ there is a transition matrix $\mathrm{R}^{\hat{\imath},\hat{\jmath}} \in \mathbb{R}^{k \times l}$.

$$\mathrm{R}^{\hat{\imath},\hat{\jmath}} = \begin{bmatrix} r_{1,1}^{\hat{\imath},\hat{\jmath}} & \cdots & r_{1,l}^{\hat{\imath},\hat{\jmath}} \\ \vdots & \ddots & \vdots \\ r_{k,1}^{\hat{\imath},\hat{\jmath}} & \cdots & r_{k,l}^{\hat{\imath},\hat{\jmath}} \end{bmatrix}, \qquad | \, r_{i,j}^{\hat{\imath},\hat{\jmath}} \in \mathbb{R}_{0+};\ i, \hat{\imath} \in \mathbb{N}_+ \le k;\ j, \hat{\jmath} \in \mathbb{N}_+ \le l$$

and$\sum_{i=1}^{k}\sum_{j=1}^{l} r_{i,j}^{\hat{\imath},\hat{\jmath}} = 1$

The elements of the matrix,$r_{i,j}^{\hat{\imath},\hat{\jmath}}$,are the transition probabilities of a stands in a particular fixed class $(\hat{\imath},\hat{\jmath})$ to graduate to any other class (i,j) between two consecutive time periods. For example, $r_{1,2}^{1,1}$, is the transition probability of a stand is in lowest stocking degree class of the youngest age class to be transferred to the lowest stocking degree class of the second age class between two consecutive years. These values are separately defined for each simulation unit or grid cell, depending on the resolution.

As the natural growth dynamic of the forests is modeled using the transition probabilities between age and stocking degree classes, there are certain rules related to defining their values.

Logical age development. There can be no abrupt jumps in the age development of the forest stands over time. Assuming that the included stands are even-aged, $r_{i,j}^{\hat{\imath},\hat{\jmath}} = 0\ \forall\ j \geq \hat{\jmath} + 2$, or in other words, the forests cannot age more than a year within a year. Furthermore, assuming that the included stands are even-aged, $r_{i,j}^{\hat{\imath},\hat{\jmath}} = 0$ wherever $0 < j \leq \hat{\jmath} + 1$ except when $\hat{\jmath} = l$, or in other words, as time passes, a stand cannot get younger or remain the same age (with one purely technical exception: the oldest age class, from which stands cannot graduate any further).

Hence, in the case of most classes $(\hat{\imath},\hat{\jmath})$, the greatest transition probability the greatest probability of transition will be to the next age class of the same stocking degree, classes $(\hat{\imath},\hat{\jmath}+1)$. However, for every age class there is a zero-stocking degree class where $(\hat{\imath} = 1)$. Since there are no trees in the stands belonging to this class, the stands do not graduate to class $(1,\hat{\jmath}+1)$, but are instead transferred to back to back to class $(k,1)$, the youngest age class with the highest stocking degree, with the transition probability 1. Also in the case of other low stocking degree classes, there can be a positive transition probability back to the youngest age class (if young trees become the dominant age group). *As the presented transition matrix model cannot be applied to uneven aged forests, the few remaining bigger trees must be removed from the biomass stock as a result of a transition to a younger age class.*

Positive probability of strong natural disturbance. For forests stands in all classes $(\hat{\imath},\hat{\jmath})$, there is a positive probability of transition to the youngest age class $(j = 1)$ with the highest stocking degree $(i = k)$, $r_{k,1}^{\hat{\imath},\hat{\jmath}} > 0$, as a result of forest fires or other strong natural disturbances. *(The assumption behind transferring all cleared forest areas to the class $(k,1)$ is that all stands start their development on the maximum biomass curve, but may be later transferred to classes with a lower relative stocking degree as a result of gradual degradation).*

Lighter natural disturbances and/or underlying exogenous forest degradation trends can be depicted by positive transition probabilities to lower stocking degree classes (when following the same development in age).

The natural recovery of degraded forests. If left alone, the biomass concentration in degraded forests may gradually recover. This can be expressed in the transition matrix model by allowing stands with a reduced stocking degree to have positive transition probabilities into higher stocking classes.

Assuming there are no harvests, the area share matrix for time period $(t+1)$ can be obtained by accounting for the transitions, from each class $(\hat{\imath},\hat{\jmath})$ in period t to other classes in period $(t+1)$, and summing up the resulting matrices. Altogether there will be $k \times l$ matrices to be summed, as one matrix is generated for the transitions from each class (or element) in $\mathrm{S}(t)$.

$$\mathrm{S}(t+1) = \sum_{\hat{\imath}=1}^{k} \sum_{\hat{\jmath}=1}^{l} s_{\hat{\imath},\hat{\jmath}}\,(t)\mathrm{R}^{\hat{\imath},\hat{\jmath}}.$$

If age classes are modeled using a time-step that is coarser than one year, the transition probabilities will have to be adjusted accordingly. When choosing the number of age classes there is a compromise that has to be made between accuracy and calculation speed. The more age classes there are, the more accurate the model is. However, using a very accurate model for each SimU will increase the computational time needed to solve the model.

2.3.4 Initialization of the FSM

The initialization of the FSM can be largely done based on data and functions from the G4M. In the G4M global forests are composed of a single representative tree species. The differences in the growth rate of the species in different growing conditions are described by a single variable, the optimum mean annual increment (MAI) shown in Figure XXX, and a set of exogenously defined parameters which define the shape of increment and mortality curves.

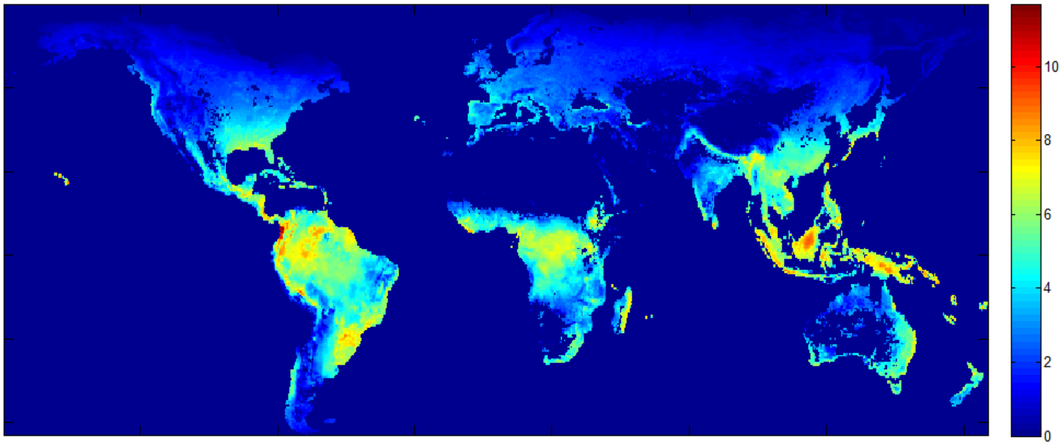

Fig.XXX: Mean Annual Increment (MAI) at increment optimal rotation time of a fully stocked forest, intC/ha/Yr**[**Data Source: *Georg Kindermann,G4M, IIASA 2010*]

Initializing D, B and C matrices. Based on the functions described in the G4M (24), stem wood volume, biomass and carbon per hectare in any simulated forest stand can be expressed as a function of stand age, *g*, and MAI. *(Although the relationships between these variables and a number of endogenous and exogenous parameters defined in the model are complex, ultimately all stand properties can be deduced if the stands age and MAI are known).* Let us note these functions for stemwood, biomass and carbon (at maximum stocking degree) by

$f_{stem\,wood}(g, MAI)$,
$f_{biomass}(g, MAI)$, and
$f_{carbon}(g, MAI)$, respectively.

Hence, the values of the elements of the **D**, **B** and **C** matrices can be defined followingly:

$$d_{i,j} = \delta_i \left(\frac{\int_{g_{j,min}}^{g_{j,max}} f_{stem\,wood}(g,MAI)dg}{g_{j,max}-g_{j,min}} \right) \qquad | \; d_{i,j}, g, g_{j,min}, g_{j,max}, MAI \in \mathbb{R}_{0+};$$

$$0 \leq \delta_i \in \mathbb{R}_{0+} \leq 1;$$
$$i \in \mathbb{N}_+ \leq k;\ j \in \mathbb{N}_+ \leq l$$

$$b_{i,j} = \delta_i \left(\frac{\int_{g_{j,min}}^{g_{j,max}} f_{biomass}(g,MAI)dg}{\int_{g_{j,min}}^{g_{j,max}} f_{stem\,wood}(g,MAI)dg} \right) \qquad | \; b_{i,j}, g, g_{j,min}, g_{j,max}, MAI \in \mathbb{R}_{0+};$$

$$0 \leq \delta_i \in \mathbb{R}_{0+} \leq 1;$$
$$i \in \mathbb{N}_+ \leq k;\ j \in \mathbb{N}_+ \leq l$$

$$c_{i,j} = \delta_i \left(\frac{\int_{g_{j,min}}^{g_{j,max}} f_{carbon}(g,MAI)dg}{\int_{g_{j,min}}^{g_{j,max}} f_{biomass}(g,MAI)dg} \right) \qquad | \; d_{i,j}, g, g_{j,min}, g_{j,max}, MAI \in \mathbb{R}_{0+};$$

$$0 \leq \delta_i \in \mathbb{R}_{0+} \leq 1;$$
$$i \in \mathbb{N}_+ \leq k;\ j \in \mathbb{N}_+ \leq l$$

where

δ_i	isthe stocking degree of class *i*relative stocking degree (compared to the maximum)
$g_{j,min}$	is the minimum age of stands belonging to age class *j*
$g_{j,max}$	is the maximum age of stands belonging to age class *j*

Initializing the S matrix. Currently, the measured forest data from the Congo Basin is inadequate for modeling forest structure at the SimU level. The procedure proposed here for initializing **S**, is a way of molding currentlyused data into the format required by the FSM, rather than depicting real world forest structure based on measured data from the actual locations.

As the area of unsustainably exploitable forests in SimUα, a_α, as well as the matrices $\mathbf{D}_\alpha$,$\mathbf{B}_\alpha$and$\mathbf{C}_\alpha$, are known it is possible to choose an area share matrix, $\mathbf{S}_\alpha$, so that the carbon stock of forest wood in the SimU matches the respective stock as it is currently defined in the input data to the GLOBIOM. This is done by skewing the age class and stocking degree distribution, by an exponent ϕ. Let us write the area share of each (i,j) class as:

$$s_{i,j} = \left(\int_{Z_{i,min}}^{Z_{i,min}} z^{\phi}\, dz\right)\left(\int_{x_{i,min}}^{x_{i,min}} x^{\phi}\, dx\right) \qquad \mid \phi \in \mathbb{R}_{0+};$$

$$x, z \in \mathbb{R}_{0+} \leq 1;$$

$$z_{i,min} = \frac{(i-1)}{k} \in \mathbb{R}_{0+} \leq 1;$$

$$z_{i,max} = \frac{i}{k} \in \mathbb{R}_{0+} \leq 1;$$

$$x_{i,min} = \frac{(j-1)}{l} \in \mathbb{R}_{0+} \leq 1;$$

$$x_{i,max} = \frac{j}{l} \in \mathbb{R}_{0+} \leq 1.$$

By selecting a suitable value for ϕ, the matrix $\mathbf{S}_{\alpha}$ can be molded to make the biomass carbon stock of forest wood match the respective stock as it is currently defined in the input data to the GLOBIOM.

$$q_{\alpha,GLOBIOM} = a_{\alpha}\mathbf{1}_{k}'(\mathbf{S}_{\alpha}(\phi)\circ\mathbf{D}_{\alpha}\circ\mathbf{B}_{\alpha}\circ\mathbf{C}_{\alpha})\mathbf{1}_{l}.$$

This method can be distribute any plausible amount of biomass carbon to the size and stocking degree classes, as long as it is between zero and the natural maximum of fully stocked old-growth forests. Furthermore, there is always only one unambiguous solution for $\mathbf{S}_{\alpha}$. However, an underlying assumption is, that the stocking degree and age distributions are both skewed in the same way (e.g. either towards old age and high stocking degree classes, or young age and low stocking degree classes). If $\phi = 1$ the area shares of all age and stocking degree specific classes are equal. If $\phi \leq 1$, the distributions are skewed towards younger age classes and lower stocking degree (i.e. these classes have larger areal shares than older classes or classes with higher stocking degree). If $\phi \geq 1$, the distributions are skewed towards older age classes and higher stocking degree (i.e. these classes have larger areal shares than younger classes or classes with lower stocking degree). This principle is illustrated in Fig. YYY with an$\mathbf{S}$matrix with 10 age classes and 10 stocking degree classes, and ϕ-values 0.75, 1.00 and 2.00.

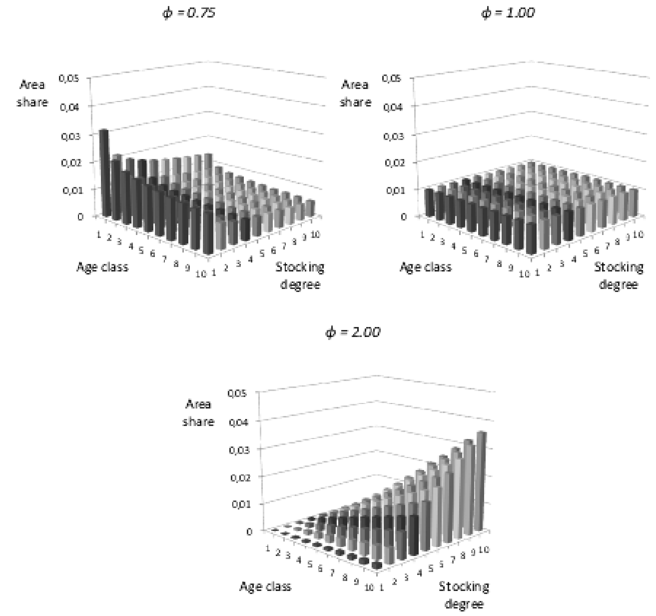

Fig. YYY: Skewed area share matrices with ϕ-values 0.75, 1.00 and 2.00.

The symmetry assumption may not always be correct: after all, the structure of real forests does not need to be symmetric in terms of age and stocking degree. Nevertheless, since there is no field data that could be used to make better assumptions of forest structure, the proposed method is the most convenient alternative as it provides the easiest way to allocate the biomass into classes by age and stocking degree.

2.3.5 Availability of wood by size-class and Simulation Unit

Recall from section 2.2.3 that in order to optimally allocate harvests according to the production cost minimization principle, the ISM requires information on the maximum harvestable volume of wood, $V_{A_{\alpha}^{\gamma}}$,in unsustainably exploitable forests by size-class (subindexγ) and SimU (subindexα). In this section we show how this information is derived from the FSM.

It is necessary to be able to provide information on the availability of wood by size class, as fuel wood and timber harvests target different size trees. Big logs suitable for industrial timber production are not available in young or sparse forests. Hence, timber can only be harvested from sufficiently old forests. On the other hand, fuel wood is usually harvested using simple technology, which makes cutting down big trees arduous. Thus, fuel wood harvests target younger forests with smaller trees. (In the absence of young stands also large trees may be targeted, but the harvesting costs will be significantly higher). However, even fuel wood harvests do not target the youngest age classes or classes with a zero stocking degree. This logic of different age stands is illustrated below using a density matrix, $\mathbf{D}$, with only sixage classes and stocking degree classes.In the matrix, the classes with too little wood to be harvested are marked black.

The classes suitable for fuel wood harvests are marked blue, and the classes suitable for timber harvests are marked red. The data for the size of the trees in each age class can be obtained from the functions in G4M.

$$\mathbf{D}=\begin{bmatrix} d_{1,1} & d_{1,2} & d_{1,3} & d_{1,4} & d_{1,5} & d_{1,6} \\ d_{2,1} & d_{2,2} & d_{2,3} & d_{2,4} & d_{2,5} & d_{2,6} \\ d_{3,1} & d_{3,2} & d_{3,3} & d_{3,4} & d_{3,5} & d_{3,6} \\ d_{4,1} & d_{4,2} & d_{4,3} & d_{4,4} & d_{4,5} & d_{4,6} \\ d_{5,1} & d_{5,2} & d_{5,3} & d_{5,4} & d_{5,5} & d_{5,6} \\ d_{6,1} & d_{6,2} & d_{6,3} & d_{6,4} & d_{6,5} & d_{6,6} \end{bmatrix}$$

In the above example for instance, the total volume of wood available for timber harvests in the SimU$\bar{\alpha}$, $V_{A^{timber}_{\bar{\alpha}}}$, is

$$V_{A^{timber}_{\bar{\alpha}}} = v_{6,4} + \sum_{i=4}^{6} v_{i,5} + \sum_{i=3}^{6} v_{i,6}$$

The availability of wood for fuel wood harvests is calculated similarly, but summing over the blue size classes in the density matrix. In this presentation, for simplicity, we implicitly assume that only growing stock is harvested for fuel wood and timber. In reality this assumption is only valid for timber. For instance, the branches of trees, which are not included in growing stock, may well be used as fuel wood. However, the availability of fuel wood can be modeled as a function of growing stock volume, assuming that the amount of wood available in branches is proportional to the amount of wood in the tree stems. Hence, I recommend the inclusion of suitable expansion factors in the actual module.

2.3.6 Acounting for harvests

Recall from Section 2.2.3, that once the ISM has received information on the availability of harvestable wood in the unsustainably exploitable forests, it solves the optimal volume of harvests by size-class and SimU. The optimal volume of harvests, by size-class (subindexγ) and SimU (subindexα) is denoted by $V_{H*^{\bar{\gamma}}_{\bar{\alpha}}}$.

Once the total volume of harvests in a simulation unit has been defined, the harvests are allocated to age and stocking degree specific classes (i,j) according to their relative growing stock volume shares. For example, the timber harvests allocated to class $(6,6)$in SimU$\bar{\alpha}$is:

$$h^{timber}_{\bar{\alpha},6,6} = \left(\frac{v_{6,6}}{V_{A^{timber}_{\bar{\alpha}}}}\right) V_{H*^{\bar{\gamma}}_{\bar{\alpha}}}.$$

(From now on, as we are operating at the level of a single SimU, the SimU index α will be dropped to simplify the notation).

Let $h_{\hat{\imath},\hat{\jmath}}(t) \geq 0$ denote the volume harvests (m^3) from class $(\hat{\imath},\hat{\jmath})$ in period t. Recall also, that the total growing stock volume in stands in a given class $(\hat{\imath},\hat{\jmath})$ in period t is

$$v_{\hat{\imath},\hat{\jmath}}(t) = a(t)s_{\hat{\imath},\hat{\jmath}}(t)d_{\hat{\imath},\hat{\jmath}}.$$

For the rest of this section, the time-indices, (t), will be dropped. Thus, we write:

$$v_{\hat{\imath},\hat{\jmath}} = as_{\hat{\imath},\hat{\jmath}}d_{\hat{\imath},\hat{\jmath}}. \tag*{[F01]}$$

This is the initial growing stock volume of stands in class $(\hat{\imath},\hat{\jmath})$ (before harvests). When wood is harvested, the aggregate growing stock volume of the stands in class $(\hat{\imath},\hat{\jmath})$ is reduced. The new growing stock volume after harvesting is

$$v_{\hat{\imath},\hat{\jmath}}(new) = v_{\hat{\imath},\hat{\jmath}} - h_{\hat{\imath},\hat{\jmath}}. \tag*{[F02]}$$

This, however, cannot be the final result, as it violates the way in which growing stock volume is defined in F01. (If $a, s_{\hat{\imath},\hat{\jmath}}$, and $d_{\hat{\imath},\hat{\jmath}}$ are constant and growing stock volume is calculated according to F01, it must also remain constant, and there can be no degradation). Hence, in order not to violate the definition of growing stock volume (F01) or the structure of the transition matrix model (for which is convenient to maintain $d_{\hat{\imath},\hat{\jmath}}$ unaltered), the impact of the harvests on forest structure must be captured by the variable $s_{\hat{\imath},\hat{\jmath}}$, representing the area shares of forests in different classes. Using this approach, degradation can be accounted for in two alternative ways. The first alternative is transferring a share of the forest area in class $(\hat{\imath},\hat{\jmath})$ to other classes of the same age, but of a lower stocking degree, so that the reduction in the growing stock volume in the forests corresponds to the harvested quantity. This approach describes selective harvesting; a number of trees are removed from the forest (hence the reduction in stocking degree), but the forests are not clear cut (and hence they are not transferred back to the youngest age class). The second alternative is to assume that a share of the forest area in class $(\hat{\imath},\hat{\jmath})$ is in fact clear cut and transferred to the youngest age class. These two approaches are described below in more detail. Both approaches are useful in describing different forms of forest utilization.

Selective harvesting. Let us first look at selective harvesting. Based on the new growing stock volume of forests in class $(\hat{\imath},\hat{\jmath})$ after harvesting, $v_{\hat{\imath},\hat{\jmath}}(new)$, we can calculate a new (mock value for the) average density of forests in the given class. We not this value by $d_{\hat{\imath},\hat{\jmath}}(new)$.

$$d_{\hat{\imath},\hat{\jmath}}(new) = \frac{v_{\hat{\imath},\hat{\jmath}}(new)}{as_{\hat{\imath},\hat{\jmath}}}.$$

Selective harvesting means that some, but not all, trees are removed from the forest stands. Hence, the stocking degree of the stands is reduced. In the presented model, this is best described by transferring a portion of the forests in class$(\hat{\imath},\hat{\jmath})$, to another class with the same age but a lower stocking degree. In order to do so, we first find the find the greatest average density value included in vector $\mathbf{d}_{i,\hat{\jmath}}=[d_{1,\hat{\jmath}} \ \cdots \ d_{k,\hat{\jmath}}]'$ that is smaller than $d_{\hat{\imath},\hat{\jmath}}(new)$. We denote this value by $d_{i*,\hat{\jmath}}$.

$$d_{i*,\hat{\jmath}} = \max\left(\mathbf{d}_{i,\hat{\jmath}}\right) | \ d_{i,j} \leq d_{\hat{\imath},\hat{\jmath}}(new)$$

Next we write $d_{\hat{\imath},\hat{\jmath}}(new)$ as a linear combination of $d_{\hat{\imath},\hat{\jmath}}$and $d_{i*,\hat{\jmath}}$, so that

$$d_{\hat{\imath},\hat{\jmath}}(new) = (1-\lambda)d_{\hat{\imath},\hat{\jmath}} + \lambda d_{i*,\hat{\jmath}} \qquad \mid \lambda \in \mathbb{R}\text{and}0 \leq \lambda \leq 1 \qquad \text{[F03]}$$

Since $d_{\hat{\imath},\hat{\jmath}} \geq d_{\hat{\imath},\hat{\jmath}}(new)$ and $d_{i*,\hat{\jmath}} \leq d_{\hat{\imath},\hat{\jmath}}(new)$ there is always one specific value of λ that satisfies equation [F03], (Except in the case where there are no harvests and, hence, $d_i = d_{j*}$. In this case any λ will satisfy the equation). By solving for λ, we get the proportion of forests in class $(\hat{\imath},\hat{\jmath})$, that need to be downgraded to class $(i *, \hat{\jmath})$ in order to account for the lost growing stock volume. Hence, after transferring a share of the forests from class $(\hat{\imath},\hat{\jmath})$ to class $(i *, \hat{\jmath})$ the final area shares of the two classes will be

$s_{\hat{\imath},\hat{\jmath}}(final) = (1-\lambda)s_{\hat{\imath},\hat{\jmath}}$ and

$s_{i*,\hat{\jmath}}(final) = s_{i*,\hat{\jmath}} + \lambda s_{\hat{\imath},\hat{\jmath}}$ respectively.

From a technical perspective, this way of transferring a share of the forests from class $(\hat{\imath},\hat{\jmath})$to class $(i *, \hat{\jmath})$has two positive features. Firstly, as a share of higher density forest is transferred to a lower density category, we can roughly capture the process of forest degradation in terms of average density and biomass concentration. Secondly, we do not need alter the average density of within any size class, and thus, the transition matrix model for growth continues to work properly.

Clear cuts are an alternative way of conducting harvests. Unlike in the case of selective harvesting, where only some trees are extracted from the forest, in the case of clear cuts all trees are removed. Nevertheless, with a minor amendment, the above-described method is also applicable in the case of clear cuts. The amendment is, that instead of describing harvest by transferring forests from class $(\hat{\imath},\hat{\jmath})$ to class $(i *, \hat{\jmath})$, harvests are described by transferring forests from $(\hat{\imath},\hat{\jmath})$ to class $(1, \hat{\jmath})$, which is the zero stocking degree class of the forest stands in age class *$\hat{\jmath}$(from which all forests are transferred back to class $(k, 1)$ by the start of the next time period, $t + 1$).*

Hence, in this case, we write $d_{\hat{\imath},\hat{\jmath}}(new)$ as a linear combination of $d_{\hat{\imath},\hat{\jmath}}$and $d_{1,\hat{\jmath}}$, so that

$$d_{\hat{\imath},\hat{\jmath}}(new) = (1-\lambda)d_{\hat{\imath},\hat{\jmath}} + \lambda d_{1,\hat{\jmath}} \qquad \mid \lambda \in \mathbb{R}\text{and}0 \leq \lambda \leq 1$$

Since $d_{\hat{\imath},\hat{\jmath}} \geq d_{\hat{\imath},\hat{\jmath}}(new)$ and $d_{1,\hat{\jmath}} \leq d_{\hat{\imath},\hat{\jmath}}(new)$ there is always one specific value of λ that satisfies equation [F03]. By solving for λ, we get the proportion of forests in class $(\hat{\imath},\hat{\jmath})$, that need to be downgraded to the zero stocking degree class $(1, \hat{\jmath})$ in order to account for the lost growing stock volume. Hence, after transferring a share of the forests from class $(\hat{\imath},\hat{\jmath})$ to class $(1, \hat{\jmath})$ the final area shares of the two classes will be

$s_{\hat{\imath},\hat{\jmath}}(final) = (1-\lambda)s_{\hat{\imath},\hat{\jmath}}$ and

$s_{1,\hat{\jmath}}(final) = s_{1,\hat{\jmath}} + \lambda s_{\hat{\imath},\hat{\jmath}}$ respectively.

Of the two proposed ways of accounting for harvests, I recommend the adoption of selective harvesting to depict the utilization of unsustainably exploitable forests in the Congo Basin. Artisanal loggers, who are responsible for most of the harvests, harvest at a low intensity using low-tech tools. Selecting only the best trees saves effort. Thus, rather than clear cuts, the harvesting patterns of the loggers are more likely to resemble selective harvests. Moreover, in the short run, selective harvests are not as visible as clear cuts and are hence the likely choice of informal sector loggers.

2.3.7 Modeling subsistence agriculture

Subsistence agriculture differs from the two other main causes of forest degradation in the Congo basin in two respects. Firstly, unlike the fuel wood and timber harvesting, subsistence agriculture is not based on the utilization of forest products, but on the utilization of forest land to grow agricultural crops. In this respect, it is a separate land use class embedded in unsustainably exploitable forests. The exchange of land between the two land use classes is fast. All the time tracts of forest are cleared to provide new land for subsistence agriculture, but simultaneously older farm plots are abandoned to be taken over by forest vegetation after producing several yields of corps. Secondly, the crops produced by subsistence farmers are generally not traded in the markets like fuel wood and timber. Some goods may be traded with neighbors or sold in the markets, given that the farmers have market access. Otherwise, however, subsistence agriculture is by definition an activity that only provides for the immediate needs of the farmers' households and does not produce large excess yields that could be sold in the markets. Hence, rather than trying to include subsistence agriculture in the ISM, it is easier to treat it as an integrated process in the FSM.

Distinguishing subsistence agriculture (as a separate form land use) from degraded forests is technically difficult using coarse resolution satellite imagery as the tracts of forest cleared for crop cultivation are usually fairly small and integrated into the mosaic of degraded forests. These limitations in the resolution of available data restrict us from quantifying the area devoted to subsistence agriculture and modeling it as a separate land use class. However, subsistence agriculture can be modeled as a process occurring within unsustainably exploitable forests. For this modeling we need the following information:

(1) The size of the rural population in the grid cell and the share of it dependent on subsistence agriculture.
(2) The amount of land devoted to subsistence agriculture needed to feed on person.
(3) The average length of tenure of subsistence plots.

Based on (1) and (2) we can estimate the total area occupied by agricultural plots within unsustainably managed forests. Combining this information with (3), we can also estimate the annual rate at which new plots are cleared and old plots are abandoned to become afforested. As result, we get a simple model of the process of rotating slash-and-burn agriculture.

The change in the rural population over time can be modeled based on population scenarios. The share of the rural population depending on subsistence agriculture may also change of time, but is highly dependent on the general economic and social development. Without the alleviation of poverty, rapid rural population growth may lead to an expansion of subsistence agriculture. On the other hand, economic development and urbanization may lead to reduction of population dependent on subsistence agriculture, if they can secure their livelihoods in formal sector jobs. The impacts of these different options can be investigated using exogenous scenario-based modeling. The endogenization of these processes into the GLOBIOM is beyond the scope of this study.

One further note can be made on the general role of subsistence agriculture in the GLOBIOM. If the share of the population engaged in subsistence agriculture is largely disconnected from the markets, as it is here assumed to be, it should be subtracted from the total population when estimating the demand for products traded in the formal sector markets to avoid the double-counting of impacts. Subsistence farmers buy very few goods. Their land-use impacts occur directly in unsustainably exploitable forests.

2.3.8 On the time-step and chronological order of harvests and growth

As the volume of harvests and their allocation to unsustainably exploitable forests changes annually (Section 2.3.4), the time-step of the FSM needs to agree with the time-step of the ISM.

Based on the availability of wood by size-class and location, the Informal Sector Module annually allocates harvests to the unsustainably exploitable forests in across SimUs. The changes in forest structure induced by these harvests in each SimU are then accounted for by the Forest Structure Module. After the wood removals have been accounted for, growth and recovery in each SimU are then simulated using the transition matrix.

2.4 Order of progression

As we have now introduced the Informal Sector Module and the Forest Structure Module, we can now summarize the procedure proposed for simulating forest degradation in the GLOBIOM. The procedure is different for years in which the GLOBIOM is solved (years at a ten year time step e.g. 2000, 2010, 2020, etc.) and the intervening years (e.g. 2001, 2002, 2003, etc.).

GLOBIOM years. In years for which the entire model is solved (Fig. VX), the first step is solving the GLOBIOM, which is considered to represent the economic activities of the formal sector. In principle, the model is solved in the same way as it is currently done, with two exceptions: (1) the markets for informal sector products are not considered, and (2) unsustainably exploitable forests are excluded from the land use optimization process, apart from possible transfers of land to the formal sector. If land use change between unsustainably exploitable forests and formal sector land use classes is endogenously defined (Section 2.2.4), the solution to the GLOBIOM will determine the areas of land that are transferred from informal to formal sector use. If the respective land use change is based on exogenously defined scenarios, it is practical to include theses scenario assumptions in the GLOBIOM rather than the separate modules. Hence, regardless of whether the land use change between the two classes is endogenously or exogenously modeled, the patterns of land use change will be simulated by the GLOBIOM.

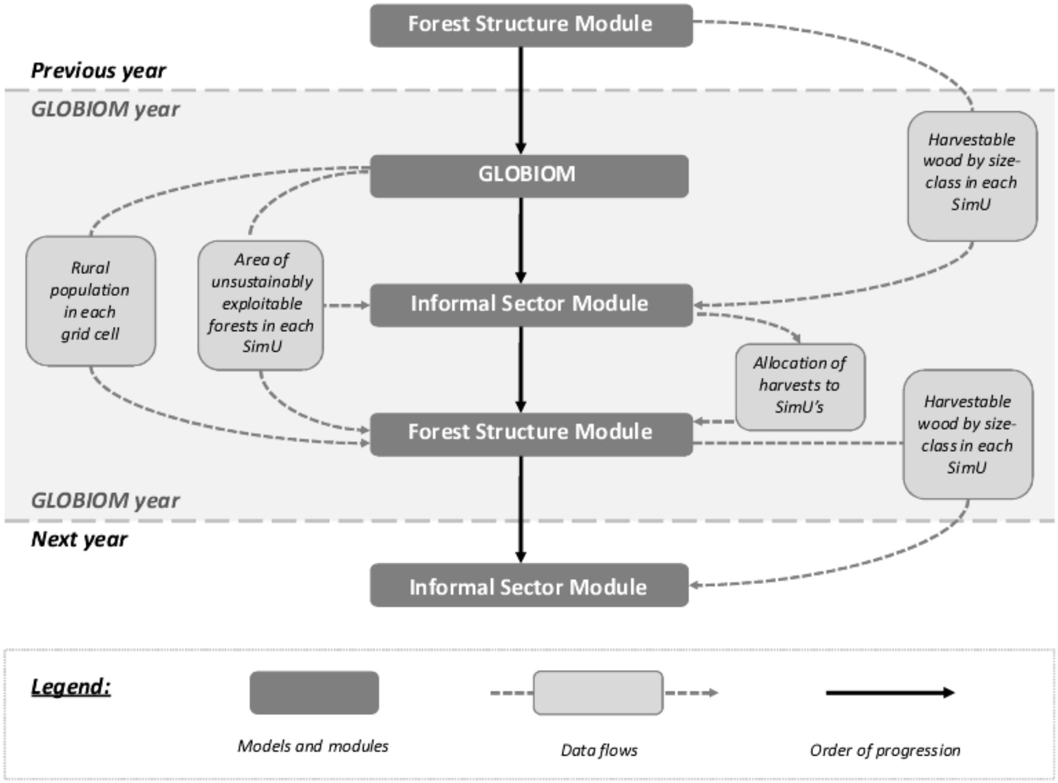

Fig. VX Procedure for modeling forest degradation in the GLOBIOM in years for which the entire model is solved.

The second step running the ISM (Section 2.2), which solves the market equilibrium for t informal sector products and allocates harvests to unsustainably exploitable forests based on the principle of minimizing harvesting and transportation costs. The ISM requires two kinds of input data: (1) information on the availability of harvestable wood by size-class and SimU from the Forest Structure Module[3], and (2) the updated area of unsustainably exploitable forests from the GLOBIOM solution, to insure that harvests are not allocated to forests that have been converted to other land use.

In the third and final step, the FSM is run to update the stocks of harvestable wood, biomass and carbon in each SimU. First, the loss of forest cover and biomass is accounted for using three types of input data. First, land use change data from the GLOBIOM solution is used to account for forest area that has been converted to other land use. Next, the volume of harvests allocated to each SimU by the ISM is reduced from the stocks. Last, the impacts of shifting subsistence agriculture are accounted for based on population data from the GLOBIOM. After accounting for wood removals in each SimU, the impacts of growth and natural recovery are simulated according to the transition matrix. The updated stocks are used as input data by the ISM in the next year.

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[3] When the GLOBIOM is solved for the first time (e.g. for the year 2000), the Forest Structure Module will have to be initialized before running the Informal Sector Module. In other years, the input data for the availability of wood is assumed from the previous year's updated stocks.

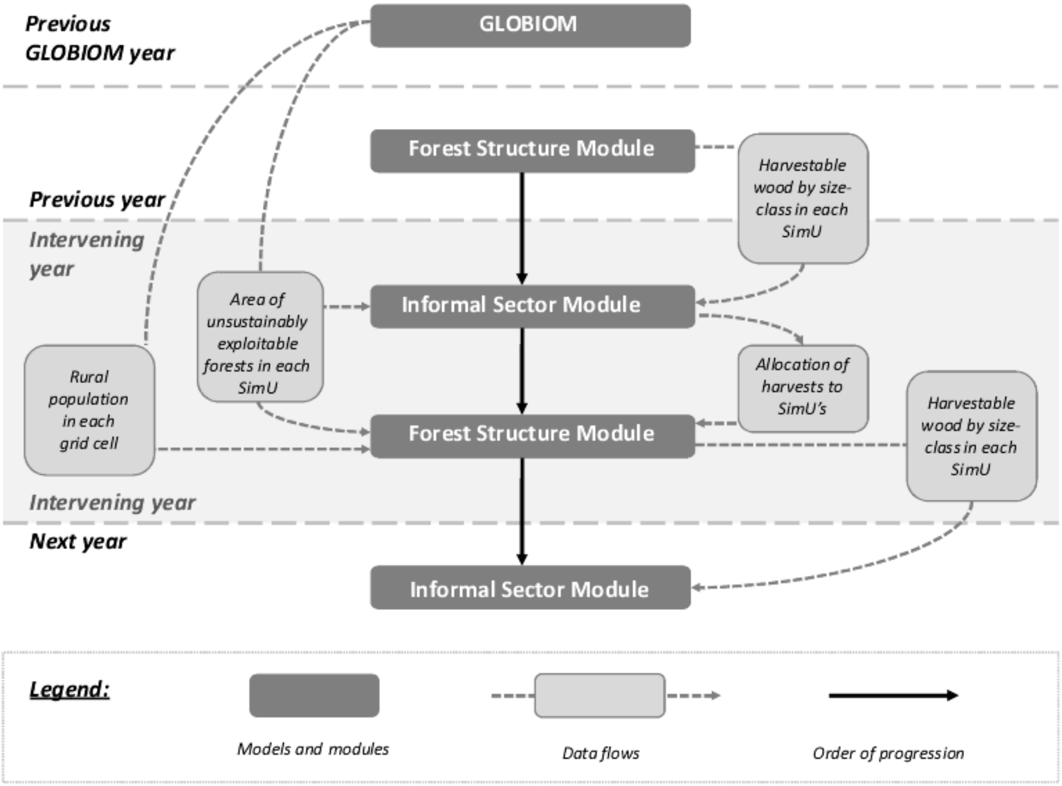

Fig.VY.Procedure for modeling forest degradation in the GLOBIOM for intervening years.

Intervening years. The procedure for intervening years is similar to the procedure for GLOBIOM years, but lighter.It is only necessary to run the ISM and the FSM. As the harvesting patterns affect the availability of wood in each SimU, and vice versa, it is necessary to simulate the changing allocation of harvests and the adjusting structure of forests also in the intervening years, in order to obtain updated data on forest structure and the availability of wood in the next GLOBIOM year. Hence, if the GLOBIOM time-step is 10 years, the procedure for intervening years is run 10 times between two GLOBIOM runs.

The input data from the GLOBIOM required by the modules can be obtained using extrapolation/interpolation procedures. The population data for the intervening years, needed to model demand for informal sector products and the extent of subsistence agriculture in each grid cell, can be obtained in two alternative ways: (1) by assuming that population in each grid cell remains constant for the whole decade, or (2) by interpolating population for the intervening years, from the population scenarios used in the GLOBIOM. Similarly the land use data, required to establish the areal extent of unsustainably exploitable forests, can be obtained in two alternative ways, depending on whether the process of land use change between the informal and the formal sector is exogenous or endogenous to the GLOBIOM. If the process of land use change is exogenous, the extent of unsustainably exploitable forests can be interpolated from data for the GLOBIOM years at beginning and the end of the interval. However, if the process is endogenous, this cannot be done, since it would require first solving the GLOBIOM (at the end of the interval), before simulating the development of unsustainably exploitable forests in the intervening years. In this case, the only feasible option is to assume, that the pattern of formal sector land use defined in the beginning of each decade remains constant for the whole decade (Fig. VY has been drawn based on this assumption).

3 Future Challenges

The report at hand contains a very general logical blueprint for a system of interacting modules that could be used to account for the carbon impacts of forest degradation in GLOBIOM simulations, especially for the Congo basin region. However, many important and more specific details, that are necessary if the design is put use, have not been considered in this paper. Some of the most important, largely data-related, issues are discussed below:

(1) The separation of unsustainably exploitable forests from the (current) class of managed forests requires additional data. One way to do this would be to extract all managed forests, that can be proven to be sustainably utilized by the formal sector into their own class, sustainably managed forests, and assume that all other forests in the current class of managed forests are unsustainably exploitable. For individual countries in the region, such as Cameroon, maps on the location of concessions are available (31). However, data may not be available for all countries in a similar format or at a similar resolution.

(2) Harvesting and transportation costs play an important role in the ISM. The GLOBIOM has its own inbuilt ways of accounting for transportation costs. Modeling the harvesting costs of the informal sector, however, may require some additional work.

(3) Currently, the FSM only accounts for the stocks of carbon in living biomass. Further modeling (based on the functions in G4M) is needed to account for the carbon pools in dead wood, litter and soil.

(4) Calibrating the transition matrix. The rules of transition described in Section 2.3.3. are merely logical building instructions for the transition matrix. If this blueprint is used for programming an actual module, a literature review of the probabilities of natural disturbances and the rates of recovery in tropical forests is needed in order to establish feasible values for those transition probabilities between classes.

(5) Forest structure data. The method for molding the current data for carbon in forest wood (Section 2.3.4) to fit the FSM is a very crude way of guessing forest structure. Ultimately, the reason for the lack of less subtle ways to initialize the FSM is the lack high resolution data on forest structure in the Congo Basin. Also, it should be noted that the utilized input data are model outputs and not based on field measurements(6, 24, 32). As the outcomes of the simulations strongly depend on the initial conditions of the model, some sort of an attempt to assess or validate the suitability of the proposed downscaling method should be undertaken to avoid designing a GIGO[4]-model that is logically coherent, but useless.

(6) Subsistence agriculture. Modeling subsistence agriculture as an integrated process in the FSM requires additional data, downscaled to the SimU level. These data include rural population and the share dependent on subsistence agriculture. For the amount of land needed to feed one person and the average tenure of subsistence plots regional averages can be used. However, also this data is currently lacking and requires conduction a literature review.

(7) Finding the right compromise between accuracy and computational speed for the FSM. A test version of the FSM was programmed in 2010. From the tests runs using the prototype at the level of a single SimU, the accurate forest structure (with one-year age classes) described in sections 2.3.1-2.3.3 proved to be too heavy and slow to be used with the GLOBIOM. In a later test run the number of age classes was significantly reduced and, the module became much quicker.

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[4] Garbage in, garbage out.

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