The Dynamic Ecological footprint –
Endogenizing the Ecological Footprint of Forestry in the Threshold21 Model of Senegal

Revised version with fixed in-text-citations!

by
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1 Abstract

*Many countries in the world are in ecological overshoot. That is the message that the **Ecological Footprint** calculated by the Global Footprint Network sends us. Since many developing countries may not be in overshoot yet, but are heading for it, it is very important that their development paths leapfrog to resilient sustainable development. But what are the policies that could bring developing countries on such desirable paths? The Ecological Footprint cannot give a good answer to such questions because as an ecological accounting tool, it is intrinsically of an ex-post nature. The **Threshold 21-models** have been developed by the Millennium Institute for the precise purpose of allowing for sustainable national development planning using System Dynamics as a method suited for long-term policy analysis in these highly complex dynamic systems. But these models currently lack the Ecological Footprint and can therefore not be used to analyze the effect of policies on it. This thesis is a pilot project assessing to what degree it could be possible to implement a dynamic version of the forest Ecological Footprint (and the forest biocapacity) in the T21-model of Senegal. It was found that while it is possible to implement a dynamic forest Ecological Footprint in T21-models, it requires a great deal more of additional information that is neither contained in the accounting methodology of the Ecological Footprint nor in the existing T21-models and that is also hard to find in publically available sources. As a result, the current endogenization state of the forestry Ecological Footprint is still limited and needs to be elaborated to allow for meaningful future projections with the help of on-the ground forestry experts in Senegal. Nevertheless the project has already lead to suggestions for improvements for the GFN methodology and the T21-model: Switching the calculations from a constant to a variable annual forest increment is the most pressing issue, as the current constant approach implies a gross underestimation of the overshoot situation. This paper also makes suggestions of how this data could be obtained. The T21-model should be extended by a conversion flow from forest land to cropland. This implies that the main forest policy spear-head in Senegal, the fuel-switch campaign to butane, may stay limited in its effect on arresting forest decline even if it is in itself successful. That is because the timber from these converted areas may in part be harvested and pushed as charcoal on the market rather than harvest following demand. Furthermore, as some of the timber removed in these conversions may not be harvested, it does not show up in the harvest data and consequently also hides itself from the calculation of the Ecological Footprint. The same problem concerns the timber removed by anthropogenic forest fires. Overall, the implementation of the whole Ecological Footprint in T-21 is highly recommendable not only for the original purpose of enabling ex-ante policy analysis concerning sustainable resource use, but also because both the T21-model and the accounting methodology of the Ecological Footprint will both benefit from it in many less expected ways.*

2 Acknowledgements

My first thanks go to the two partner institutions, the Millennium Institute, and the Global Footprint Network for their interest in cooperating in this project. My special thanks go to Matteo Pedercini, who made all of this possible for all his support, Gunda Züllich for her kind, patient in-depth email support in understanding the T21-Model on the MI side, and David Moore for equally sophisticated and open support from GFN side. My thanks also go to Juan Carlos Morales and Joy Larson for their interest in this project. I thank Erling Moxnes for his "birds-eye" insights.

I am also using this opportunity to thank everybody who made the EMSD Program possible, esp. Pål Davidsen and Jac Vennix. This program grows the future! May the resource stocks upon which it is built always have greater in- than outflows!

Lastly, I thank the Norwegian unions for their system of coercive striking!

3 Table of contents

4 Introduction

The Threshold21 System Dynamics (SD) models developed by the Millennium Institute are tools for national sustainable development planning. They endogenously produce economic indicators such as GDP and development indicators such as the ones used for the Millennium Development Goals.

Blindly following the economic growth paradigm however may lead to ecologic collapse (Forrester, 1971; Meadows, 1972; Meadows, Randers, & Meadows, 2005), and preventing collapse necessitates an operational indicator of ecological overshoot *before* collapse occurs. The ecological overshoot preceding a collapse occurs when the human impact on the ecological system is greater than the ecological system's capacity to compensate for it (Meadows et al., 2005). The T21 already includes a few potentially limiting resources such as agricultural area and fossil energy resources. Still, its ability to adequately include sustainable resource management into national development planning could be expanded.

One aggregate indicator to measure the human impact on the environment proposed outside of the System Dynamics discipline, is the *Ecological Footprint* (hereafter *EF*). It represents amount of productive area that would be necessary to sustain a country's consumption in terms of production of the necessary resources consumed and absorption of the wastes produced. The comparison of the Ecological Footprint with the *Biocapacity* (hereafter *BC*) –the amount of bioproductive area actually available in the country– allows for assessing the degree of ecological overshoot (Ewing, Reed, Galli, Kitzes, & Wackernagel, 2010).

Figure 1 shows the ecological Footprint and Biocapacity of the whole world, indicating the start of ecological overshoot around 1970.

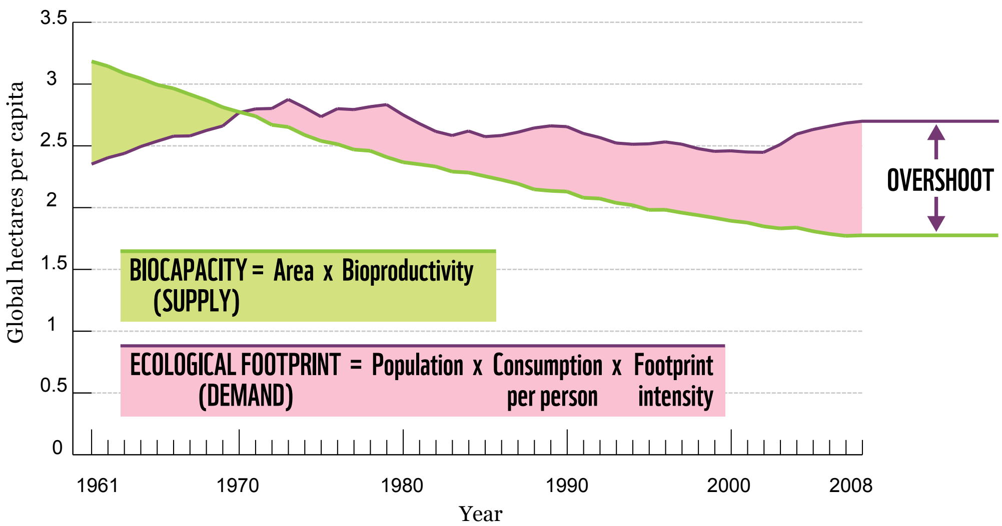

Figure 1: Global Ecological Footprint (purple line) and Biocapacity (green line) (source: WWF International, 2012)

The big advantage of the EF is that it can uncover overshoot prior to collapse and make ecological overshoot easy to understand even for laymen. It is however limited to ex-post evaluations because its accounting nature implies that it cannot be used to assess the consequences of different policies or different scenarios.

Such ex-ante evaluations could however be made possible by implementing the EF&BC in a simulation model that produces EF&BC estimates for the future as a supplement to relying on ex-post evaluations that use data collected in the past.

The Millenium Institute's T21 models for national development planning are such simulation models. In contrast to statistical models, they do not use algorithms to find patters in past time series data to extrapolate future development. T21 models rely on System Dynamics to build a very complex system of ordinary but highly non-linear differential equations representing real world processes. Its sophistication lies in the fact that the input to scenario-analyses and ex-ante policy evaluations is as far as possible not based on assumptions but is instead also calculated by the model. Representing the complex causal loop nature of reality, it is possible to anticipate some of the sudden never-before-seen changes in the real world that are unforeseeable using statistical models.

Using T21 models for scenario analysis and policy testing with respect to the EF and BC has the advantage that a lot of the real-world causes driving the changes in EF and BC are already represented in the models.

Since T21 models are already used by many developing countries for national development planning, model updates containing the EF and BC would allow for assessing potential consequences of active or considered national development policies with respect to their influence on ecological overshoot and may also help finding new or improved policies for sustainable management of natural resources.

A stump of an EF&BC sector already exists in the T21 models but it needs improvement as currently only the carbon-uptake land footprint is somewhat endogenized[*] to some degree and while the footprints of cropland, grazing land, fisheries and build-up land and all biocapacity components are still exogenous.

As an example country the model of which is used to implement the EF&BC, Senegal was chosen, because of data availability and representativeness as a sub-Saharan country in western Africa which is the current focus of the work of the Millennium Institute.

In order to keep the project manageable within the time-frame of a master thesis the scope was reduced from total EF and BC to one of its constituents, the forestry EF&BC. It serves as a "proof-of-concept" for roll-out to all the constituents as it has a similar basic renewable resource nature as the cropland, grazing land, fisheries EF&BC but it has lower complexity terms of product types etc.

Furthermore, unlike world-wide models, national models require to keep track of the EF embedded in imported and exported products. Hence the EF&BC sector of the Senegal model needs to be adapted so that it is harmonized with the Global Footprint Network accounting methodology enough to adequately reproduce time series data of the static national EF&BC. It also needs to be endogenized as far as possible rather than relying on time series data or constants so to become capable of reliable ex-ante policy evaluations.

Thus the research questions of this thesis are:

[*] Endogenization is the process replacing time series data input of variables or assumptions of constancy (both termed *exogenous*) with

- To what degree is it possible to introduce model sector in the T21 of the Ecological Footprint and the Biocapacity of Senegal that is sufficiently congruent in its core meaning and past behavior to be considered quasi-identical with the static accounting ecological footprint of forestry?
  - Here, “sufficiently congruent in its core meaning” requires that a) the structure the dynamic SD implementation of the Global Footprint Network EF&BC accounting arithmetic in T21 is built sufficiently close along the same concepts that the equations of the static accounting EF were built upon. It also requires that b) the data that is fed into this accounting structure is endogenously derived from model structure that adequately represents real world causality.
  - “Sufficiently congruent in past behavior” requires that the historic data of national EF&BC (reference modes) that have been calculated using the static accounting methodology can be reproduced with sufficient accuracy.
- To what degree will that dynamic EF&BC model structure be able to produces meaningful future projections? To what degree does the model structure also include presently dormant causalities that may become active in the future, so that model simulations beyond the present can be used for ex-ante policy evaluations?
- What additional benefits can be delivered to the Global Footprint Network by implementing it in an System Dynamics manner rather than pure spreadsheet accounting?
- What additional benefits can be delivered to the Millennium Institute and T21 through integrating the EF&BC?

The overarching hypothesis of this thesis is that this merger is possible and that a dynamic EF&BC can deliver notable benefits compared to a static spreadsheet accounting implementation.

5 Definitions and Methods

5.1 Introduction of System Dynamics modeling symbol system

In the following the System Dynamics symbols are explained for readers who are familiar with the EF&BC but who are not familiar with System Dynamics modeling, using the forestry EF&BC as an example.

It can be seen in Figure 2 that from a System Dynamics modeling point of view the *harvest* of wood is conceptually an ***outflow*** (double arrow) from a ***stock*** of *timber* (box symbol). The timber stock grows through an ***inflow*** of *reproduction and regrowth*. In analogy to a water tank, the in- and outflows can be thought of as pipes that fill or empty a stock, respectively. The sum of the flows to and from (negative) a stock constitutes the stocks net rate of change.

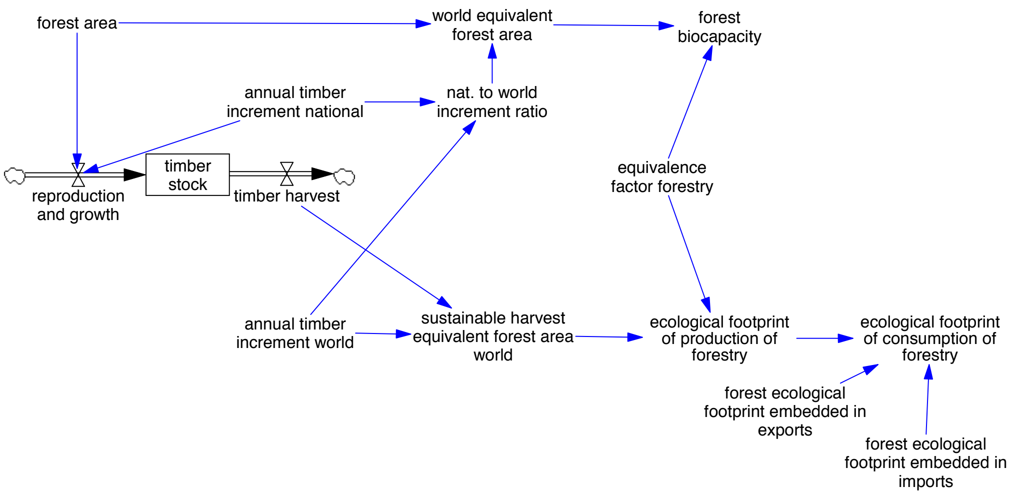

Figure 2: Simplified representation of the Global Footprint Network accounting methodology for the Ecological Footprint and Biocapacity (Ewing et al., 2010) expressed System Dynamics symbols of the Vensim software (Ventana Systems, Inc., 2008)

Flows are non-instantaneous relationships (e.g. the timber stock changes only slowly in response to a change in the reproduction inflow, it accumulates the inflow). The double triangle symbols on the flows can be thought of as valves that regulate the flows. Here, *reproduction and regrowth* is calculated as the product of *annual timber increment national* [m^3 (ha · year)$^{-1}$] and the *forest area* [ha]. Single arrows – ***connectors*** – are used to represent instantaneous causal relationships (e.g.: if the *forest area* changes, the *reproduction and growth* inflow immediately changes accordingly). Variables including flows but not stocks are always calculated from other variables or stocks from which arrows point to them. In contrast, stocks only change through their flows. Variables can also be constants (considered not to change over the simulation horizon).

5.2 The Global Footprint Network accounting framework for the Ecological Footprint & Biocapacity

In the following, the EF&BC accounting methodology (Ewing et al., 2010; Ewing et al., 2010; Global Footprint Network, 2009; Global Footprint Network, 2011; Kitzes, Galli, Rizk, Reed, & Wackernagel, 2008) developed by the Global Footprint Network (hereafter GFN), is explained in a simplified manner to readers familiar with SD symbols in the modeling language of the software Vensim (Ventana Systems, Inc., 2008)..

5.2.1 The Ecological Footprint

At its core, the Ecological Footprint is based on the concept that in managing a renewable resource sustainably one should not extract more resource per time than can be regrown in the same time period[†]. If the harvest is larger than the regrowth for prolonged periods of time, the stock will be drained and eventually seize to exist.

[†] There are also sink resources: Carbon emissions form an inflow to a stock of sequestered carbon into the sink-resource atmosphere which has as compensating outflows e.g. forests or ocean water. Furthermore, the ecological footprint has a component, which is not a renewable

To facilitate various comparisons and ease the grasp by laymen, both inflows and outflows are converted to units of area as follows:

Suppose for example that the *timber harvest* is greater than the *reproduction and regrowth* in Figure 2. One can calculate the ***hypothetical*** area of world-average forest that ***would be needed*** to sustain this *timber harvest*-outflow (*sustainable harvest equivalent forest area national* in Figure 2) by dividing the *timber harvest* with the global average forest growth rates (*annual timber increment world* [unit: world-ha]). Note that this assumes that this area would bring about an equally sized *reproduction and regrowth*-inflow, which presupposes a growth rate that is only dependent on forest area.

There are other composite EFs besides forestry, termed *land use types* in GFN accounting methodology, (e.g. grazing land footprint or cropland footprint). Since the land areas of these land use types have been calculated using different productivities (e.g. m^3 of roundwood per year and metric tons of wheat per year), their areas cannot simply be summed up. They need to be converted to an equivalent area of a hypothetical average land-use type. This conversion is facilitated by an equivalence factor [global-ha world-ha^{-1}]. Ideally these equivalence factors should be area-weighted averages of net-primary productivity for each land use type, but since such data is not available they are currently calculated as area-weighted averages of the suitability scores form the Global Agro-Ecological Zones model by FAOStat and IASA (details see (Ewing et al., 2010)). The area resulting from multiplication with the *equivalence factor of forestry* is the *Ecological Footprint of production* [global-ha].

Since the EF&BC is a consumption-based approach, the EF embedded in imports of wood-based products is added to the production footprint and the EF embedded in exports of wood-based products is subtracted to yield the *Ecological Footprint of consumption of forestry*. For traded forest-derived products harvest data is not available, only data on traded quantities. The latter (e.g. paper) are converted to the timber harvest quantities they originate from. This is facilitated by using average Technical Conversion Factors (hereafter TCF), which is not displayed in Figure 2 for reasons of simplicity.

5.2.2 The Biocapacity

The forest area actually available is converted to a forest area of world-average productivity (*world equivalent forest area* [world-ha] in Figure 2) using the ratio of the *annual timber increment national* to the *annual timber increment world*. To facilitate summation with BCs from other land use types, a multiplication with the *Equivalence Factor Forestry* is necessary to yield the *Forest Biocapacity* [global-ha].

It is important to understand that the GFN accounting framework is only a conversion methodology that converts the inputs (exogenous time series data on harvest and forest area) to the EF and BC respectively. The annual timber increments (national and world) are considered constant (due to lack of time series data). The Equivalence Factors on the other hand vary from year to year and are calculated from separate exogenous time series data are input.

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resource or sink, the 'build-up land EF". It can be understood as former agricultural biocapacity that after conversion to build-up land is "cancelled out" by an EF of equal size.

Note that the timber stock itself is not used in the calculation of the forest BC or the forest EF.

5.3 Method used for the integration of the GFN EF&BC accounting framework in T21

5.3.1 The System Dynamics modeling process

The integration of the EF&BC accounting framework in T21-Senegal follows the established System Dynamics modeling process:

First a problem is defined, in this case the overarching problem is formulated as the research question and it is broken down into sub-problems of how to implement which aspect as an SD model. The model structures created to implement the integration of the EF&BC in T21 are considered hypotheses. They are analyzed and thoroughly tested. This is an iterative process where test results frequently lead to reformulations of the hypothesized model structures or even of the problem formulations or lead to the formulation of new problems (additional structures or parameter values discovered to be necessary). The analysis ends if the model not only reproduces past time series data with sufficient accuracy, but the model structure generating this is also sufficiently close to the structures of the real world so that it can also be used for meaningful future projections. Within the scope of this project, the latter demands that the conditions outlined in the research question (see section 4) be satisfied.

In order to achieve that the following steps are necessary:

5.3.2 Representation of EF&BC conversion structure in T21

First the EF&BC accounting framework is implemented as a new sector in T21. This done using *partial model testing*: the structure is fed exogenously with the same time series data that is used by the GFN to calculate the EF&BC it in their spreadsheets (harvest data, forest land data and import and export data). If the tests are successful, the resulting EF&BC should be the same than the ones derived using GFN spreadsheets.

5.3.3 Endogenization

Once the EF&BC conversion structure is verified as described above, the next step is to replace the exogenous harvest and forest area time series data input with data that is endogenously calculated within the T21 model. Ideally all inputs should be derived from T21, but due to time and information constraints endogenization had to stay limited.

Some outputs of the T21-Senegal34 model can be directly used as inputs to the EF&BC conversion structure (such as forest area data from the stock *forest land*). Other data first needs to be converted (e.g. the EF&BC structure reqires harvest data in terms of m^3/year of merchantable roundwood, whereas T21-Senegal34b produced wood harvest as kg/year (roundwood & branches).

In some cases additional structures need to be created for model outputs that are not readily available in T21-Senegal34. FAO harvest data for example, shows notable amounts of industrial roundwood harvest, whereas T21-Senegal34 previously only considered wood harvest for charcoal or firewood. Still these structures are linked to preexisting structures, wherever reasonable (e.g. *industrial wood demand* driven by *industrial capital*).

Further new structures are necessary to correctly represent reality. For example T21-Senegal34 considered all wood harvest to be clear-cutting (i.e. deforestation), whereas research shows that in fact there is notable thinning taking place (wave of charcoal thinning described by Tappan, Sall, Wood, & Cushing, 2004). This was not important for the previous purpose of T21 but it is important for the EF&BC since thinning is a harvest that only influences the EF directly but not the BC, whereas harvest as deforestation influences both EF and BC directly.

Since some of the structures that are altered used to feedback on pre-existing structures elsewhere in T21-Senegal34, it can become necessary to change the structures are necessary to safeguard the consistency of these feedbacks. Here this involved adapting the structure which converts harvest quantities into financial output from which are needed by the sector calculating the contribution of forestry to GDP from due to the harvest unit change indicated above.

Furthermore some variables that are considered constant by GFN methodology due to lack of time series data, but that have to be considered to be variables based on knowledge of the real world have to be represented as variables in the model.

5.3.4 Parameterization

Many of the new structures created in the processes above need to be parameterized, i.e. new constants or time series data need to be found that to populate the model with real-world values. Data availability in developing countries like Senegal is severely limited and so is time for looking for such within the time frame of a master thesis. Hence it was often necessary to introduce additional structures that convert known data into the units required by parameters. Sometimes existing structures or the definitions of existing structures needed to be changed so that known parameter values could be applied.

5.3.5 Calibration

There are often some parameter values for which no data can be found because no one every bothered to measure it or because data is not available to the modeler. In such cases the modeler may decide to calibrate the values so that the output of model parts matches known time series data. Such calibration is always to be avoided if possible, because they may cause the model to produce the right behavior for the wrong reasons. A value that could have been extracted from data but is instead determined through calibration, precludes the chance to find discrepancies between model behavior and real world behavior and thus find errors in the model or in the data. If however, no data is available, calibration is better than setting the value of the parameter to zero or one (which is often the implicit result of deleting it).

It is important to understand that oftentimes when calibrating a variable that fluctuates heavily, it is not possible to reproduce all the fluctuations but only the trend of the data with the simulation (see also discussion on reference mode reproduction test below).

Furthermore, exogenous data (time series data parameters) are not to be blindly to be trusted. They can be biased, or even manufactured. Therefore data was probed for consistency and tested in terms of reasonableness with respect to knowledge about the forestry system in Senegal.

5.3.6 Testing

During the modeling process, the modeler is continuously testing the model structure to increase confidence in the model. A number of tests are available (Barlas, 1996), a selection of which were used for this analysis:

Parameter/Data verification test

Pre-existing (T21-Senegal34b) or new parameters and exogenous data series are reviewed if they correctly represent the real system. Where possible, values from the literature / internet are used. Due to limited availability of data, not only values from peer-reviewed journals are used but also other data, preferable from governmental or intergovernmental organizations in the hope that these have an interest in collecting reliable data and care about consistency of data. Where multiple values are available this allows for reasoning if they really rely on the same definitions and or measurement methods, which may lead to additional structural insights. If multiple comparable values are available they indicate an uncertainty range of this variable and may thus call for sensitivity analysis (see further below). Experts from GFN and MI were consulted, and provided valuable information.

Structure verification test

It is naturally of high importance that the model structure does not contradict knowledge about the real system. Knowledge about the system is again gathered from literature sources as described under parameter verification and in consultation with Experts from GFN and MI.

Sometimes there is a trade-off between structure verification and parameter/ data verification: from a structural point of view a certain type of model structure may be preferable (e.g. in this case modeling the stock of total above ground biomass because it is the basis for growth) but from a parameter verification point of view another structure may be more desirable (e.g. in this case modeling a stock of standing timber excluding branches, leaves etc.).

Boundary adequacy test

Of course, every model is limited in the sense that it may not contain a certain level of detail. But whether or not more detailed representations are necessary for the model purpose is dealt with by this test. These decisions can involve both considerations on the structural level and behavioral analysis (comparing simulations with and without more detailed structures). If only the latter were used, past data may be reproduced well but future behaviors may not be. Therefore also necessary are structural considerations along the lines of "what may become important in the future that is not important yet". This test not only deals with detail and aggregation level but also whether some structural components are necessary at all or not, which again depends on the model purpose (which may also change during a project).

Unit consistency test

The equations of a model should be set up in such a manner that there are no violations of dimensional consistency and that there are no “fudge”-factors involved which only serve the purpose of “fixing” the units. Special care needs to be taken with s.c. “effects” of one variable on another that are modeled using graph functions or elasticities, because such formulations allow for causally connecting any unit to any other unit without error messages from Vensim’s built-in unit consistency check.

Extreme condition test

This test often uncovers structural weaknesses, which only become apparent once the system operates out of its normal range. Stock levels are put to very low or zero value or very high values and then it is checked if the rates/flows are still behaving in a manner that is reasonable. Not all of the tests carried out in this project, are documented here in detail. It was frequently necessary use rate formulations that prevent a stock or a flow from going negative (e.g. using Min(Stock/Stock-empty-time; normal rate formulation), Max(0,normal rate formulation); and combinations of these). But these cannot be applied to just any flow (e.g. in co-flow structures they should only be used in the governing flow if possible). Similarly, graph functions should also be put to extreme values and see if the outputs make sense.

Sensitivity test

Often some parameters are not known and are thus only crude estimates with an estimated uncertainty range are possible. It would not be sufficient to simply use one model run as the real value of the parameter in question may be different from the chosen one. Sensitivity analysis tests this by running the model with different values for one parameter to assess its effect. If the effect is notable it is necessary to acquire better data to gain a reliable simulation. Note that in this thesis sensitivity tests have been carried out manually, not using Vensims automated sensitivity test tool.

Reference mode reproduction test

This most intuitive test involves comparing the development of a variable in the model gained by a simulation with existing data on this variable.

Sometimes one cannot expect the two to match in detail though because there may be random fluctuations in the data that cannot be reproduced. In such case it is tested if the simulation at least reproduces the general trend of the data. It is hoped that the trend and the fluctuations are being caused by different mechanisms in the real world and that the simulation captures the causal mechanism behind the trend but not the mechanism behind the fluctuations. If the fluctuations are random in nature in the real world, it is not even possible to reproduce them precisely. Even with a random number generator it would only be possible to generate fluctuations that have a similar shape (e.g. similar amplitude, similar random distribution, standard deviation etc.).

Comparison of the pattern can also include comparing amplitudes, frequencies, autocorrelations of periodic fluctuations etc.

The first suspicion if there is a marked difference between simulation and data is that there is something missing in or wrong with the model. But when tracing causality through the model in search for such, one may also grown suspicion if the reference mode data is correct or if its definition was understood correctly. In developing countries like Senegal, good data is hard to find so this second possibility needs to always be kept in mind. Search for additional data may become necessary.

Importantly, this test is alone not sufficient for to build confidence in a model, as a model can reproduce past trajectories “for the wrong reasons” i.e. false assumptions about causalities. If that is the case, one cannot expect the model to behave accurately under conditions out of its past range of behavior.

<u>Partial model testing</u>

This technique is not only used for testing the correctness of transferring arithmetic developed in another modeling paradigm to System Dynamics, as outlined above for the EF&BC calculation sector. In case of large models like T21 it is often valuable to isolate certain model sectors by cutting the feedback loops connecting it to other model parts. To this end it is necessary to have reliable data on the outputs of the model sector to other model sectors and replace the outputs with exogenous data. As a result, the rest of the model behaves the same regardless of any changes in the model sector that is altered. This is important as the other model sectors have feedbacks on this sector and it would otherwise be hard to know if changed behavior in this model sector is the result of structures inside of the altered model sector or due to effects on the rest of the model that feed back on the model sector because they provide input to it.

Similarly, the model sector can also be shut of from inputs from other model sectors by providing exogenous input, either from known data or hypothesized inputs. The latter can be interesting to test the sub-model under a wider range of conditions than observed in past behavior of the rest of the model. In this project, a simplified version of the core model is first tested with a wide range of hypothesized harvest inputs for example. This also had the advantage that the sub-model could be tested over a longer time span than it was possible in the T21-model.

<u>Application of tests</u>

In case of this modeling project, first the original model implementation for Senegal (T21-Senegal34b), was tested part by part for adequacy to the new purpose (boundary adequacy, structure verification parameter verification) and if not it was adapted to suit the new purpose.

Vensim-implementations of the GFN accounting structure were not only scrutinized for correct implementation (reference mode reproduction, partial model testing). It was instead also asked if the underlying logic and its implementation was adequate for the system under study. Emerging issues were discussed with experts from GFN and MI as much as possible. An iterative process of building model structure testing consequentially altering model structure and testing again formed the next stage of the modeling process.

Due to limited availability of data and time not all limitations of the model could be resolved within this thesis project. They are discussed where appropriate.

6 Model description and analysis

In the following, the model will be described and analyzed sector by sector starting with the Vensim implementation of the EF&BC calculation sector. Special emphasis is put on description and analysis of the core model, because it contains the most important feedbacks and is thus the source of most of the dynamic complexity seen in the behavior. Its analysis is first done on a more theoretical level as isolated model, detached from the T21-Senegal model (partial model testing). Emphasis is put on making the reader understand this small model step by step with increasing complexity. In the following the rest of the model sectors then describe the somewhat more disaggregated implementation of the core model in the T21 as well as the necessary additional inputs such as timber demand as well as EF embedded in wood-derived products. Note that due to time constraints of a master thesis some tests and analysis that should have been carried out could not be.

6.1 Ecological Footprint and Biocapacity calculation sector

This sector implements the EF&BC accounting methodology (2011 version) (Ewing et al., 2010; Ewing et al., 2010; Global Footprint Network, 2009; Global Footprint Network, 2011; Kitzes et al., 2008) as a simulatable Vensim structure.

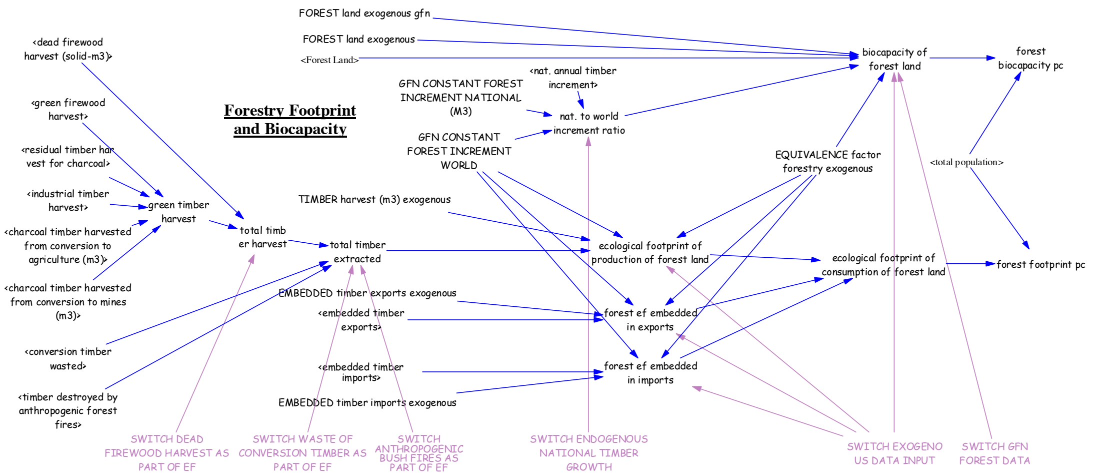

Figure 3: Model structure for converting harvest, timber imports and timber exports to the EF and for converting forest area to BC.
Light purple arrows are switches, variables derived form other model sectors carry < >, variables in Times New Roman were taken unchanged from T21-Senegal34, variables in Comic Sans MS were added or modified in this project

The sector converts harvest data into global ha of EF. First, the *total timber harvest* data is divided by the constant *GFN forest increment world* to (yielding an equivalent forest area of world average forest productivity) and multiplied by the *equivalence factor forestry exogenous* (yielding an equivalent area of average bioproductivity of all land use types, which is the *EF of production of forest land*). The *equivalence factor* forestry was implemented as an exogenous data series input with an assumption for future development (see Figure 4).

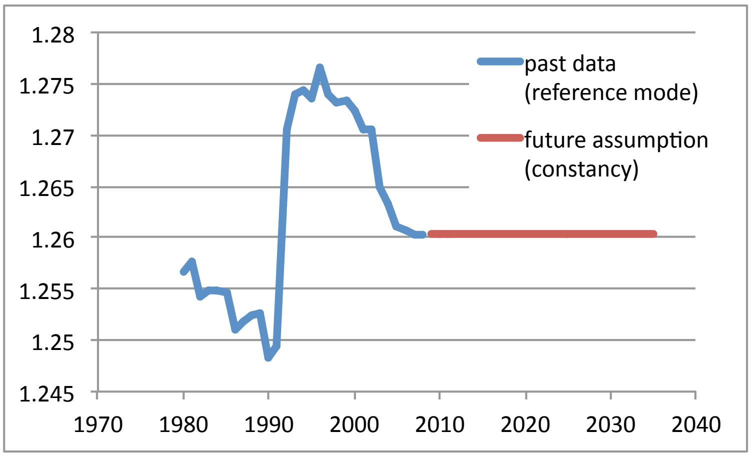

Figure 4: Development of the equivalence factor forestry for past data and future assumption

The variables *embedded timber exports* and *embedded timber imports* represent the amounts of roundwood that were at some point harvested from a forest to produce the exported and imported products. They are thus in the same units as harvest data [solid m^3 of harvested roundwood] (for details see section 6.6). Hence the variables *forest EF embedded in exports* and *forest EF embedded in imports* can be converted to footprint units in the same way as harvest is converted to the ecological footprint of production.

The ecological footprint of consumption of forest land is the sum of the ecological footprint of production and the net imports (imports minus exports) of embedded forest footprint.

The *forest land* area is converted to biocapacity of forest land via multiplication with the *national to world annual increment ratio* to convert the national forest area to an equivalent area of world average forest productivity. Multiplication with the *equivalence factor of forestry exogenous* then converts this to equivalent an area of average bioproductivity of all land use types.

Both the EF and the BC are converted to a per capita basis by division with the *total population* derived from the population sector.

The switches *switch anthropogenic forest fires as part of EF, switch waste of conversion timber as part of EF, switch dead firewood harvest as part of EF* can be used to either in- or exclude certain types of timber removal from being included in the EF calculation. They are explained in more detail in other sectors.

Partial model test of EF&BC conversion structure

A partial model test evaluates whether the arithmetic of the GFN calculation methodology was implemented correctly in Vensim and if the conversion of FAO harvest data to primary harvest data according to the GFN extraction rates (performed in Excel prior to import to Vensim) have been carried out correctly. As can be seen in Figure 3, the *switch exogenous data input* (values 1 if exogenous and 0 if endogenous) is used to switch between feeding the sector with exogenous data or with variables endogenously derived from other parts of the T21 model. When fed with the exogenous data, the sector should reproduce the results obtained with GFNs excel spreadsheets (partial model testing see section). When fed with endogenous variables it should also reproduce past behavior with sufficient accuracy but it should also allow for simulation into the future.

Timber harvest (*m*³) *exogenous, Embedded timber exports exogenous* and *Embedded timber imports exogenous* are based on FAOstat forest production/trade dataSource: (FAO Statistics Division, a) that was converted to solid-m^3 where necessary (e.g. charcoal production in tonnes) by dividing with GFN extraction rates (Ewing et al., 2010; Global Footprint Network, 2011). Note that for domestic production only "primary" products (raw harvest products) and wood fuel production are summed because it is assumed that primary production data includes the wood that that is then turned into "derived" products (e.g. charcoal), whereas for imports and exports derived products are also included (Ewing et al., 2010; Global Footprint Network, 2011).

Forest land exogenous GFN is FAOstat data (FAO Statistics Division, b) as used by GFN and T21-Senegal34b.

The partial model test in Figure 5 shows that the curves are almost completely congruent. There is a deviation for the BC prior to 1990 though.

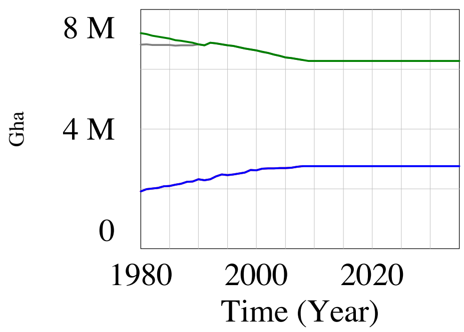

Figure 5: Partial model test of the EF&BC conversion structure.
Development of the *EF of consumption of forest land* based on exogenous harvest data and trade data input (blue) congruent to GFN data for the same variable (red); development of the *BC of forest land* based on exogenous forest land data (green) compared to GFN data for the BC (grey).

The reason is that FAO does not provide *forest land* data for Senegal prior to 1990 and the GFN methodology and and T21-Senegal34b have made different assumptions to fill that data gap (see Figure 6).

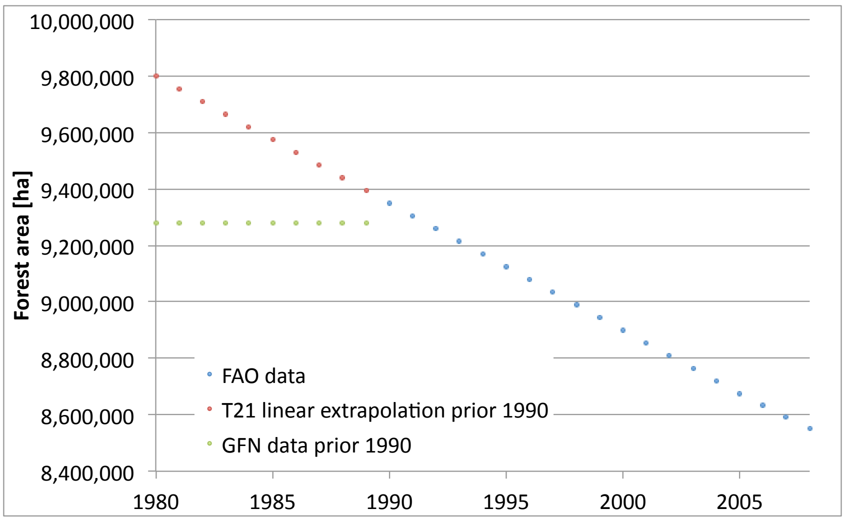

Figure 6: *Forest land* data and differing assumptions of T21 and the GFN accounting methodology to fill the data gap prior to 1990

Since the linear extrapolation using the same annual deforestation as in the years 1990 to 2005 appears more reasonable, this version is used in the following.

Note that the seemingly trivial partial model test revealed an important difference in T21-Senegal34b and GFN methodology.

<u>Limitations of the EF & BC calculation sector</u>

The *equivalence factor forestry* has been used in the model as time series exogenous data. This variable should ideally also be endogenized as far as possible, but since it varied so little, this was given a low priority and thus was not implemented in this project yet.

6.2 Description of the simplified core model

6.2.1 Derivation of nat. annual timber increment and introduction of a dynamic timber stock

As described under (6.1) due to lack of data, the GFN EF&BC accounting methodology considers the annual timber increment (which is the growth in m^3 of timber per ha per year) constant. In reality the net growth of a forest (and of many other renewable biotic natural resources) is often density dependent (e.g. Ford, 1999; Moxnes, 1998; Moxnes, 2000; Moxnes, 2004). This means that the growth is in some way dependent on the resource stock, relative to a maximum resource stock (often also termed ecological capacity). The ratio of the stock relative to the maximum stock is a measure of the "density" of the resource.

T21-Senegal34b did not contain an explicit timber stock, rather the timber stock was implicitly defined as the product of *forest land* and *weight of wood per ha* (see Figure 7). Modeling density dependent growth however, requires modeling the resource as an explicit stock with in- and outflows.

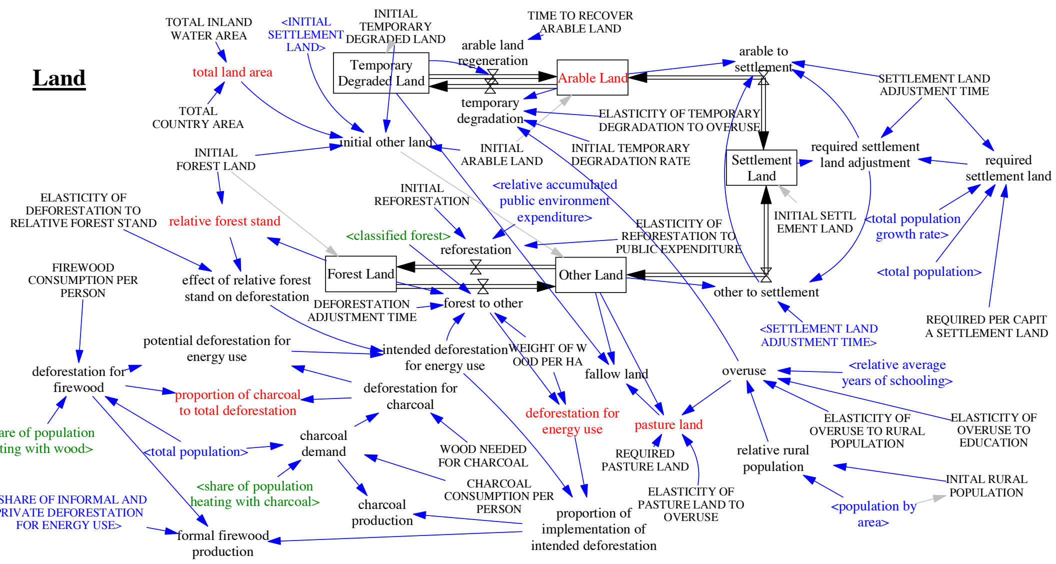

Figure 7: Original Land sector in T21-Senegal34b.

Also, the former implicit resource stock was defined as wood mass of tree trunks plus some branches in kg. This definition is not feasible any more if industrial wood harvest is introduced because the latter is defined as roundwood. As a consequence, the stock units were switched to *timber volume* (m^3 of roundwood, i.e. stems only). This is also more convenient as the FAO data on harvest and standing timber are commonly reported in these units and it is convenient because the harvest data-input to the EF is in m^3 $year^{-1}$.

As Figure 8 shows, the inflow of reproduction and growth and a mortality outflow under natural conditions were collapsed in the net-flow *net natural reproduction and growth*. This flow is the product of the *forest land* area and the *national annual timber increment*. The *timber volume per ha* – a measure of stand maturity and forest density – is calculated as the ratio of *timber volume* to *forest land* area.

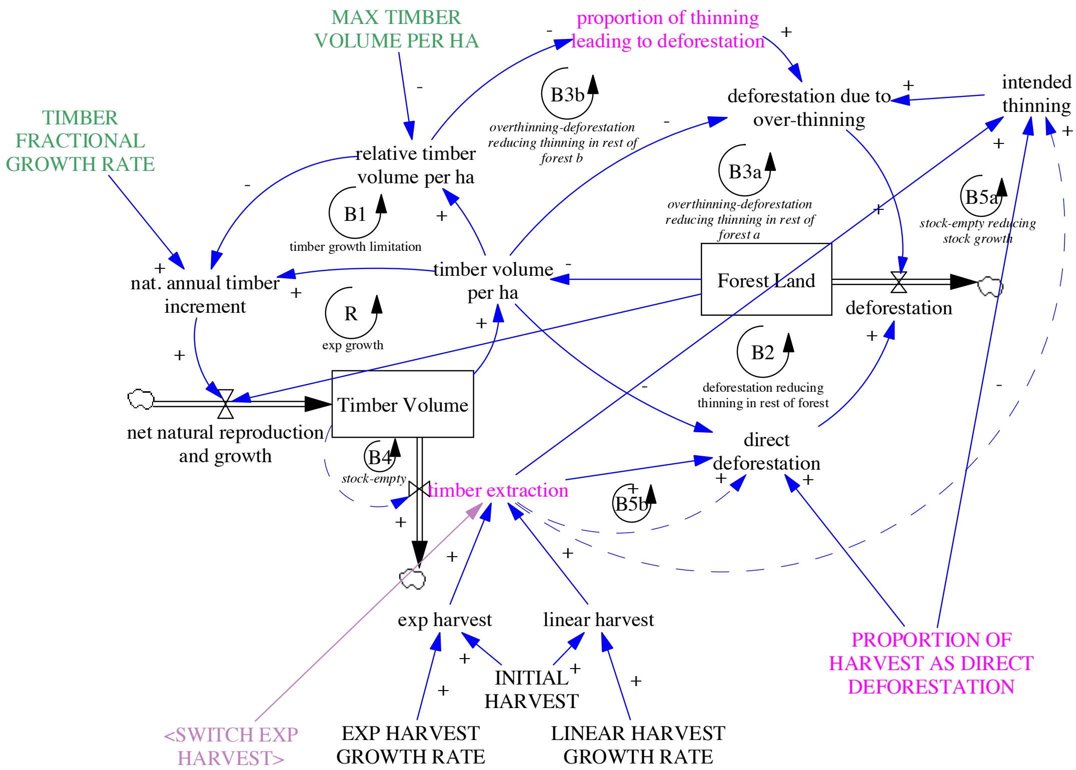

Figure 8: Simplified core model incl. feedbackloops.
It is not attached to T21 and fed with different hypothesized exogenous harvest developments. Parameter values based on literature sources in green, parameters based on assumptions only in pink, switches in light purple. Dashed loops only come into effect when the *timber volume* stock is very low.

A simple logistic growth model was used so that the *national annual timber increment* is not a constant as assumed by the GFN methodology but depends on the *timber volume per ha*, as show in in Equation 1.

Equation 1: *National annual timber increment* as function of the *timber volume per ha*

$$I = D \cdot g_f \cdot \left(1 - \frac{D}{D_{max}}\right)$$

where:

I = (net) *nat. annual increment* [m^3 ha^{-1} $year^{-1}$]

g_f = *timber fractional* (net) *growth rate* [$year^{-1}$]

D = Density of forest and stand maturity (*timber volume per ha*) [m^3 ha^{-1}]

D_{max} = *Max. timber volume per ha* [m^3 ha^{-1}]

D/D_{max} relative timber volume per ha

Since *D* can be calculated from the timber volume and the forest area, Equation 1 transforms to:

Equation 2: *National annual timber increment* as function of the *timber volume* and *forest land*

$$I = \frac{T}{A} \cdot g_f \cdot \left(1 - \frac{\frac{T}{A}}{D_{T_{max}}}\right)$$

where:

T = *timber volume* [m^3]

A = Area of *forest land* [ha]

Since however, the *timber volume per ha* i.a. depends on the forest area, the resulting growth patterns can be quite a bit more complicated dependent on the development of the *forest land* area. The dependency between the timber *volume stock* and its inflow *net natural reproduction and growth* is:

Equation 3

$$G = T \cdot g_f \cdot \left(1 - \frac{\frac{T}{A}}{D_{T_{max}}}\right)$$

where:

G = *net natural reproduction and growth* [m^3 $year^{-1}$]

The parameter values were determined as follows:

6.2.2 Parameterization and calibration of the core model

The *max. timber volume per ha* was determined using the upper bound of biomass stock estimate ranges for tropical forests in Africa (first column Table 1) and converting these to timber volume (second column Table 1) by reverse-applying IPCC Biomass Expansion and Conversion Factors (BECF) Table 2. For this reverse application it is necessary to know in which stock density category we are operating (i.e. some prior knowledge on the result). Since we are looking at the maximum timber volume per ha, it is only reasonable to use the highest category (<80 m^3 ha^{-1}), i.e. a BECF of 0.66. Since Senegal has both types of forest we know that the value must lie between 144 and 488 m^3 ha^{-1} and probably more likely even in the range of 197 to 295 m^3 ha^{-1}. Senegal does however also have some shrublands that have even lower biomass of which no data for maximum above ground biomass data is available. It is however very likely that *maximum timber volume per ha* there is lower and that therefore the national average of the *maximum timber volume per ha* is likely not going to be at the high end of this spectrum. Consequently a value of 250 m^3 ha^{-1} was chosen.

Table 1: Calculation of *maximum Timber volume per ha*. Data source: (Penman et al., 2003). d.m. = dry matter; Calculated values in *italic.*

Forest type	Max. above-ground biomass stock in naturally regenerated forests in Africa [$t_{d.m.}$ ha^{-1}]	*Maximum timber volume per ha* (min. – max.) [m^3 ha^{-1}]
Moist with long dry season	130	*197 (144-325)*
Dry	195	*295 (217-488)*

The *timber fractional* (net) *growth rate* was determined using estimated values of above-ground biomass in natural forests and above-ground net biomass growth in natural forests as shown in Table 3 and BEFCs from Table 2.

Table 2: Bimoass Expansion and Conversion Factors[‡] [$t_{d.m.}$ m^{-3}] (IPCC, 2006). d.m. = dry matter; Calculated values in *italic*

	stock density category [m^3 ha^{-1}]			
BEFC used for:	<20	21-40	41-80	>80
stock (average)	5	1.9	0.8	0.66
stock (min)	2	1	0.6	0.4
stock (max)	8	2.6	1.4	0.9
increment	1.5	0.5	0.55	0.66
harvest	5.55	2.11	0.89	0.73
BEFC ratios:				
increment/stock$_{average}$	*0.30*	*0.26*	*0.69*	*1.00*
increment/stock$_{min}$	*0.75*	*0.50*	*0.92*	*1.65*
increment/stock$_{max}$	*0.19*	*0.19*	*0.39*	*0.73*

Table 3: Calculation of *timber fractional growth rate*. Data source: (IPCC, 2006). d.m. = dry matter; Calculated values in *italic*

Forest type	Above-ground biomass in natural forests [$t_{d.m.}$ ha^{-1}]	Above-ground net biomass growth in natural forests [$t_{d.m.}$ ha^{-1} yr^{-1}]	*timber (net) fractional growth rate [yr^{-1}]*
Tropical moist deciduous forest	180	5.0	*0.028*
Tropical dry forest	130	2.4	*0.019*

[‡] Note that BECFs are normally used to convert stock estimates [m^3] into total above ground dry-matter biomass [$t_{d.m.}$] in order to calculate above ground carbon stocks using average dry-matter carbon contents. They combine a measure of the basic density of the wood [$t_{d.m.}$ m^{-3}] with biomass expansion factors [$m^3_{\text{biomass with branches, twigs}}$ m^{-3}_{timber}] that. They differ depending on whether stock values, increment values or harvest values are converted.

Tropical shrubland	70	1.0	*0.014*

The stock values of "tropical moist deciduous forest" and "tropical dry forest" are in the highest *timber volume per ha* category (>80 m^3 ha^{-1}) of the BECFs, since none of the conversion factors in any of the other categories can produce such high above ground dry-matter values after application of the conversion factor. Since in this category the BEFC is the same for annual increments and stock values (0.66 $t_{d.m.}$ m^{-3}) the two cancel out, i.e. at this highest forest density the fractional growth rate in is the same irrespective of whether it is based on volume of timber or tons of above-ground dry biomass. The matter is more complicated for tropical shrubland since any *timber volume per ha* category could produce an above-ground biomass of 70 $t_{d.m.}$ ha^{-1} (dividing this value with any of the stock-BEFCs (including uncertainty range) in Table 2 yields a timber stock that is within the range of every *timber volume per ha* category). Hence, since we lack any a-priory knowledge on the kind of timber density at which the measurements were taken, we cannot calculate definite values for the fractional growth rate for tropical shrublands. If we knew however, in which category the measurement was taken, we would have to multiply the fractional growth rate calculated using the dry-matter biomass with the ratio of the $BEFC_I$/$BEFC_S$ as shown in the last row of Table 2. Since the other two other forest types seem to have been measured in the highest density, this is also likely for the tropical shrubland, in which case again a fractional growth rate of the timber volume would equal that of the fractional growth rate of the agove-ground dry biomass. If it was measured in a lower *timber volume per ha* category, it would be multiplied with a factor >1 as columns 2, 3, 4 in the last three rows of Table 2 show. Hence the fractional growth rate for tropical shrublands could even be substantially lower than 0.014. Since some of Senegals Savannas classify as tropical shrublands, this could reduce the average growth rate of all forests in the country. Hence the fractional growth rate will likely not be at the very high end of the possible spectrum of 0.014 to 0.028. A value of 0.02 was chosen.

The parameters *timber fractional growth rate* and *maximum timber volume per ha*, are not independent of each other. If e.g. Senegal had a *maximum timber volume per ha* at the lower end of the spectrum this would mean that it had a large amount of moist deciduous and a lower amount of dry forests but that would also imply a *timber fractional growth rate* at the lower end of its possible spectrum.

Initial timber volume per ha: From FAO Forestry Department (2010) one value of the timber stock for the year 2004 is known. This together with the knowledge about the possible ranges of the *timber fractional growth rate* and *maximum timber volume per ha*, and the knowledge that the two are not independent of each other can be used in an attempt to calibrate the core model to a certain degree. The *initial timber volume per ha* is and the *timber extraction* and *timber removed by forest fires* also influence the stock though. Even if the extraction by forest fires is taken as a given and fixed assumptions are made about the *timber extraction* it is only possible to limit the parameter range somewhat, but not to only one set of parameters. Since there are a lot of further unknowns in the way that the *timber extraction* is determined, there is a large range for the three parameters in the core model could take and still meet the little knowledge we have about past behavior. A value of 39 m^3 ha^{-1} was chosen for the base run because in combination with the other base run values it reproduces the 2004 value and a decreasing timber volume stock.

6.3 Long-term analysis of simplified core model

In this section, the simplified core of the new model structure introduced is first analyzed separately from the rest of the model structure (partial model testing), using hypothesized harvest inputs and without feeding its outputs to other model sectors. This allows for analyzing a wider range of its behavior than can be observed given the parameterization in the T21 model, because the T21-Senegal model only allows for simulations form 1980 to 2035 which is still quite short for forest dynamics to play out. The model is developed step-by-step adding complexity so that with a bit of patience even non-system-dynamicists should be able to understand how the model creates which developments. This will be helpful for understanding the full model, since that actually doesn't have much dynamic structure added, it is only more disaggregated.

The analysis starts with a simple logistic model considering only selective harvest (thinning), then direct deforestation is added followed by additional structure for deforestation through over-thinning. The models are tested with different harvest inputs (constant, linearly increasing, exponentially increasing). The section concludes with an analysis of some prerequisites for sustainable forest management.

6.3.1 No harvest

The model is first run under hypothesized conditions of no timber extraction and no deforestation and thus constant *forest land* area (9.8 mio ha, = 1980 value) but starting at a very low *initial timber volume per ha* of 1 m^3 ha^{-1} (which would imply that there are only very small trees on all of the area). The *maximum timber volume per ha* and *timber fractional growth rate* were set at 250, 0.02, respectively (see section 6.2.2 for respective ranges). As can be seen in Figure 9, this leads to simple logistic growth.

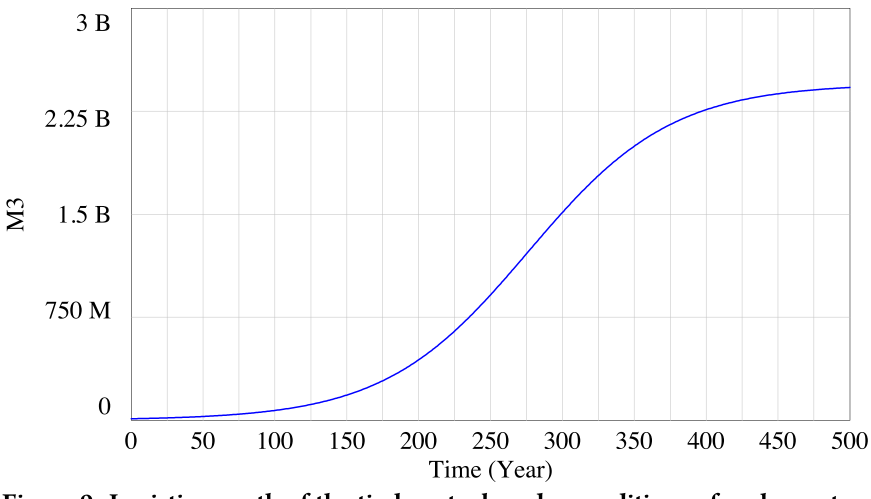

Figure 9: Logistic growth of the timber stock under conditions of no harvest and constant forest area starting at a very low initial timber density of 1 m^3 ha^{-1}

Furthermore, Figure 10 shows that the reason is the net growth inflow, which first rises slowly then peaks and then falls again and tends to go to zero after 500 years, which is why the timber stock stagnates at a high level.

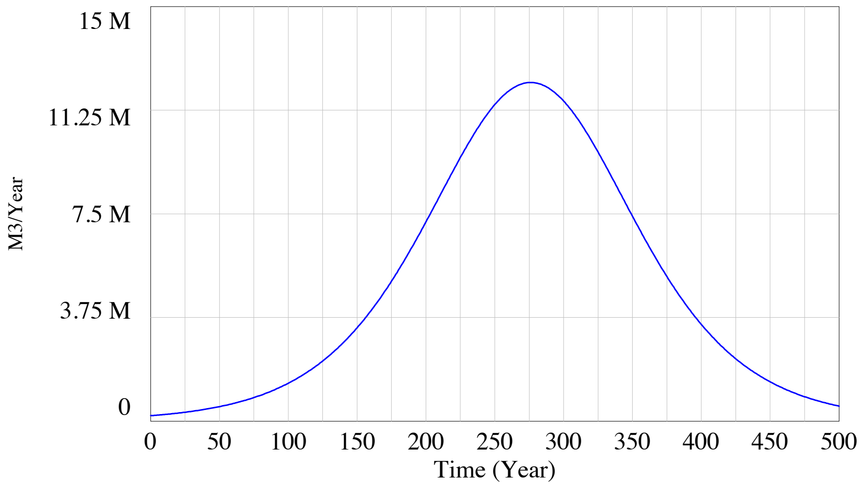

Figure 10: Development of *National annual timber increment* over time starting at a very low initial timber density of 1 m^3 ha^{-1} and constant forest area

Responsible for this development are two feedback loops in this model structure: In the beginning when the forest density is still low, the reinforcing *exponential growth* loop (R) still dominates, since the *relative timber volume per ha* is still very small (see Figure 8, Equation 1).

Thus the growth is initially only limited by the low density of the forest as a driving force. One could imagine a land that has only tree seedlings, so the photosynthetic area is still very small and thus per area timber growth is initially miniscule, but the more leaves the more photosynthesis the more leaves the next time around, so the timber growth rises steeply, once the timber has accumulated enough. But as the *relative timber volume per ha* grows the other balancing feedback loop gains strength (*timber growth limitation –loop B1,* Figure 8). In reality this limitation stems from both the maximum height of the trees, which is limited by its statics and genetics, and the maximum density of trees competing for resources such as light, water and nutrients. The limitation would probably play out not only as a growth limitation but also as a flow equilibrium where a timber growth is balanced by an equally large timber die-off. These mechanisms are modeled in a simplified manner here using a net-growth inflow (growth minus die-off). It is important to understand that the dominance of the feedback loops switches from the exponential growth loop to the growth limitation loop and that this switch is facilitated by forest density (indicator *relative timber volume per ha*). As a result the national annual timber increment is not constant but it depends in a quadratic manner on the timber volume per ha (see Equation 4, Figure 11).

Equation 4: ***Equation 1 rearranged to show quadratic term***

$$I = g_f \cdot \left(D - \frac{D^2}{D_{max}} \right)$$

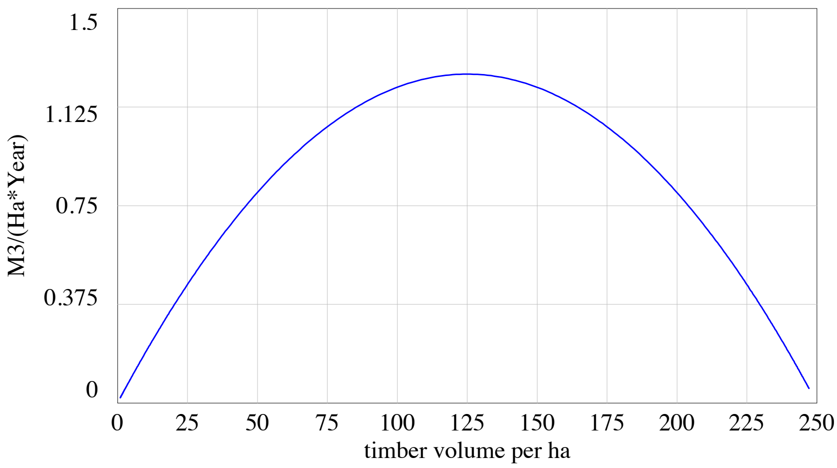

Figure 11: ***National annual timber increment*** **as function of the** ***timber volume per ha***
Note that this is not a graph over time, but a phase diagram relating a flow to its respective stock.

6.3.2 Constant selective harvest

Next we consider a situation, of the stock being at *maximum timber volume per ha* (before human interference). If a constant selective harvest (thinning) is applied, the behavior of the system depends on the size of the harvest relative to maximum growth that the system can observe. If the harvest is smaller than the maximum growth (see Figure 12 and Figure 14), the timber stock will only decline until the growth that results from that timber stock will be equal to the harvest and the system will stabilize there. If the harvest is larger than the maximum ability of the system to grow, the timber stock will be depleted.

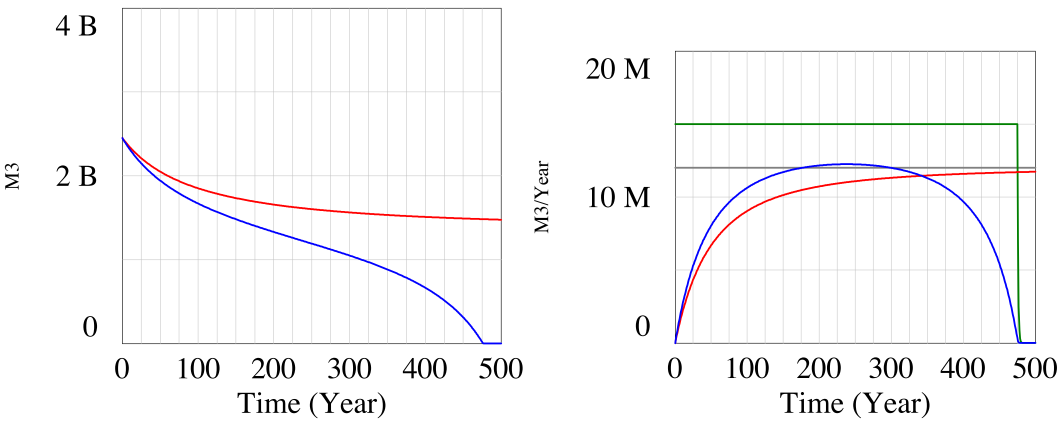

Figure 12 Left pane: Development over time of the ***timber volume*** **stock under conditions of constant selective harvest for a harvest smaller and larger than maximum** ***net natural reproduction.*** **Right pane: Harvest rates (grey, green) compared to the respective developments of the** ***net natural reproduction***
Harvest: 12 million and blue 15 million m^3 $year^{-1}$ (grey and green lines in right pane, and respective variable developments in red and blue)

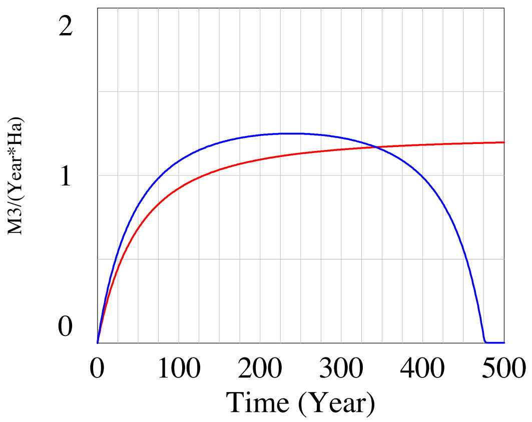

Figure 13: Development of *national annual increment* for a harvest smaller and larger than maximum *national annual increment*
Red: 12 million and blue 15 million m^3 $year^{-1}$

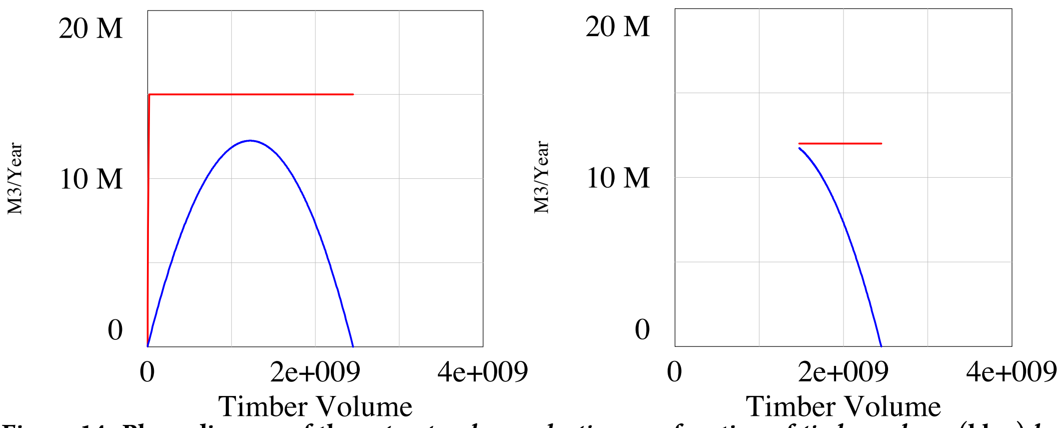

Figure 14: Phase diagram of the *net natural reproduction* as a function of *timber volume* (blue) *harvest* (red) under conditions of constant selective harvest.
Right pane: *harvest* rate larger than the maximum net reproduction (peak of the blue curve). Left pane: harvest rate lower than maximum net reproduction. Note that in both panes the time would be progressing from right to left since the timber value is sinking because harvest is larger than net growth for any timber value.

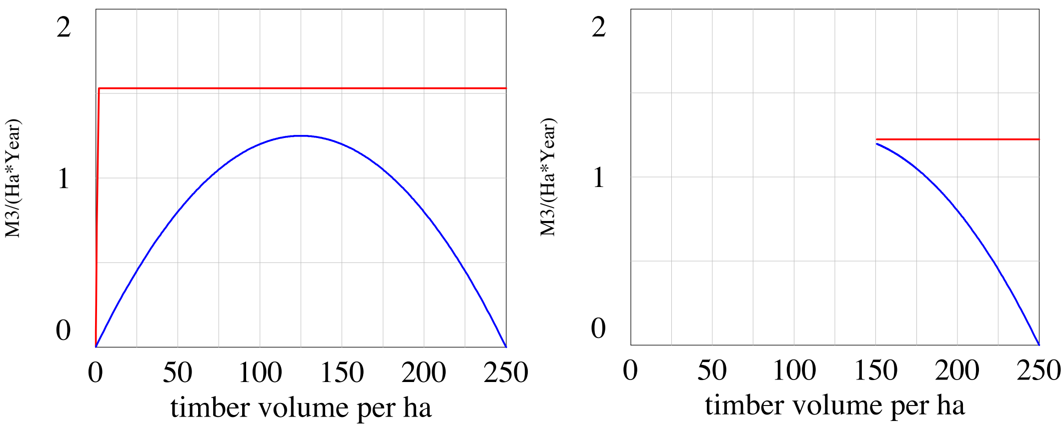

Figure 15: Phase diagram of the *national annual timber increment* as a function of *timber volume per ha* (blue) with a constant selective harvest (red) under conditions of constant selective harvest.
Right pane: harvest rate larger than the maximum net reproduction (peak of the blue curve). Left pane: harvest rate lower than maximum net reproduction. Note that the shape is similar to Figure 14 since the forest area is constant if only selective harvest takes place.

Interestingly however, for the first 250 years the decline in the timber stock seems to decelerate, which may lead observers managing the system to believe that it will stabilize, but it then "suddenly" starts accelerating the decline again. The reason is that as the timber stock falls, the growth of the system first increases since it is released from the growth limitation loop (B1 in Figure 8) and the exponential growth loop thus gains relative strength (see blue curve in right pane of Figure 12, R-loop in Figure 8). As even the maximum growth generated by these two loops is however smaller than the harvest rate (see green curve in right pane of Figure 12), the growth loop gets overpowered by the harvest. As a consequence, the timber stock falls below the value at which it yields maximum growth after which the decline accelerates because the exponential growth loop now loses strength due to the declining timber stock.

Since the *forest land* area is considered constant here, the development pattern of the *national annual increment* mimics that of the *net natural growth* (Figure 13).

While the developments of the two different harvests are quite different (collapse vs. sustainable harvest) the mechanisms behind them are similar as can be seen in Figure 14 and Figure 15: as the *timber volume* falls the *net natural growth* and the *annual increment* first increase. In case the harvest is smaller than the maximum *net natural growth*, the latter rises to the value of the former and then reaches a flow equilibrium (right panes of the two figures). In case the harvest is higher, an equilibrium of the two flows is only reached once the *timber volume* stock is depleted, because at the very end the harvest also collapses (rapid fall of the harvest rate, close to the *timber volume* of zero, caused by the fuzzy min function built into the *timber extraction* flow). Note that for constant *forest land* area the phase diagrams for the *net natural growth* and the *national annual increment* look very similar, in fact they can be converted into each other using the forest area as a factor.

6.3.3 Linearly increasing selective harvest

Of course the scenario of a harvest suddenly starting at high levels and staying constant is not very realistic. It appears more likely that harvest is increasing, e.g. due to growth of the population and or of economic prosperity. We first explore a linear increase scenario starting at no harvest and increasing by 60,000 m^3 $year^{-1}$. That seems less realistic than an exponential one, which is explored after this one (see 6.3.4), but it is worth exploring to understand the dynamics better and also because actual wood fuel harvest data of the period 1980 to 2008 actually appears to be roofing in for grounds explored under (see section 6.4.1, Firewood- and charcoal demand in reaction to butanzation campaign).

It can be seen in Figure 16 that the decrease of the timber stock resulting from a linearly increasing harvest is initially moderate but then accelerates. The reasons for this can be inferred from the left pane of Figure 16: while the *harvest rate* is actually all the time larger than the *net natural growth*, for a long time the growth almost compensates for the harvest. That is because the harvest releases the forest from competition (weakens the timber growth limitation loop), so that it can start to grow again (exponential growth loop gains strength). At some point however, the harvest rate (red curve in Figure 17) surpasses the maximum net natural growth (peak of the blue curve in Figure 17). From that point onwards the net natural growth curve in in Figure 16 starts dropping and consequently the timber volume stock decline accelerates. The problem with this system behavior for resource managers is that they may initially underestimate the problem, until it is too late.

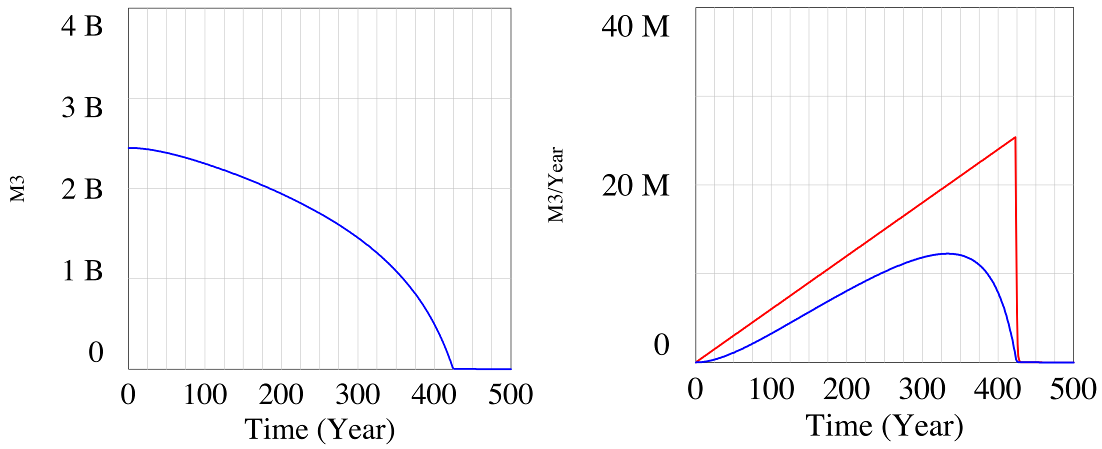

Figure 16: Development of *timber volume* and *net natural regrowth inflow* under conditions of linearly increasing harvest.
Left pane: *timber volume* stock. Right pane: *net natural regrowth inflow* (blue) and the *harvest* outflow (red)

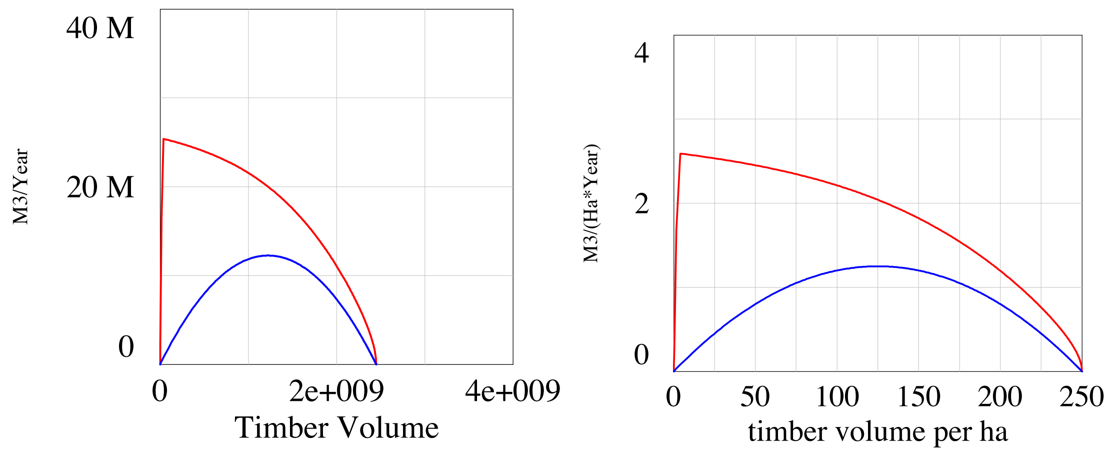

Figure 17: Phase diagrams under conditions of linearly increasing harvest.
Left pane: net natural growth (blue) and timber extraction (red) both as a function of the timber volume. Right pane: nat. annual increment (blue) and timber extraction per ha (red) as function of timber volume per ha.

6.3.4 Exponentially increasing selective harvest

Both the growth of population and economic output are often exponential. Since more people require more resources and more productive economies also tend to demand higher resources, an exponential growth pattern for *timber extraction* appears to be (at least ignoring other factors) the most reasonable one.

The right pane of Figure 18 shows the exponentially increasing timber extraction (red curve).

The left pane of Figure 18 shows a stock development, which compared to the linearly increasing timber extraction case shows hardly any decline at the beginning but followed by a much steeper decline at the end. The reason is that exponential growth is initially rising more slowly than linear growth due to the very low initial value ($1m^3$ $year^{-1}$) but after a while accelerates much faster (growth rate 3% $year^{-1}$). It is reasonable to assume a harvest starting at a low value (e.g. due to very low population) but given enough time even this small initial value will “explode” at some point, once it has gained enough momentum.

This means that in this more realistic case of an exponential development of a harvest management of the resource is even more difficult than in the linear case since the initial decline is slower and the final collapse is thus more unexpected and in addition to that happens much faster.

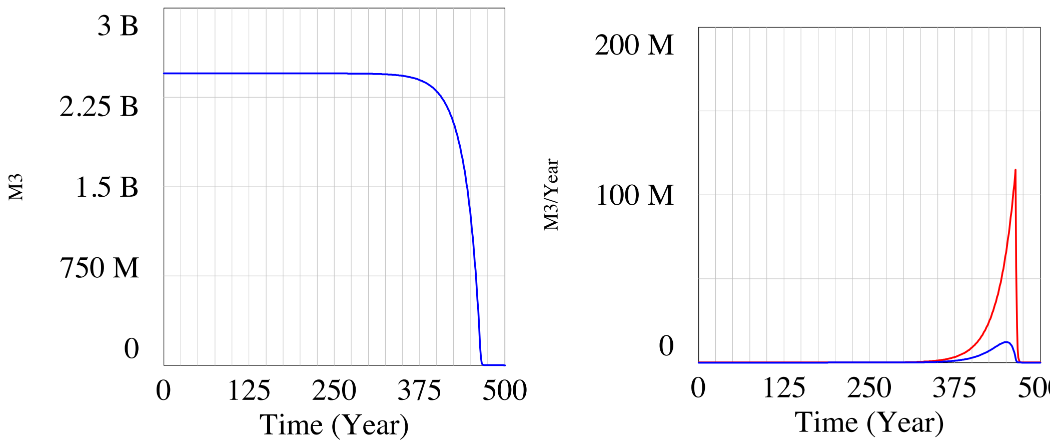

Figure 18: Development of *timber volume* and *net natural regrowth inflow* under conditions of exponentially increasing harvest.
Left pane: *timber volume* stock. Right pane: *net natural growth* (blue) and *timber extraction* (red)

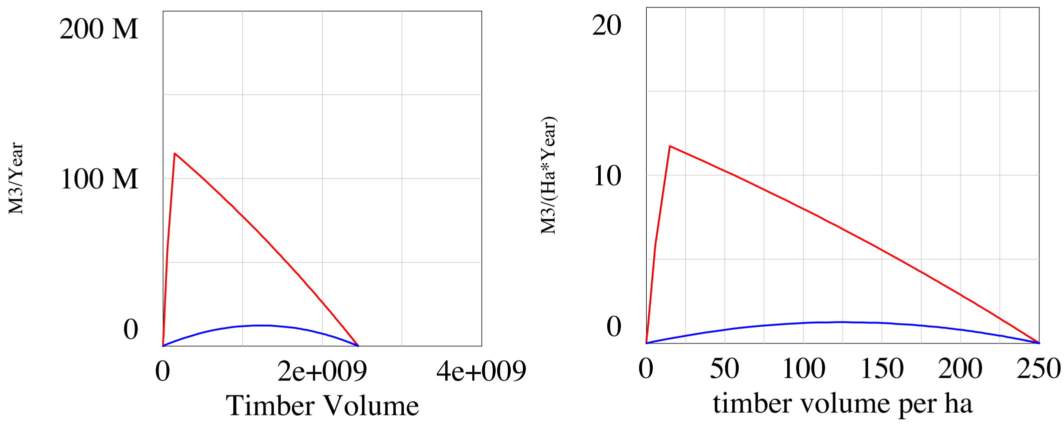

Figure 19: Phase diagram for exponentially increasing harvest.
Left pane: net natural growth (blue) and timber extraction (red) both as a function of the timber volume. Right pane: nat. annual increment (blue) and timber extraction per ha (red) as function of timber volume per ha.

Figure 19 shows that the exponential harvest is increasing much faster with sinking timber volume than in the linearly increasing case. The curves of the *net natural growth* and *nat. annual increment* however, stay unchanged. The reason is that every every causal combination of *timber volume per ha* and the resulting *net growth* is passed by in the development of both linearly increasing and exponential timber extraction, the difference is the point in time when these states are realized.

6.3.5 Constant harvest with differing mixes of selective harvest and deforestation harvest

It appears reasonable to assume that certain types of timber extraction are not selective i.e. do not only thin the forest stand but instead clear-cut forest area, i.e. for conversion to other land-uses such as agriculture. This implies that the stock of *forest land* area is reduced. In the following the implications of different proportions of the total harvest being carried out as deforestation vs. thinning are explored.

Figure 20 shows the development of the *timber volume* stock and its inflow the *net natural growth* rate under conditions of constant harvest (15 million m^3/year) at varying proportions of the timber extraction being carried out as deforestation.

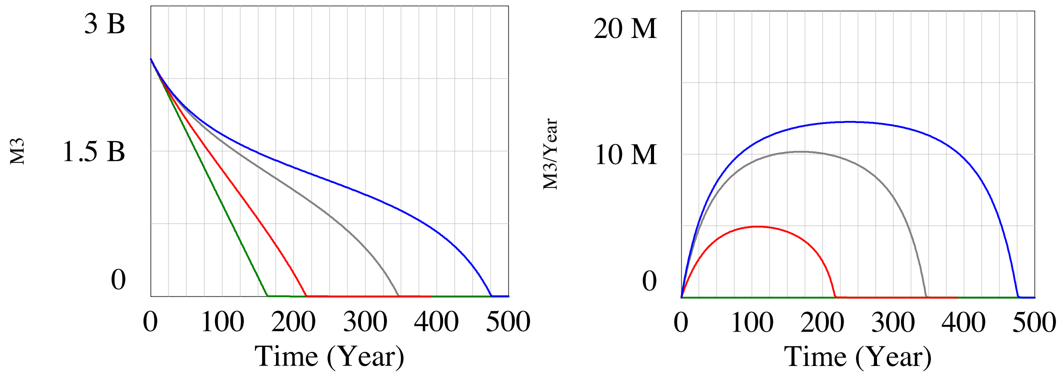

Figure 20: Development of *timber volume* stock (left pane) and the *net natural growth* rate (right pane) under conditions of constant harvest and varying mixes of selective and deforestation harvest.
Blue: selective harvest (same as 6.3.2); green: all harvest as deforestation, red: 50% of harvest through deforestation, grey: 10% of harvest through deforestation.

It can be seen that the initial deceleration and final acceleration of the decline (blue curve of 0% deforestation, discussed under 6.3.2) morphs into a straight green line for 100% deforestation. This means that with increasing deforestation-proportion, the compensating effect of the growth potential (discussed under 6.3.2) diminishes as can be seen in the right pane of Figure 20. That is reasonable, since the growth potential of the timber stock depends not only on the forest property *national annual timber increment*, but also on the amount of *forest land* area, which is decreasing.

Note also that with increasing percentages of deforestation, the effect on the time when the timber stock runs out decreases: on the decline of the timber stock decreases: The effect of a 50% deforestation compared to 10% is about the same than going from 0% deforestation to 10%, and increasing from 50% deforestation harvest to 100% is rather small compared to the former 50%.

Figure 21 shows that for 100% of the timber extraction being carried out as deforestation, the forest area declines linearly (green line left pane) due to the linear deforestation rate (green line right pane). The linear *deforestation* rate is caused by both the constant *timber extraction* rate and the constant *timber volume per ha*. In the 100%-deforestation-case for any m^3 of timber extracted, exactly the corresponding amount of forest is lost (according to the *timber volume per ha*), and thus the *timber volume per ha* stays constant (see green line in Figure 22). In other words, the *deforestation* rate and the *timber extraction* rate are co-flows.

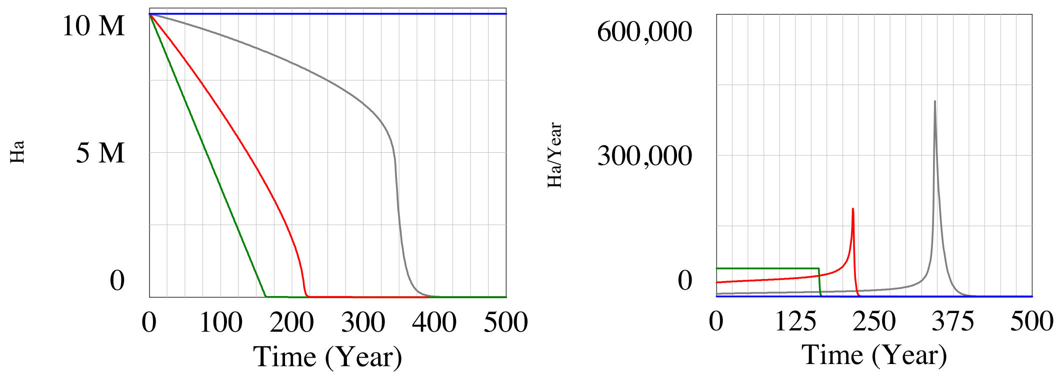

Figure 21: Development of the *forest land* area (left pane) and the *deforestation* rate (right pane) under conditions of constant harvest and varying mixes of selective and deforestation harvest.
Blue: selective harvest (same as 6.3.2); green: all harvest as deforestation, red: 50% of harvest through deforestation, grey: 10% of harvest through deforestation.

If however, there is a mix of deforestation and thinning, the *forest land* area initially decreases more slowly because part of the harvest is carried out as thinning and thus does not directly lead to deforestation. It suddenly decreases much more rapidly in the later years, though. The explanation can be found in the right panel of Figure 21: the *deforestation* rate has a sharp peak before the stocks run empty. That is because the amount of forest clear-cut needed to provide the constant deforestation-related harvest has to increase to compensate the decreasing *timber volume per ha*.

This decrease can clearly be seen in Figure 22. The variable is calculated from the two stocks, so for the no-deforestation case the curves in Figure 22 follow only the timber volume stock curve as the forest area is constant.

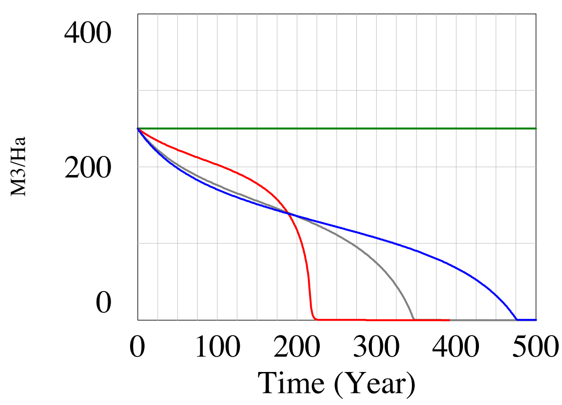

Figure 22: Development of the *timber volume per ha* under conditions of constant harvest and varying mixes of selective and deforestation harvest.
Blue: selective harvest (same as 6.3.2); green: all harvest as deforestation, red: 50% of harvest through deforestation, grey: 10% of harvest through deforestation.

In case of some degree of deforestation the development of the *timber volume per ha* is also influenced by the decline of the *forest land* area through the balancing feedback B2 in Figure 8: The decline of the *forest land* area initially compensates for the decline of the *timber volume* compared to the thinning-only case, so that the *timber volume per ha* decreases somewhat slower. In real-world-terms: Since some of the forest is clear-cut, the other remaining forest is thinned less than it would have been, had all the harvest been carried out as thinning (balancing feedback B2 in Figure 8). The later development is more rapid than the thinning-only case though, because the *timber volume* looses more and more of its reproductive potential (*net natural growth* inflow) due to the loss of the *forest land* area. The resulting faster decline of the *timber volume* over-compensates the falling *forest land* in the later years.

Figure 23 shows that the loss of the reproductive potential is not only due to the loss of forest land area, but also due to the loss of *national annual increment.* Initially it is decreasing only marginally because the *timber volume per ha* is only decreasing slowly and it decreases all the more rapidly as the latter variable accelerates its decrease (see Figure 22).

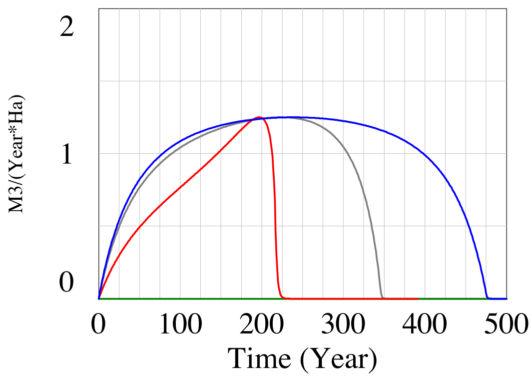

Figure 23: Development of the *national annual timber increment* under conditions of constant harvest and varying mixes of selective and deforestation harvest.
Blue: selective harvest (same as 6.3.2); green: all harvest as deforestation, red: 50% of harvest through deforestation, grey: 10% of harvest through deforestation.

The peak is getting thinner with increasing proportion of deforestation harvest because a linear increase of the harvest means that the *timber volume per ha* is first decreasing slower because deforestation releases the non-deforested part of the forest from some of the thinning (balancing feedback B2 in Figure 8). The decrease of the *timber volume per ha* after its peak is faster in for cases with deforestation (recall explanations for the more rapid decline in Figure 22 and look at the right pane in Figure 24).

Interestingly in Figure 23 though, the *national annual increment* still reaches the maximum of the blue curve (thinning-only case) at some point in time, but the amount of time it is near this maximum decreases. That is because while the *timber volume per ha* is decreasing it will always pass the value where the *national annual timber increment* is at its maximum as can be seen in the right pane of Figure 24.

The development of the national annual increment which looks rather complicated in the time series diagram in Figure 23 becomes much easier to understand when looking at phase diagrams as in Figure 24. It can be seen that the decrease of the *forest land* area reduces the *net natural growth* inflow. Note that unlike in Figure 17 and Figure 19, the two panes are not similar any more. While the *net natural growth* rate changes in response to the sinking *forest land* area, the *national annual increment* stays unaffected. The forest inherent ability to grow has not changed, all of the curves are congruent in the right pane.

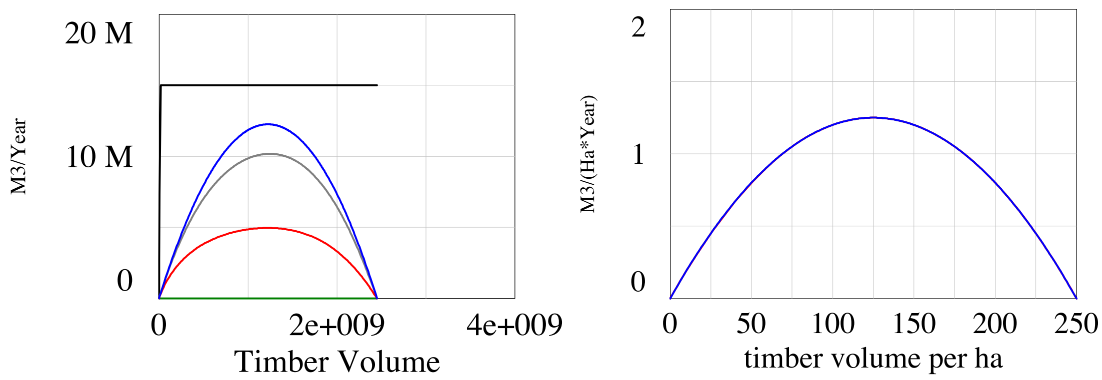

Figure 24: Phase diagrams of the *net natural growth* rate and the *timber extraction* rate as a function of the *timber volume* stock (left pane) and the *national annual increment* as function of the *timber volume per ha* (right pane) under conditions of varying mixes of selective and deforestation harvest.
Blue: pure selective harvest, green: all harvest as deforestation, red: 50% of harvest through deforestation, grey: 10% of harvest through deforestation, *timber extraction* rate (black). Note that all increment curves are congruent in the right pane.

6.3.6 Linearly increasing harvest with deforestation

In this section the case of a linearly increasing harvest visited under 6.3.3 is inspected again, but not only as pure thinning but also under different proportions of the harvest being carried out as thinning vs. deforestation.

When comparing Figure 25 with Figure 20 and Figure 26 with Figure 21 the differences are not very large in terms of the qualitative pattern. Due to the linearly increasing harvest the all curves of *timber volume* decline accelerates continuously instead of first in a decelerated manner. The reason is simply that the timber extraction is initially small and then increases. As a result the case of 100% deforestation (green) is not a line any more (const. harvest case) but a curve. The initially slower decrease of the *timber volume* however also implies that the *net natural growth* rate increases more slowly (weakening the growth limitation loop is initially slow) which is why the peaks of the curves are later in time. Again it can be seen that increasing proportions of deforestation limit the *net natural growth* rate until it vanishes for the 100% deforestation harvest since the *timber volume per ha* stays constant.

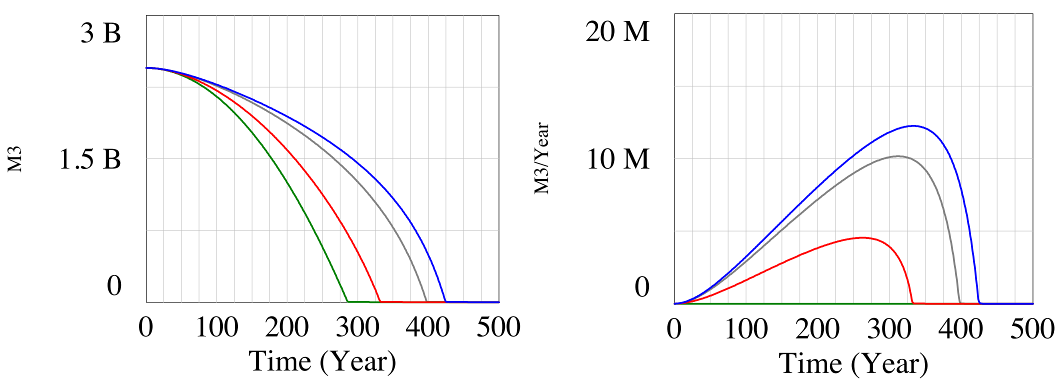

Figure 25: Development of *timber volume* stock (left pane) and the *net natural growth* rate (right pane) under conditions of linearly increasing harvest and varying mixes of selective and deforestation harvest.
Blue: selective harvest only, green: all harvest as deforestation, red: 50% of harvest through deforestation, grey: 10% of harvest through deforestation.

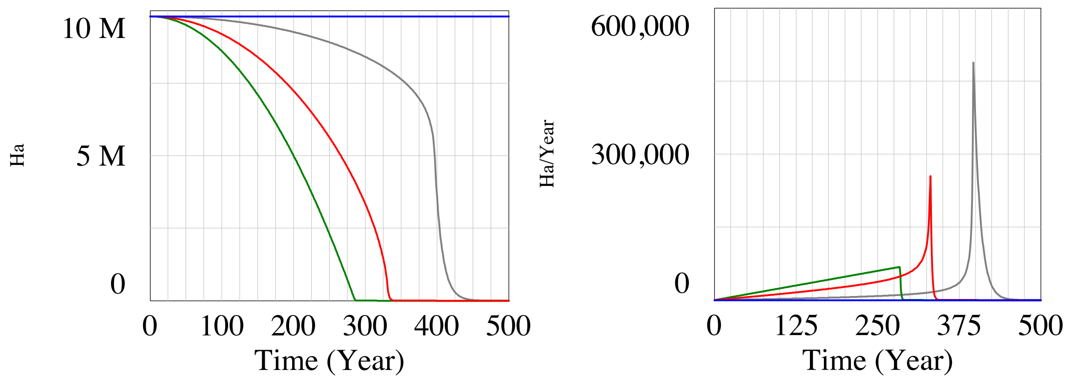

Figure 26: Development of the *forest land* area (left pane) and the *deforestation* rate (right pane) under conditions of linearly increasing harvest and varying mixes of selective and deforestation harvest.
Blue: selective harvest only; green: all harvest as deforestation, red: 50% of harvest through deforestation, grey: 10% of harvest through deforestation.

As should be expected the decline in *forest land* area (left pane of Figure 26) is now also a curve and not a straight line any more. The basic pattern of decline of the other curves (50%, 10% and 0% deforestation) differs qualitatively little from the constant harvest case, although also here the initially somewhat slower decline rate is notable.

Figure 27 shows that in comparison to the constant harvest case (Figure 23) the peaks of the *annual increment development* are thinner and skewed to later years. The reason is that the linear increase means that the release of the forest from the growth limitation loop B1 takes a longer time because the harvest is initially small, but it also means that in the later years the harvest will be larger than in the constant harvest case so that the decline is faster.

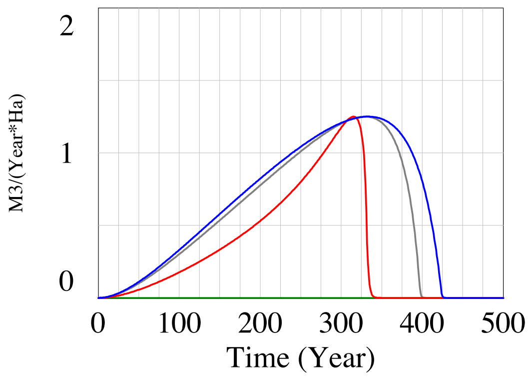

Figure 27: Development of the *national annual timber increment* under conditions of linearly increasing harvest and varying mixes of selective and deforestation harvest.
Blue: selective harvest (same as 6.3.3); green: all harvest as deforestation, red: 50% of harvest through deforestation, grey: 10% of harvest through deforestation.

When comparing the left panel of Figure 28 with the left panel of the constant timber extraction case (Figure 24) apart from the obvious change in the *timber extraction* rate curve, it can be seen that the curves with some degree of deforestation are not symmetrical any more, the peaks have moved to the left. When looking at the right pane it becomes clear that the maximum growth still happens at the same *timber volume per ha* but since as described above the *forest land* area initially sinks more slowly than in the constant area case, the same *timber volume per ha* will be reached at time when the *forest land* area is still higher but the *timber volume* is consequently lower.

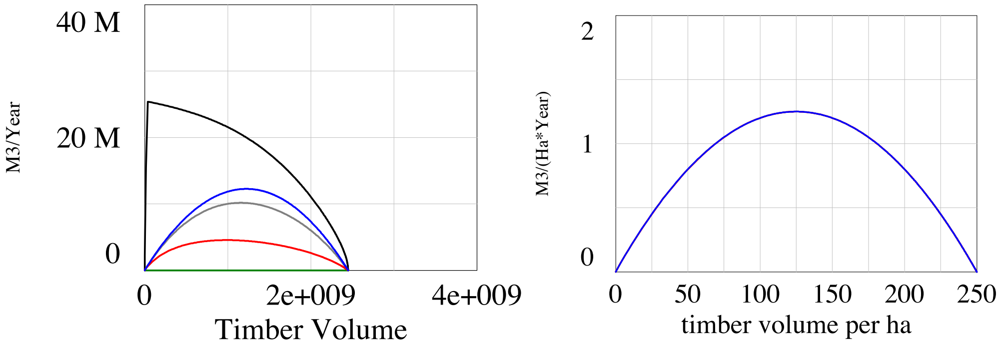

Figure 28: Phase diagrams of the *net natural growth* rate and the *timber extraction* rate as a function of the *timber volume* stock (left pane) and of the *national annual increment* as function of the *timber volume per ha* (right pane) under conditions of exponentially increasing *timber extraction* and varying mixes of selective and deforestation harvest.
Blue: pure selective harvest, green: all harvest as deforestation, red: 50% of harvest through deforestation, grey: 10% of harvest through deforestation, *timber extraction* rate (black). Note that all increment curves are congruent in the right pane.

6.3.7 Exponentially increasing harvest with deforestation

When looking at the development of the timber volume stock under conditions of exponential timber extraction with varying degrees of deforestation (Figure 29) it is striking that the degree of deforestation seems to hardly play a role. The exponential growth rate of the timber extraction relative to the growth rate of the resource matters: Recall that the timber fractional growth rate is 2% per year which means that at half the *maximum timber volume per ha*, the forest has its maximum timber growth rate at 1% per year (recall Equation 3). At any other *timber volume per ha* values, the growth rate of the resource is smaller than 1%. In other words if the timber extraction grows at 4%, the growth unleashed by the decreased timber stock is easily overcompensated by the harvest. From the point in time when the exponential growth picks up speed (ca. 300 years in this example) and thus first reduces the timber stock to release it from its competition, it takes only a short period of time until the *timber volume per ha* has sunk below the maximum growth rate. This can be seein in the right pane of Figure 29 which compared to the linear growth is "squeezed" thin. The growth reaches the same heights but for shorter period of time. The area under the growth curves is much smaller, which means that the total growth that can happen before the resource is depleted is much smaller.

Growth rates of population in developing countries can be expected to be high. The T21-Senegal model shows *total population growth rates* at 3% in the 1990s and even in 2008 it was still above 1%. In addition, economic growth is also fuelling timber extraction at *real GDP growth rates* fluctuating around 2 % - 3% heading for over 4% in future projections.

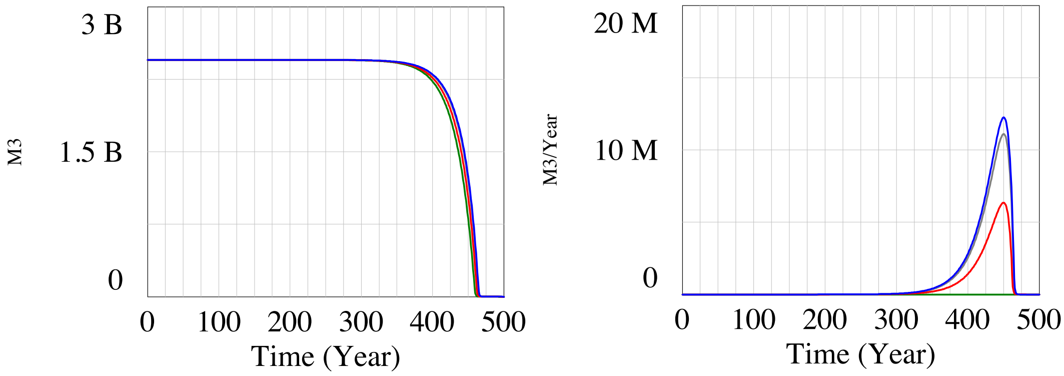

Figure 29: Development of *timber volume* stock (left pane) and the *net natural growth* rate (right pane) under conditions of exponentially increasing harvest and varying mixes of selective and deforestation harvest.
Blue: selective harvest only, green: all harvest as deforestation, red: 50% of harvest through deforestation, grey: 10% of harvest through deforestation.

Figure 30 shows a somewhat similar picture for the *forest land* area stock and its outflow. The proportion of timber extraction carried out as deforestation has a much weaker spreading effect on the trajectories of the *forest land* area than in the linear harvest case. Notably, due to the rapid decline of the *timber volume per ha*, the harvest rates not only peak at higher levels than for the linearly increasing harvest case, but are also much loser together. Note however that there is still more spread due in the curves than in the curves of the *timber volume*, because the strength of the exponential tendency of the *timber extraction* is only partially transmitted to the decline of the *forest land* area, depending on the proportion of deforestation.

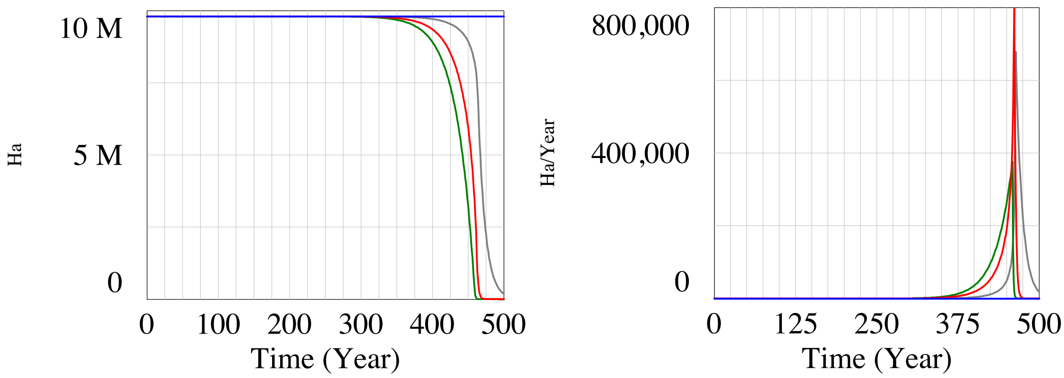

Figure 30: Development of the *forest land* area (left pane) and the *deforestation* rate (right pane) under conditions of exponentially increasing *timber extraction* and varying mixes of selective and deforestation harvest.
Blue: selective harvest only; green: all harvest as deforestation, red: 50% of harvest through deforestation, grey: 10% of harvest through deforestation.

When comparing the development of the *national annual increment* for the exponentially increasing harvest case in Figure 32 with the linearly increasing and the constant harvest cases (Figure 27, Figure 23 resp.), it becomes obvious that the peaks are even more narrow and even further towards later years. That is because the low initial value chosen here implies that the harvest is initially growing even slower than in the linear harvest case, but growing even faster in later years, hence the steep decline of the *national annual increment*.

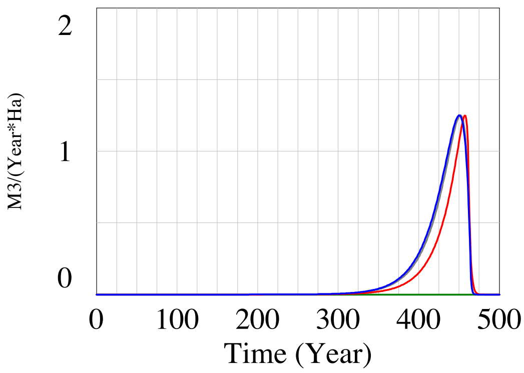

Figure 31: Development of the *national annual timber increment* under conditions of exponentially increasing harvest and varying mixes of selective and deforestation harvest.
Blue: selective harvest (same as 6.3.4); green: all harvest as deforestation, red: 50% of harvest through deforestation, grey: 10% of harvest through deforestation.

Interestingly, the phase diagram of the exponentially growing *timber extraction* case (left pane of Figure 32) show higher *net natural growth* rates for the same *timber volume* than in the linearly increasing case. The right pane of the same figure shows that the annual increment is exactly the same as for the linear growth case, hence the *forest land* area must still be higher at the same *timber volume*. This can be seen in Figure 33. To understand the reason, recall the higher spread in the curves of the *forest land* area decline for different proportions of deforestation than for the *timber volume*. For the linearly growing timber extraction case there is also a higher spread for the *forest land* area than for the *timber volume* but the spread differs more in the exponential growth case.

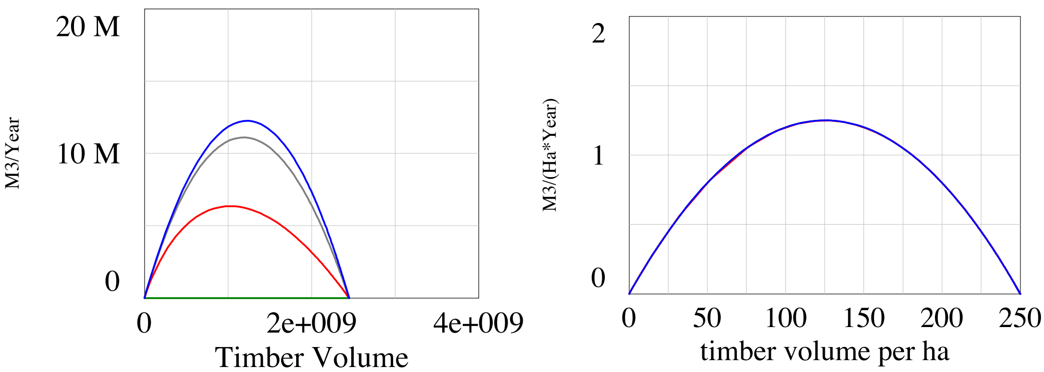

Figure 32: Phase diagrams of the *net natural growth* rate and the *timber extraction* rate as a function of the *timber volume* stock (left pane) and of the *national annual increment* as function of the *timber volume per ha* (right pane) all under conditions of exponentially increasing *timber extraction* and varying mixes of selective and deforestation harvest.
Blue: pure selective harvest, green: all harvest as deforestation, red: 50% of harvest through deforestation, grey: 10% of harvest through deforestation, *timber extraction* rate (black). Note that all increment curves are congruent in the right pane.

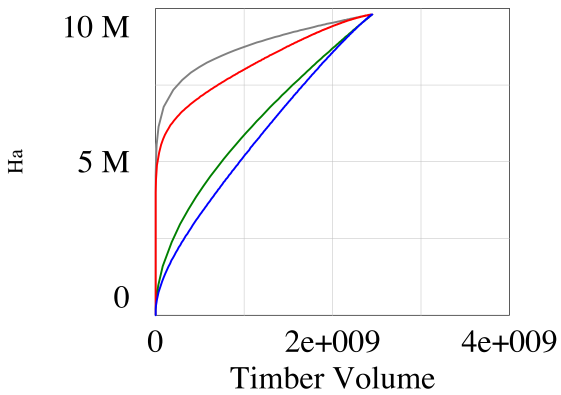

Figure 33: Phase diagram of the *forest land area* as a function of the *timber volume* for 50% of harvest through deforestation (blue and green curves for linear and exponential harvest respectively), and for 10% of harvest through deforestation (red and grey curves for linear and exponential harvest respectively)

6.3.8 Constant selective harvest with over-thinning

In the sections 6.3.2 to 6.3.4 we have considered a hypothetical case of purely selective harvest whereas in sections 6.3.5 to 6.3.7 we have considered some part of the harvest being carried out as clear cutting and have seen that this leads to forest area decline. But going back to the purely selective harvest case, the model produces a constant forest area. Even when all the timber is gone the forest area is still unchanged. That is clearly unrealistic. In reality, selective harvest may not be possible in very thinned forests any more since preferred species / diameters may no longer be available. Under such conditions harvest may become increasingly unselective, leading to deforestation in the vicinity of peoples dwellings.

In the model this is implemented as follows (see Figure 8): Not all of the harvest which is which does not lead to *direct deforestation* is only *intended thinning*, i.e. it is not automatically 100% thinning but there may instead be some *proportion of thinning leading to deforestation*. The amount of this deforestation is calculated as the product of this proportion with the *intended thinning* divided by the *timber volume per ha.* While one may argue that the actual density of the forest which is destroyed due to over-thinning is likely much lower (otherwise it would not be threatened by over-thinning), it is still necessary to use the average density, because otherwise the forest area stock including the deforestation outflows would also need to be disaggregated, which was omitted here, to keep the model at a reasonable aggregation level. The *proportion of thinning leading to deforestation* depends on the *relative timber volume per ha,* which expresses the degree to which the forest has already been thinned (degraded).

The *proportion of thinning leading to deforestation* is defined as a non-linear graph function. The based case is shown in Figure 34. This case is based on the assumption that thinning is likely to take place spatially heterogeneously: Some areas are thinned heavily (e.g. close to dwellings) while more remote places are initially thinned much less intensively and are therefore not yet threatened by over-thinning. It is assumed here that instead of disaggregating this through modeling several stocks of forest, this development can be aggregated on a national level by the a concave graph function. It indicates that selective harvest initially mostly just decreases overall density, hardly leading to any deforestation, but that as more and more forests are already very degraded, further thinning increasingly leads to deforestation.

As the exact curvature is unknown, the influence of a curvature where the effect kicks in at even lower forest densities (Figure 35) was explored in a sensitivity analysis. It implies that thinning is initially more homogeneous as in the based case and that the switch to non-selective harvest happens more abrupt and in a spatially more synchronized manner. As a limit-case (sensitivity & extreme condition test) it was also explored what a linear relationship would mean for the system (Figure 36). It implies that there is no hard switch from selective to non-selective harvest but that both happen at the same time, and progress over the land in a smooth manner, the selectivity of logging could be a very simple function of the distance to the resource for example, without any inconvenience threshold.

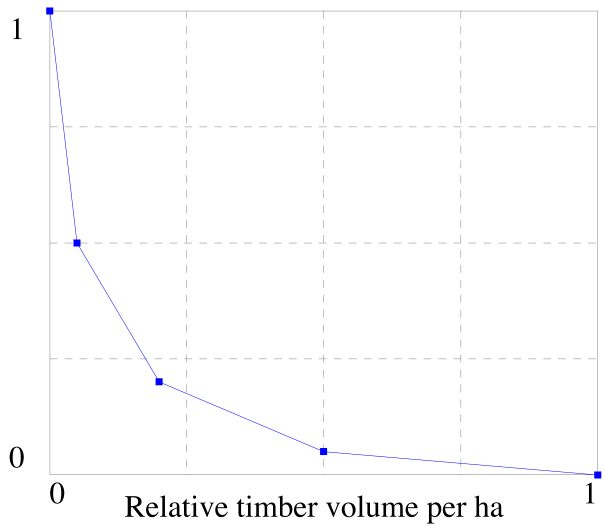

Figure 34: ***Proportion of thinning leading to deforestation*** **as a function of the** ***relative timber volume per ha*****, base case with moderate curvature**

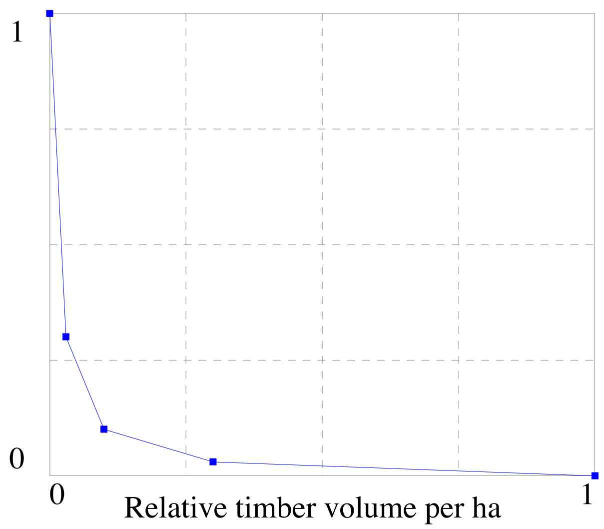

Figure 35: ***Proportion of thinning leading to deforestation*** **as a function of the** ***relative timber volume per ha*****, abrupt switch case with more extremely concave curvature**

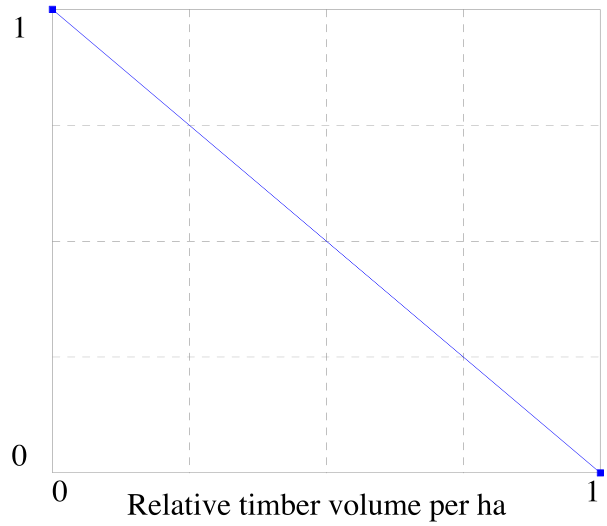

Figure 36: *Proportion of thinning leading to deforestation* as a function of the *relative timber volume per ha*, linear case with smooth transition from uniform thinning steadily increasing proportion of deforestation

As can be seen in the right pane of Figure 37 the behavior is as expected: the introduced over-thinning structure leads to a *forest land* area decline. The more concave the graph function of *proportion of thinning leading to deforestation*, the more there is a threshold before which the *forest land* area declines only slowly, but after which it suddenly declines rapidly, whereas in case of a linear graph function the transition is smooth. It can also be seen that the development of the *timber volume* is somewhat similar to normal direct deforestation (Figure 20) although over-thinning related deforestation will not lead to a linearly declining timber stock even in case of a linear graph function for *proportion of thinning leading to deforestation* since the *forest land* area is not decreasingly linearly in this case.

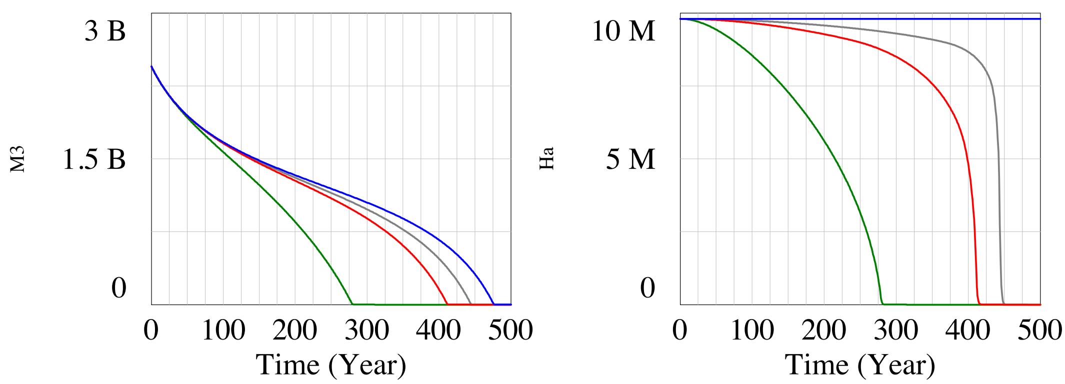

Figure 37: Development of the *timber volume* (left pane) and the *forest land* area (right pane) under conditions of constant harvest of 15 million m³ year⁻¹ and varying degrees of over-thinning.
Blue: no over-thinning (same as 6.3.2); grey: abrupt switch case (Figure 35), red: moderate base case (Figure 34), green: linear smooth transition case (Figure 36).

Furthermore comparing Figure 37 with Figure 21 it can be seen that over-thinning related deforestation takes effect much later than direct deforestation for concave graph function. This means that since in the beginning there is predominantly only thinning going on and very little over-thinning related deforestation, the timber density will fall faster as compared to a case where the forest area is also starting to fall early. Therefore the same *timber volume per ha* values will be reached at a point in time when the timber volumes are already lower. This explains why the curves with the more conca

The left panel of Figure 38 shows the familiar pattern of maximum growth being lower under conditions of deforestation since a smaller forest area implies smaller growth potential. It also shows that the curves are skewed towards high timber values and that this skew is smaller with decreasing concavity of the graph function. The skew can be understood by looking at the development of the *forest land* area: if the graph function is very concave, the forest area initially increases very little, which means that it is initially very close to the case without over-thinning, i.e. for high timber volumes the grey curve stays very close to the blue curve but then departs as the forest area starts falling. Since for a less concave graph function the forest area starts falling earlier, the red and the especially the green curve depart from the blue curve already at higher *timber volumes*. Another way too look at this is to recall the symmetric curves in Figure 24 are a case of constant *proportion of harvest as direct deforestation*, whereas in the case discussed here the analog, the *proportion of thinning leading to deforestation* is increasing with time. Hence we can construct the development discussed here as a gradual switching to lower and lower curves in Figure 24 while the timber volume is decreasing.

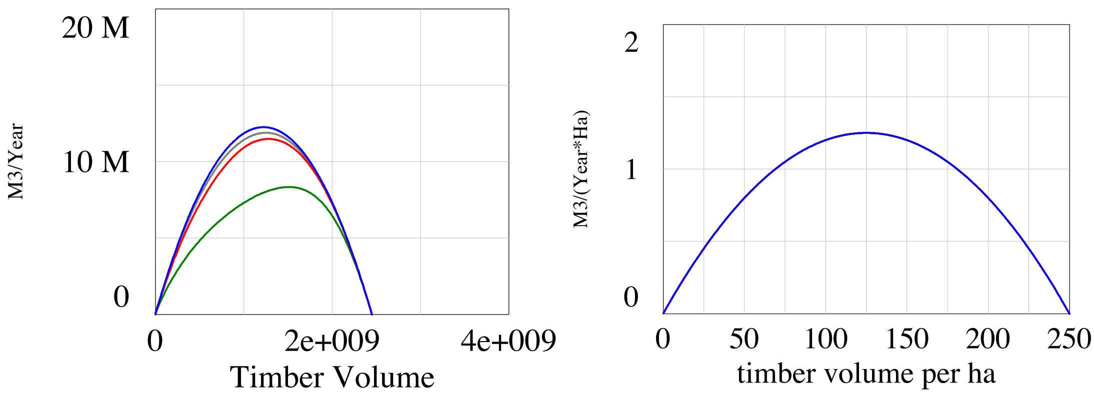

Figure 38: Phase diagrams of the *net natural growth* rate as a function of the *timber volume* stock (left pane) and of the *national annual increment* as function of the *timber volume per ha* (right pane) all under conditions of constant harvest of 15 million m³ year⁻¹ and varying degrees of over-thinning.
Blue: no over-thinning (same as 6.3.2); grey: abrupt switch case (Figure 35), red: moderate base case (Figure 34), green: linear smooth transition case (Figure 36). Note that all increment curves are congruent in the right pane.

Interestingly, it can again be seen in the right panel of Figure 38 that the relationship between the *national annual increment* and the *timber volume per ha* stays unaffected by over-thinning.

6.3.9 Constant harvest with different degrees of direct deforestation and over-thinning

In a realistic situation, it is likely that both direct deforestation and over-thinning are taking place. In the following we explore a situation where we again postulate a constant harvest of 15 million m^3 $year^{-1}$, and look at 10% and 50% direct deforestation and see what additional influence over-thinning has (moderate concavity of the graph function governing over-thinning, see Figure 34).

Figure 39 shows that even if there is only 10% direct deforestation the, the additional influence of over thinning on the *timber volume* development is not very large and for 50% direct deforestation it is hardly discernable. The influence on the development of the *forest land* area is somewhat larger as should be expected but again diminishes with increasing percentages of direct deforestation.

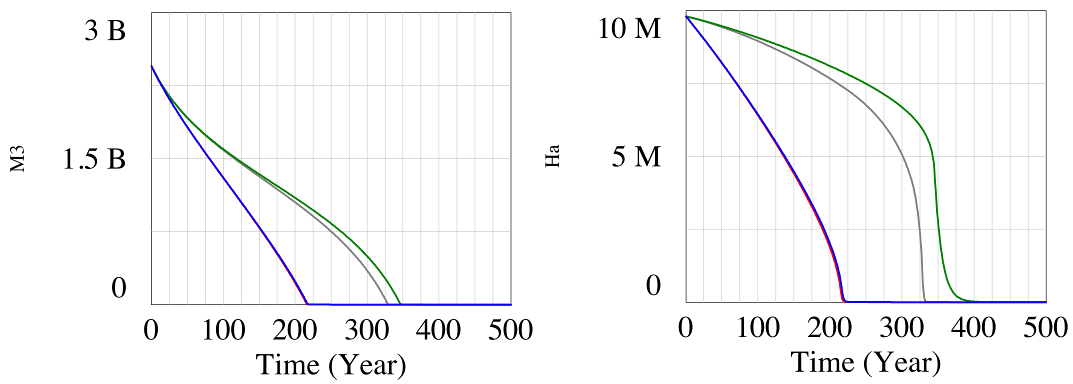

Figure 39: Development of the *timber volume* (left pane) and the *forest land* area (right pane) under conditions of constant harvest of 15 million m³ year⁻¹ and different degrees of direct deforestation with and without over-thinning.
Green: 10%direct deforestation, no over-thinning; grey: 10% direct deforestation and over-thinning; blue: 50% direct deforestation, no over-thinning, red: 50% direct deforestation and over-thinning

The same can be seen in the left pane of Figure 40, where the *net natural growth* rate differs only very little if the over-thinning structure is turned on, esp. for 50% direct deforestation. Notably again, even a combination of over-thinning and direct deforestation does not affect the relationship of the *timber volume per ha* and the *national annual increment* (right pane of Figure 40).

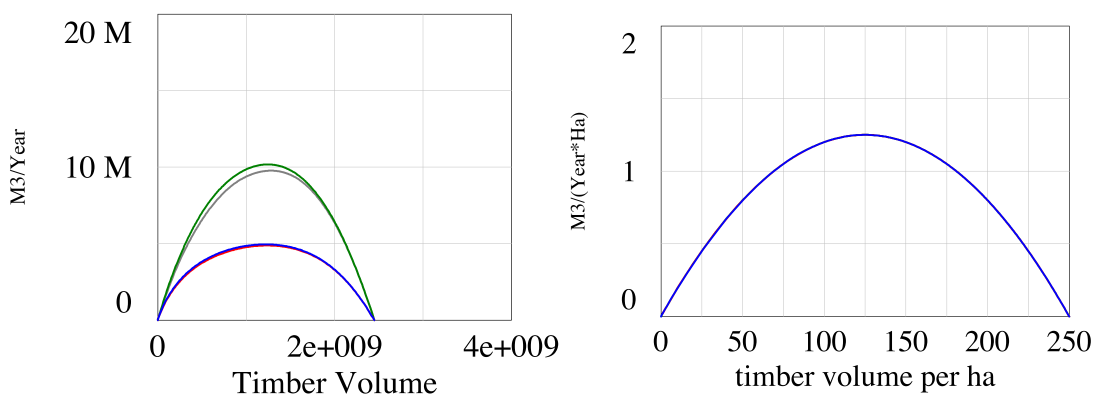

Figure 40: Phase diagrams of the *net natural growth* rate as a function of the *timber volume* stock (left pane) and of the *national annual increment* as function of the *timber volume per ha* (right pane) all under conditions of constant harvest of 15 million m³ year⁻¹ and different degrees of direct deforestation with and without over-thinning.
Green: 10%direct deforestation, no over-thinning; grey: 10% direct deforestation and over-thinning; blue: 50% direct deforestation, no over-thinning, red: 50% direct deforestation and over-thinning Note that all increment curves are congruent in the right pane.

While not all possible combinations can be displayed here it shall be noted that using the more extremely concave or the linear graph function governing over-thinning does not make a difference for high proportions of *direct deforestation* either (see Figure 41). For low proportions of *direct deforestation* (10% see Figure 42) however, the linear graph function (Figure 36) would speed up deforestation considerably.

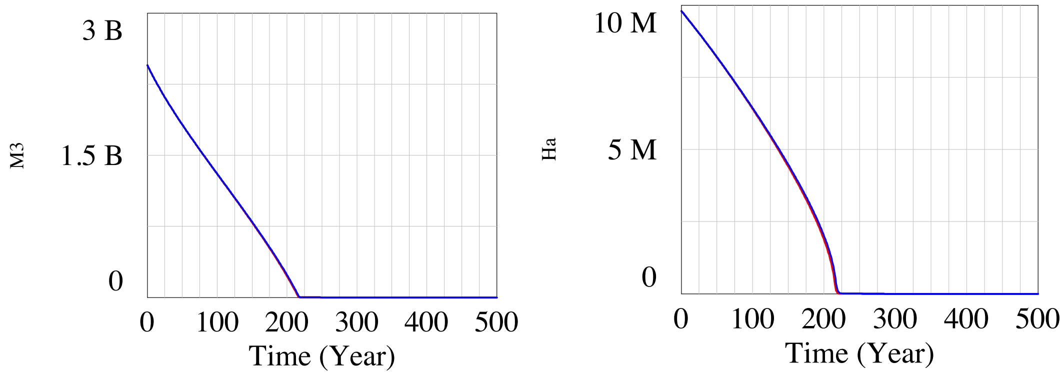

Figure 41: Development of the *timber volume* (left pane) and the *forest land* area (right pane) under conditions of constant harvest of 15 million m^3 year^{-1} and 50% direct deforestation and different concavities of the graph function *proportion of thinning leading to deforestation*.
Blue: no over-thinning, green: abrupt switch case (Figure 35), red: moderate base case (Figure 34), grey: linear smooth transition case (Figure 36).

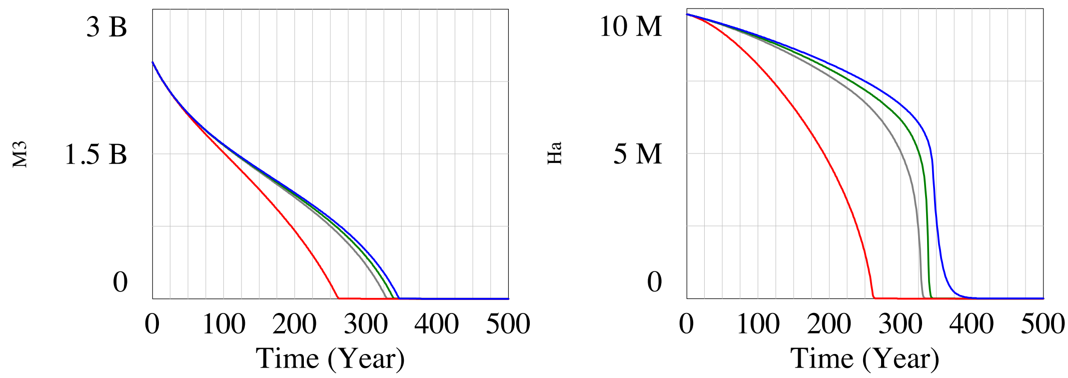

Figure 42: Development of the *timber volume* (left pane) and the *forest land* area (right pane) under conditions of constant harvest of 15 million m^3 year^{-1} and 10% direct deforestation and different concavities of the graph function *proportion of thinning leading to deforestation*.
Blue: no over-thinning, green: abrupt switch case (Figure 35), grey: moderate base case (Figure 34), red: linear smooth transition case (Figure 36).

Hence it can be concluded that the somewhat concave graph functions i.e. a situation where over-thinning-related deforestation takes effect only in later phases of development once a threshold of forest degradation has been reached, hardly play a role even if there is a low degree of direct deforestation. Only if the way that the over-thinning-related deforestation takes effect gradually (at or close to linear graph function, Figure 36) and the direct deforestation is very low is could the over-thinning-related deforestation have as strong or stronger an influence than the direct deforestation.

6.3.10 Linearly & exponentially increasing harvest with over-thinning

Lastly it is now explored what influence over-thinning would have on a linearly increasing or an exponentially increasing timber extraction would have. For this analysis we choose the case of 0% direct deforestation and the moderate concavity of the graph function governing the over-thinning (Figure 34). We use the same harvest inputs as previously, i.e. a linear growth rate of 60,000m^3 $year^{-2}$ for the linearly increasing harvest starting at 0 m^3 $year^{-1}$, and an exponential growth rate of 4% $year^{-1}$.

The results are shown in Figure 43 and Figure 44. The timber volume development is hardly affected by over-thinning, in the linearly increasing harvest case and not at all in the exponentially increasing harvest case.

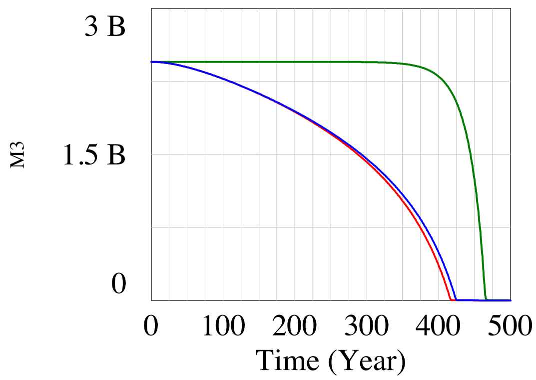

Figure 43: Development of the *timber volume* (left pane) and the *forest land* area (right pane) under conditions of 0% direct deforestation and the moderate concavity of the graph function governing the over-thinning (Figure 34).
Blue: linearly increasing harvest without over-thinning; red: linearly increasing harvest with over-thinning; green: exponentially increasing harvest without over-thinning, grey: exponentially increasing harvest with over-thinning. Note that the green and grey line are congruent in the left pane and the blue and the green line are congruent in the right pane.

That is not surprising given that:

a) we found already under 6.3.5, 6.3.6 and 6.3.7 that under conditions of linear harvest the spread of the timber volume trajectories is smaller than in the constant harvest case and that the spread is even smaller for the exponentially increasing harvest case and that

b) we found under 6.3.9 that the direct deforestation has a much stronger influence on the development of the stocks than the over-thinning-related deforestation even for moderate degrees of deforestation.

Hence the influence spread caused by over-thinning vs. no over-thinning should be even smaller than the spread caused by different degrees of deforestation, which is precisely the case.

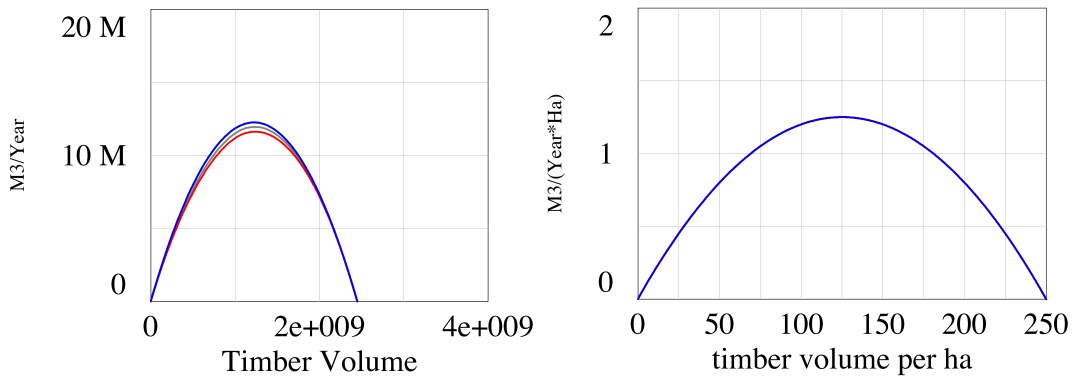

Figure 44: Phase diagrams of the *net natural growth* rate as a function of the *timber volume* stock (left pane) and of the *national annual increment* as function of the *timber volume per ha* (right pane) under conditions of 0% direct deforestation and the moderate concavity of the graph function governing the over-thinning (Figure 34).
Blue: linearly increasing harvest without over-thinning; red: linearly increasing harvest with over-thinning; green: exponentially increasing harvest without over-thinning, grey: exponentially increasing harvest with over-thinning. Note that all increment curves are congruent in the right pane.

It is important to note that an important variable used for the calculation of the biocapacity the *national annual increment* can be determined solely by measuring the forest density (*timber volume per ha*) and by knowing the shape of the relationship between two variables, which should not be influenced by any other part of the system.

6.3.11 Zero cut-off value

For some simulations a numerical instability appeared which could not be solved by shortening the time step of the simulation or changing the integration method (see Figure 45). That is because it is rooted in the unavoidable truncation errors when calculating and storing variables in Vensim. The simulation investigated here involves a linearly increasing harvest (60,000 m^3 $year^{-2}$), 100% deforestation. The issue concerns the *relative timber volume per ha*. Under conditions of 100% deforestation this value should always be equal to one, since when the *timber volume* is reduced by a certain amount, a corresponding amount that is calculated using the *timber volume per ha* is taken out of the forest land area stock. Since therefore the two stocks are sinking in corresponding speeds to one another, the *timber volume per ha* should stay at exactly one. Since the software however has to truncate the values for both the *timber volume* and the *forest land* stock, the calculated ratio of the two may slightly diverge from 1. Therefore the model would produce an annual increment and a growth-inflow which are not equal to zero as they should be. While in the example below this led to fluctuations in of negligible size, some these errors were amplified in some of the tested structures (not all of which are discussed here) and led to more serious problems. As a precaution of this issue causing trouble in the simulations ahead, the solution was retained in the model.

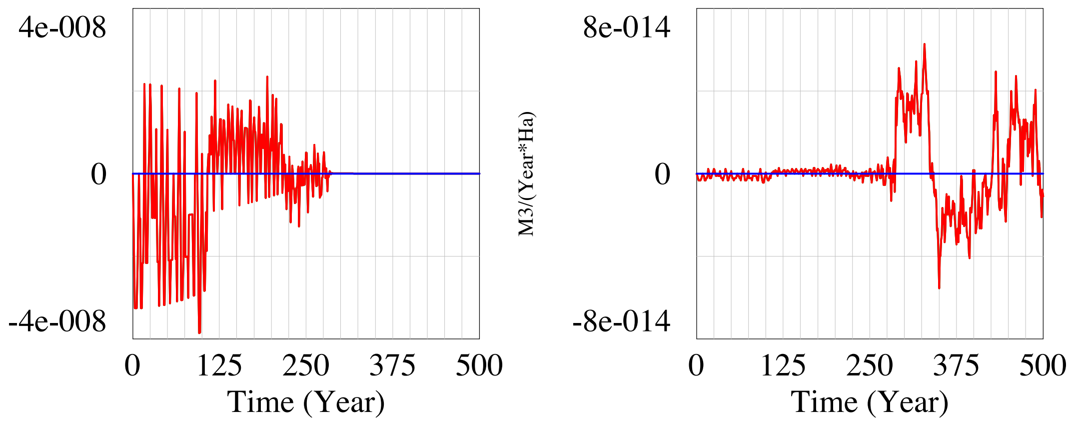

Figure 45: Numeric instability problem with (blue) and without (red) use of the *zero-cut-off-value* solution. Left pane: *net natural growth*, right pane *national annual increment.*

The solution applied here involves forcing the value of the *timber volume per ha* to be equal 1, whenever its calculated value falls below a threshold distance from 1, which is specified in the *zero-cut-off value* using an if-then-else function. The value was determined by calibration (starting at a very small value which was increased until the fluctuations vanished).

6.3.12 Implications of dynamic annual increment for the forestry footprint of production and forest biocapacity (simplified core model)

The core model provides two important inputs for the calculation of the BC the *national annual increment* and the *forest land* area for the. The *timber extraction* rates which are used for the calculation for the EF were simply hypothesized for the above analysis of the core model but have an influence on how the BC develops through the dynamics of the core model. It is however necessary to explore these possible harvests to gain an understanding of how the dynamics of the EF and the BC play out over longer time spans, because the T21-Senegal-EFf1 only simulates from 1980 to 2035, which although being a long time horizon for human planning is still short for forestry dynamics.

Notably, the GFN accounting methodology works with a constant *national annual increment* due to lack of data on time series of this variable. The developments of the core model provide an opportunity to explore the implications of using a constant versus a dynamic variable. Hence in the following the core model is attached to a simplified EF&BC calculation model sector, which concerns only the forestry footprint of production (thus excluding the EF trade balance) and the BC (see Figure 46).

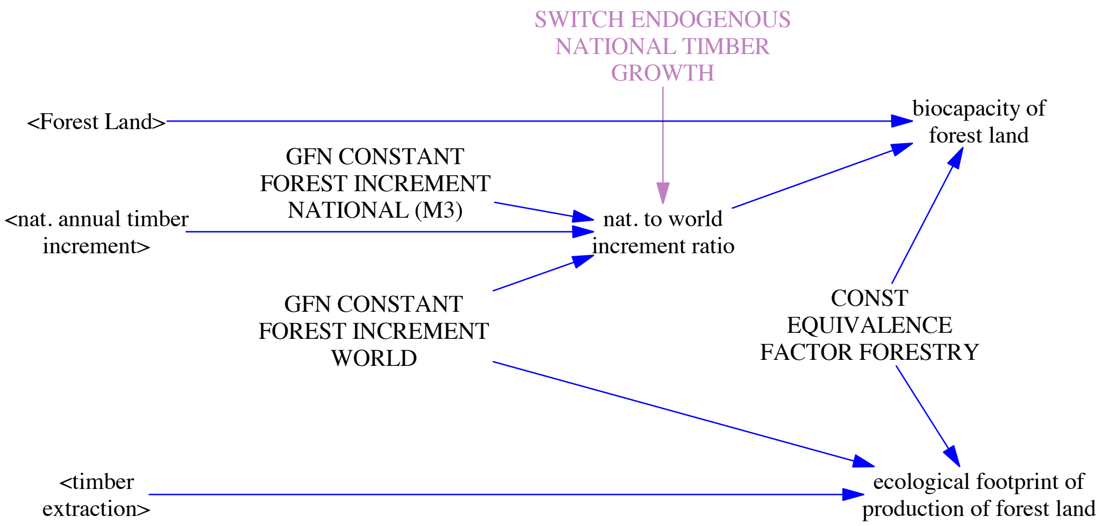

Figure 46: Model diagram of the simplified calculation sector for the EF / BC that was attached to the simplified core model. Note that the *equivalence factor forestry* is assumed constant and the model can be switched between constant exogenous annual increment and endogenous variable annual increment. The values in <x> are derived from the core model.

Since the time series data for the *equivalence factor* used for the simulations with the full new model (hereafter T21-SenegalEFf1) spans only from 1980 to 2035, an average equivalence factor of these years is applied here (1.262492685 Gha/Wha). The standard deviation of this average is only about 0.7%, so that for the sake of the following argument the average value should suffice here.

Figure 47, Figure 48 and Figure 49 show that the EF is not influenced by switching to a dynamic annual increment. That is not surprising because for forestry the *national annual increment* cancels out in the calculation of the EF and thus does not have any influence. Only the world forest increment is used, which is assumed to be constant here.

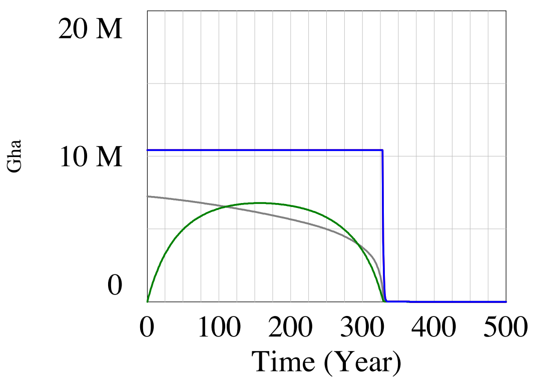

Figure 47: Implications of dynamic annual increment for the forestry footprint and the biocapacity, constant harvest case.
***Forestry footprint of production* with *national annual increment* being: endogenous dynamic (blue), constant (GFN-value, red). *Biocapacity of forest land* with *national annual increment* endogenous being dynamic (green), constant (GFN-value, grey). Harvest at 15 million m^3 $year^{-1}$.**

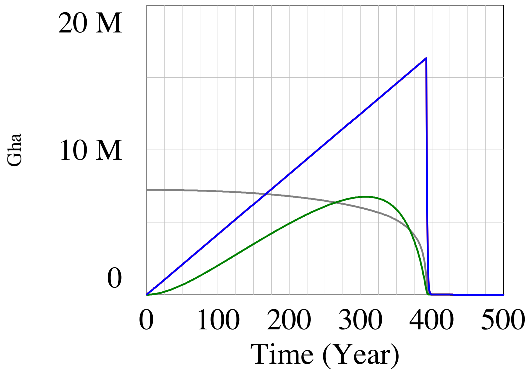

Figure 48: Implications of dynamic annual increment for the forestry footprint and the biocapacity, linearly increasing harvest case.
Forestry footprint of production with national annual increment endogenous dynamic (blue) and constant (GFN-value, red). Biocapacity of forest land with national annual increment endogenous dynamic (green) and constant national annual increment (GFN-value, grey). Harvest at starting at 1 m^3 $year^{-1}$ and increasing by 60,000 m^3 $year^{-2}$.

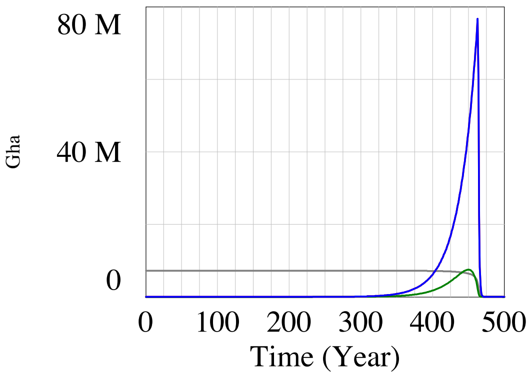

Figure 49: Implications of dynamic annual increment for the forestry footprint and the biocapacity, exponentially increasing harvest case.
Forestry footprint of production with national annual increment endogenous dynamic (blue) and constant (GFN-value, red). Biocapacity of forest land with national annual increment endogenous dynamic (green) and constant national annual increment (GFN-value, grey). Harvest at starting at 1 m^3 $year^{-1}$ and increasing at a fractional rate of 4% $year^{-1}$.

For the development of the BC on the other hand it makes a strong difference whether a constant exogenous or a variable endogenous *national annual increment* is used. Figure 47, Figure 48 and Figure 49 show that using the dynamic *national annual increment* the BC first increases starting at a very low value and then decreases, whereas when using the constant *national annual increment* the BC starts at a quite high value and then decreases. The two curves do not differ in the time that the BC reaches zero. The reason for the difference is that when using the constant *national annual increment* the BC traces the development of the *forest land* area, because, because the latter is the only variable influencing it. And under conditions of deforestation (even if only 10% as in this example), the BC must decrease since the forest is decreasing. If using the dynamic *national annual increment* the BC is also dependent on this second variable, it traces the shape of the *net natural growth* curves. And as we have seen above, if we assume that in pre-modern times when human populations were low forests were at their maximum densities, the annual increment must initially be very low. Only once the forest is released from the internal competition by decreasing the density, will the annual increment increase. Hence from a forest management perspective a certain degree of thinning can increase productivity, which is a well-known fact in countries where sivicultural practices have a long tradition such as Scandinavia and Germany. It is important to note, that would be a one-dimensional since it has been shown in these countries that some state variables such as biodiversity may decline when such measures to raise productivity are carried out.

When assessing the sustainability of forestry using the EF&BC concept graphs like the figures above with the BC and the EF are used. An important criterion is the intersection point where the EF surpasses the BC.

Figure 47, Figure 48 and Figure 49 show however, that when using the dynamic annual increment, there is no such intersection point. The EF footprint larger than the BC from the very beginning. If the harvest and therefore the EF keeps increasing at the same constant or even exponential rate, the increasing BC has no chance to catch up with it. That is because the increase of the BC is caused by the harvest but it with a delay caused by the *timber volume* stock: only once the stock has decreased by a notable amount does the BC increase notably. In other words: initially the removal of 1m^3 of timber causes much less increase in the BC than in at the point where the *timber volume per ha* is already lower.

A Sustainable forestry system

One important question from a management perspective would be: what needs to happen to make the system sustainable. Firstly, the harvest needs to be below the systems ability to regrow. Figure 50 shows such a development: It is initially exponential due to the exponential development of its drivers but then the timber extraction is stabilized at a level within the systems capacity to grow (here 8 million m^3 year^{-1}).

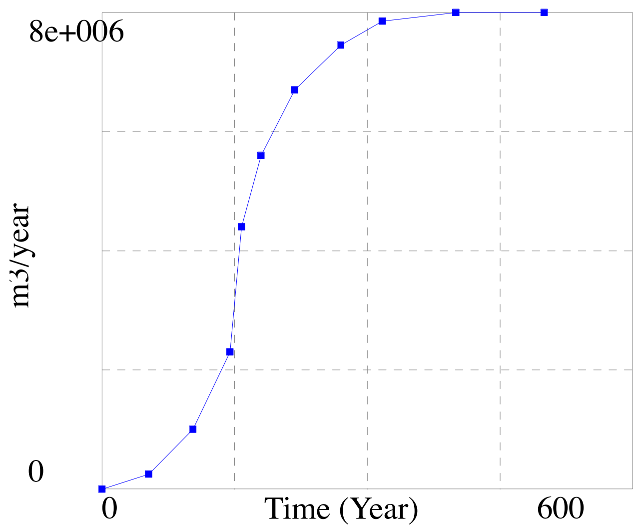

Figure 50: Hypothesized desirable development of the *timber extraction* rate, as a prerequisite for sustainability (implemented as a graph function in the model)

As the forest in Senegal does not spread, the deforestation needs to be gradually reduced to zero (proportion of harvest as deforestation was assumed to be decreasing from 0.5 to 0 as shown in Figure 51.

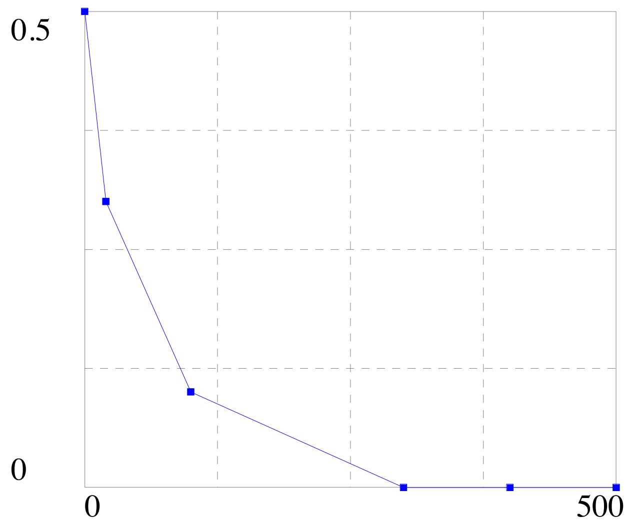

Figure 51: *Proportion of harvest as deforestation* gradually decreasing to zero as prerequisite for sustainability

This is also important as we have seen that the deforestation reduces the forests potential to regrow, so the more deforestation progresses, the lower the future sustainable selective harvest may be. Importantly, not only the *direct deforestation* needs to be halted but also the *deforestation due to over-thinning*. In other words the graph function *proportion of thinning leading to deforestation* needs to be at zero for a large range of densities (Figure 52).

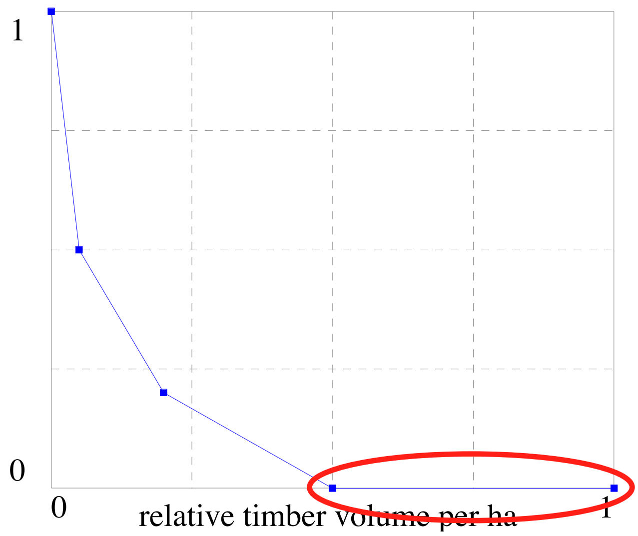

Figure 52: *Proportion of thinning leading to deforestation* =0 for a large range of values of the *relative timber volume per ha* (red oval) as prerequisite for sustainability.

In real world terms this means that the spatial harvest pattern needs to be altered so that thinning happens in a more uniform manner all over the country. This is naturally easier to achieve at high *timber volume per ha* values. Therefore it is not only important that harvest is smaller than regrowth but it is also important that this equilibrium is reached early because the later it is reached the lower the forest density and consequently the harder it would be to solve the over-thinning problem. If the graph function was strongly concave, the initially small deforestation due to over-thinning could also be counteracted by a relatively small reforestation inflow (e.g. by fencing out animals to let forest regrow). But again this would only work if deforestation would stop and thinning would reach equilibrium with regrowth early, when the *timber volume per ha* is still relatively high. Once the threshold point is passed, no reforestation could stop the deforestation due to over-thinning.

Figure 53 shows that the forestry system with the above described specifications indeed becomes sustainable, both stocks stabilize.

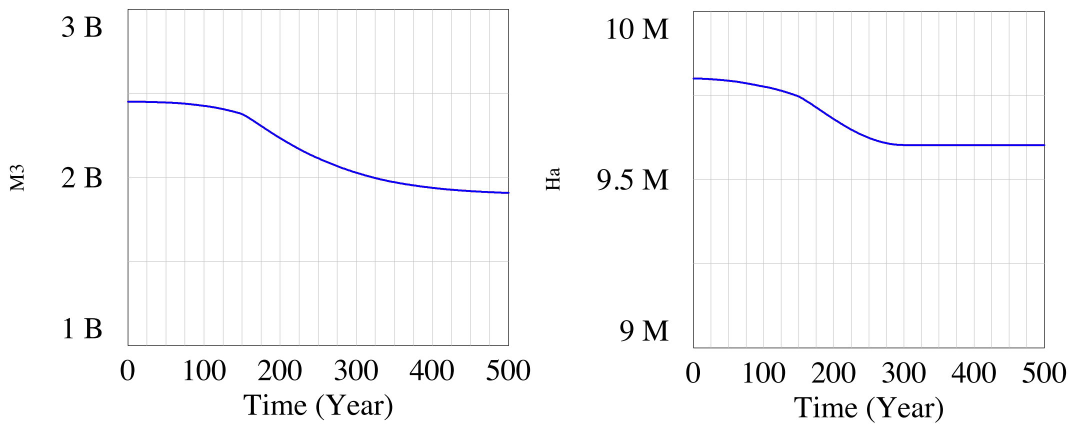

Figure 53: : Development of the *timber volume* (left pane) and the *forest land* area (right pane) under conditions of the *timber extraction* rate specified in Figure 50, proportion harvest as deforestation as specified in Figure 51 and proportion of thinning leading to deforestation as specified in Figure 52.

The EF and BC corresponding to this sustainable case can be seen in Figure 53. The BC which was derived from both the *forest land* area and the endogenously modeled *national annual increment* rises up to meet the stabilizing EF. That is because the EF is a converted outflow from the *timber volume* stock (*timber extraction*) and the BC is a converted inflow to the *timber volume* stock (*net natural growth*). And the stock can only be in equilibrium (i.e. in a sustainable state) if its flows sum to zero. When looking at the BC that was derived from the forest land, using a constant average *national annual increment*, the two curves do not meet, which is a violation of that principle. If that BC was correct, the timber stock should be expanding since its inflow would be greater than its outflow.

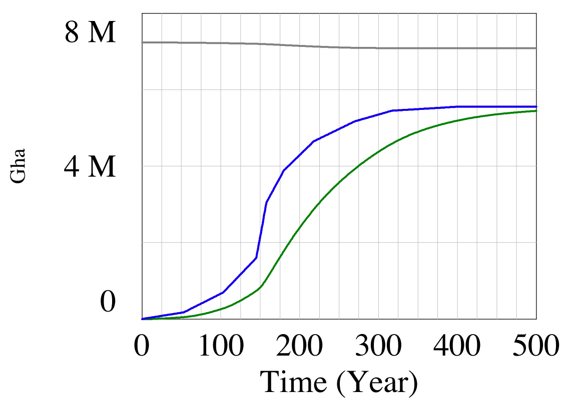

Figure 54: Implications of dynamic annual increment for the forestry footprint and the biocapacity, sustainable case.
Forestry footprint of production (blue) Biocapacity of forest land with national annual increment endogenous dynamic (green) and constant national annual increment (GFN-value, grey).

If the assumption that the forest was initially at its maximum *timber volume per ha* is relaxed (e.g. on the grounds that large wild herbivores were keeping it down which is not unreasonable in Africa), the dynamics could be even more complex (see Figure 55, showing a situation where the *initial timber volume per ha* is only 150 m³ ha⁻¹.

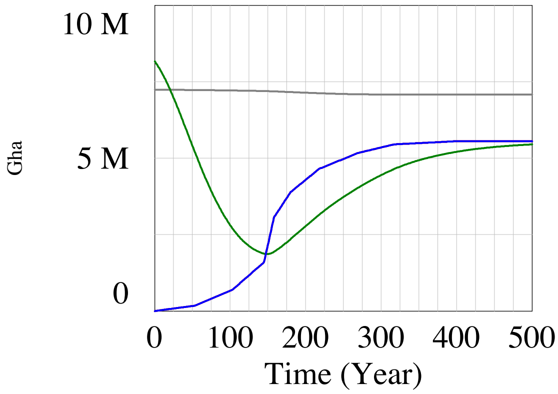

Figure 55: Implications of dynamic annual increment for the forestry footprint and the biocapacity, sustainable case but starting with an *initial timber volume per ha* smaller than the *maximum timber volume per ha*
(150 m^3 ha^{-1}, 250 m^3 ha^{-1} respectively). *Forestry footprint of production* (blue) *Biocapacity of forest land* with *national annual increment* endogenous dynamic (green) and constant *national annual increment* (GFN-value, grey).

The Biocapacity is initially very high due to the high *national annual increment* which results from the fact that the *relative timber volume per ha* is initially at 0.6 which is fairly close to its value for the maximum national annual increment (0.5). Since the harvest is initially small, but the other factor that reduced the forest density to 0.6 (like the large wild herbivores) was removed, the *timber volume* rises, which makes the *net natural growth* decrease until the *timber extraction* rate is risen beyond the *net natural growth*. At that point the *timber volume* peaks and starts sinking again. This sinking timber volume stimulates *net natural growth* so that the BC starts increasing again. Since the forest area was only reduced by a relatively minor amount, it does not have much influence on the BC development. Contrary to this counterintuitive development of the BC using the endogenously derived *national annual timber increment*, the grey line signifying the development of the BC when using only the constant exogenous GFN *national annual increment*, shows hardly any change at all (because the forest area does not change much). This shows what scale of potential difference can exist between the exogenous and the endogenously derived *national annual increment.*

Limitation of the Simplified core model:

The above analysis has one conceptual errors that was only discovered too late into the project to do all the analysis again: It doesn't make sense to start the simulation with the forest area and timber volume of 1980, both should start much higher. This should however not influence the principal pattern of the development of the trajectories but the values for the timber and forest land stocks and the speeds of change may be quite a bit off.

6.4 Timber demand sector

6.4.1 Firewood and charcoal demand

Firewood- and charcoal demand in reaction to butanzation campaign

The purpose of this sector is to derive the main input to the EF, the timber harvest data. As explained in section 5.2.1, timber harvest has to be expressed in solid m^3 for calculation of the EF. In T21-Senegal34 (see Figure 7) wood demand had two components "deforestation for firewood" and "deforestation for charcoal". As the terminology seemed a bit confusing since they are both in units of kg/year they are have been renamed *firewood-demand (air-dry kg)* and *charcoal demand* in T21-SenegalEFf1 (see Figure 56).

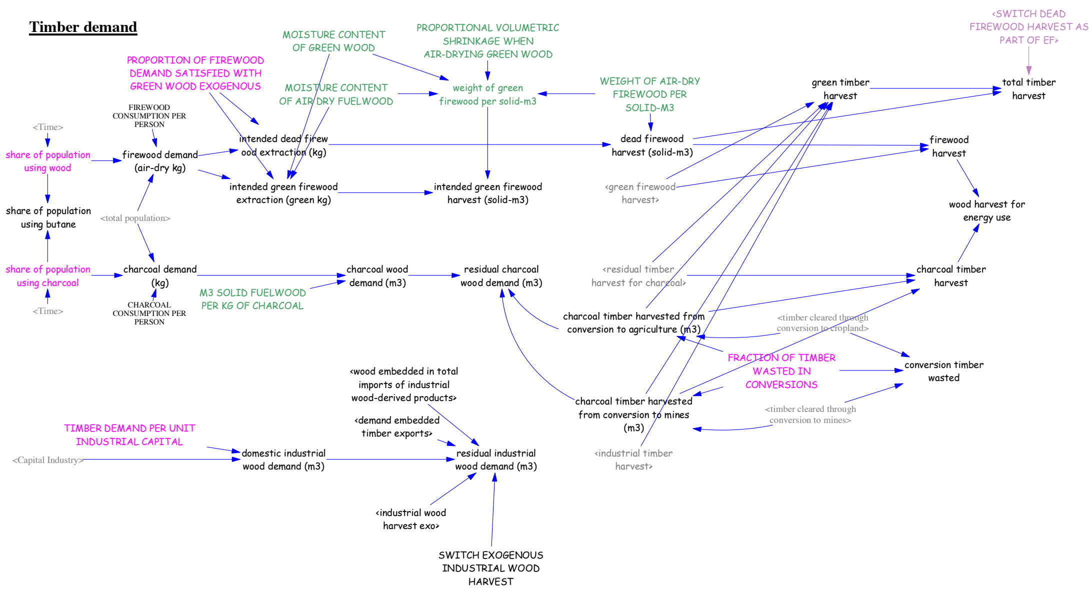

Figure 56: Timber demand sector
Parameter values based on literature sources in green, parameters based on assumptions only in pink, switches in light purple. Variables derived form other model sectors carry < >, variables in Times New Roman were taken unchanged from T21-Senegal34, variables in Comic Sans MS were added or modified in this project. Please zoom in for details.

The derivation of these variables has remained almost unchanged in T21-SenegalEFf1: They are respectively determined by the *firewood consumption per person,* the *charcoal consumption per person* and the share of the population using these fuels. Note that the variables "share of population heating with wood / -charcoal" have been renamed *share of population using wood / -charcoal* since in such a warm country fuel is used for cooking not heating). These shares have been sinking due to a campaign and incentives to make the population switch to liquid petroleum gas / butane as cooking fuel (Ministere De L'economie, Des Finances Et Du Plan - Direction De La Prevision Et De La Statistique, 1997; Ministere De L'economie, Des Finances Et Du Plan - Direction De La Prevision Et De La Statistique, 2004)..

Correction of 1980 values of charcoal and firewood demand

For the variables *population using wood / -charcoal past*, the value for the year 1980 did not pass a parameter verification test: the two shares (0.622, 0.392) were adding up to more than one. The data sources that were used for T21-Senegal34b (Ministere De L'economie, Des Finances Et Du Plan - Direction De La Prevision Et De La Statistique, 1997; Ministere De L'economie, Des Finances Et Du Plan - Direction De La Prevision Et De La Statistique, 2004) contain two data points 1995 and 2004. The rest of the data series was estimated and it does not show the kind of pattern that one would expect from a diffusion process (S-shaped growth of the butane percentage, see Figure 57).

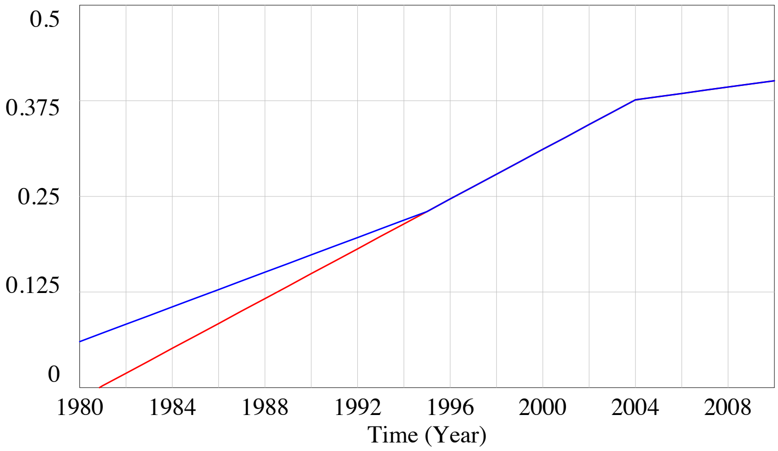

Figure 57: Development of the *share of population using butane.*
Former T21-Senegal34b (red) and new model T21-SenegalEFf1 (blue). Note that from 1995 the two lines are congruent and that the new curve is more S-shaped.

Since the butanization program actually started in 1974 (Devotta & Asthana, n.d.) there should already be some degree of butane use in 1980, and assuming an S-shaped growth this value was assumed to have been 6%. The new values for *population using wood past / -charcoal past* in 1980 were assumed to be 0.58 and 0.36, respectively. The resulting developments of these exogenous variables can be seen in Figure 58. Note that the new curves are more S-shaped.

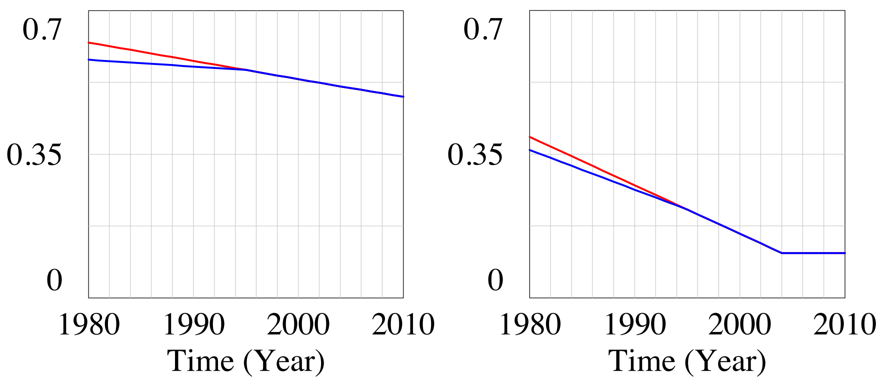

Figure 58: Development of th *share of population using wood* (left pane) and *share of population using charcoal* (right pane).
Former T21-Senegal34b (red) and new model T21-SenegalEFf1 (blue). Note that from 1995 the two lines are congruent

Sensitivity analysis different future scenarios of wood and charcoal demand

Since the influence of butanization is implemented as exogenous data input, future projections have to rely on made-up scenarios. It is important to test how much the results (EF and BC) will differ under different plausible scenarios. (Thomas, Touré, & Sokona, 2003) states that subsidies on butane were necessary to convince people to switch from charcoal to butane and that these were gradually reduced over the years and were supposed to be eliminated in 2002 (not confirmed that this happened). A sensitivity analysis explores scenarios where

a) No-subsidy scenario: butanization will not continue without subsidies-> *share of population using wood* constant after 2010 (charcoal is stable any way)

b) Peak-fossil scenario: an extreme case where people switch back to wood / charcoal (50% wood and 50% charcoal used in 2035 with a linear development from 2010, due to rising world market prices for fossil fuels incl. butane.

To this end, the variables share of *population using wood / -charcoal* are turned into graph functions to facilitate sensitivity analysis with respect to different future scenarios. They were formerly fed by two exogenous data variables each (one for the past and one for future development) which have been deleted.

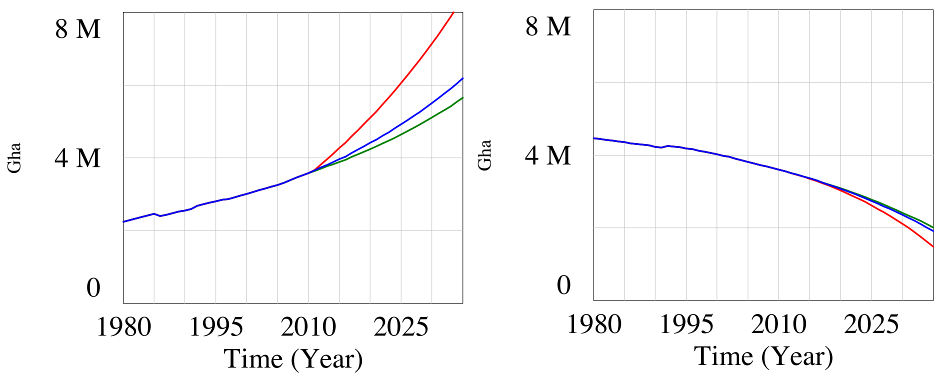

Figure 59: Sensitivity of the *forest EF of consumption* (left pane) and the *biocapacity of forest land* (right pane) to changes in the future projections of the *share of population using charcoal* and *–wood*. Green: base run, blue: share of population using wood constant after 2010, "Peak-fossil"-scenario in red: both shares linearly rise to 50% from 2010 to 2035

Figure 59 shows that in case of the no-subsidy scenario, the increase in the *forest EF* is moderate, but the effect on the *biocapacity of forest land* barely noticeable. In case of the peak-fossil scenario, the *forest EF* rises strongly compared to the base run and also the *biocapacity of forest land takes* is decreasing faster, but again the effect is weaker than for the forest EF. The reason for the weaker response of the biocapacity compared to the EF is that the effect is mediated via over-thinning which involves the strongly non-linear effect *proportion of thinning leading to deforestation.* Also, the EF is essentially a flow whereas the latter is caused mostly by a stock (forest area), which reacts with a delay compared to its flows.

Limitations of firewood and charcoal demand / butanization:

The sensitivity analysis leads to the conclusion that the butanization is an important determining factor of the EF and hence it should be questioned whether modeling this as exogenous data / policy variables makes sense.

Information in Thomas (2003) suggests that the two could be endogenized by using the butane prices as an important factor. The author states that the Senegalese government has attempted to stabilize the butane price by granting subsidies in times of high butane world-market prices and collecting taxes on butane in times of very low butane world-market prices. This policy is probably meant to keep butane competitive to charcoal. It is also stated by (Thomas et al., 2003) that the government recently reduced subsidies to reduce the rising costs caused by the successful policy. This means that the total annual costs of the subsidies could influence the subsidies per kg of butane. And the former depend on the share of the population using butane and the population. So there may be a balancing feedback loop here. Rising world-market prices may put additional pressure on the government to reduce subsidies, which could also be included in modeling this endogenously. Such a structure requires further information on the elasticity of the *share of the population using butane* to price changes of butane. In other words, is it easy to switch back to charcoal use or not? In modeling this, it may become necessary to disaggregate the population into rural and urban population because their elasticities may be different. Also for the rural population not only the price but accessibility of suppliers may be an important issue.

Furthermore the charcoal prices could decrease due to the increasing share of the population using butane. That could reduce the relative attractiveness of butane in another balancing feedback loop. This could then cause additional measures by the government (increased butane subsidies or increased taxes on charcoal). Of course the question to which degree the charcoal supply is elastic to demand plays another potential role. Is charcoal production mostly demand-driven or a by-product of forest conversions for other reasons?

Boundary adequacy and structure verification tests green vs. dead firewood

Researching about the way firewood is collected in Africa, as "headloads" it is reasonable to assume that people will try to gather deadwood if they can because it is lighter to carry and it also smokes less when burning it. If however, notable quantities of firewood are collected as deadwood it is not correct to consider them as part of the harvest (structure verification test failed). Since collection of dead firewood vs. green firewood have very different effects on the forest and its reproductive potential, the model explores these separately as *intended dead firewood extraction [kg]* and *intended green firewood extraction [green kg]* (see Figure 56). Note that the air-dry kg need to be converted into green kg because green wood has almost double the weight than air-dry wood. Conversion is facilitated via the *moisture content of green wood* and *the moisture content of air-dry fuelwood*.

Normally the EF does not distinguish if wood is harvested is dead wood or green wood, since dead wood is not distinguished from green wood in FAO statistics. In fact, data delivered to FAO may be extrapolations of population and individual wood, which is partially satisfied with deadwood. From an SD perspective, this is a problem because this wood harvest does not constitute an outflow of the *timber volume* stock. Instead it should be an outflow to a dead wood stock, which is at this stage not included in the model. The switch allows exploring the impact of taking the dead wood out of the EF calculation. The *green* *timber harvest* contains only living timber and excludes deadwood. Using the *switch dead firewood harvest as part of EF* the *dead firewood harvest* can be excluded. If the switch is off only the *green timber harvest* is summed into the EF.

In order to clarify if it is necessary to build additional structure (boundary adequacy test) to model the dynamics of dead wood harvest, first a combined sensitivity analysis is carried out that varies the *proportion of firewood demand satisfied with green wood* but also examines this not only under the base-run scenario but also under a scenario where dead wood harvest is excluded from the EF calculation (implemented in the model via the *switch dead firewood harvest as part of EF*).

Figure 60 shows that the *proportion of firewood demand satisfied with green wood* does not have much of an influence on the EF unless it was decided that dead fire wood harvest was not counted as part of the EF.

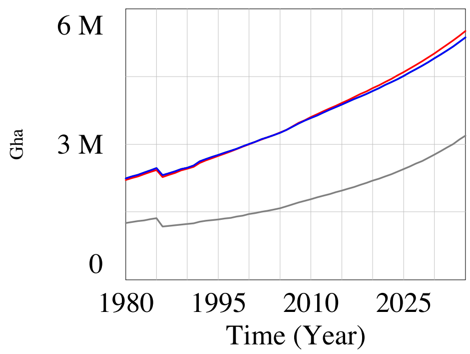

Figure 60: Sensitivity of the *forestry footprint of consumption* to changes in the *proportion of firewood demand satisfied with green wood.*
0% green wood collection (red), 100% green wood = base case (blue), 0% green wood collection and dead wood not counted as part of forestry footprint (grey)

A second sensitivity and boundary adequacy test was carried out with respect to the influence of the *proportion of firewood demand satisfied with green wood* on the BC differentiating cases where the BC is calculated with the constant GFN annual increment and the dynamic annual increment. Figure 61 shows that the *proportion of firewood demand satisfied with green wood* has a strong influence on the *biocapacity of forest land*. The more wood is collected green, the lower the biocapacity.

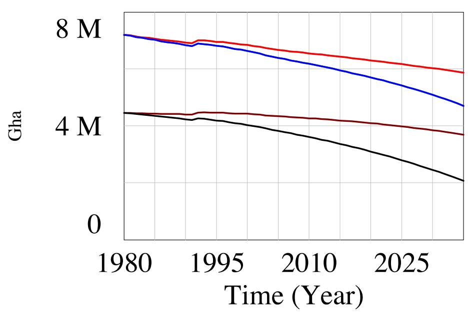

Figure 61: Sensitivity of the *biocapacity of forest land* to changes in the *proportion of firewood demand satisfied with green wood exogenous.*

Red: 0% green wood collection (constant *national annual increment*); Blue: 100% green wood collection = base case (constant *national annual increment*); Black: 0% green wood, endogenous *national annual increment*), Brown: 100% green wood and endogenous *national annual increment*.

The reason is that green wood collection reduces the timber stock and thereby also the *timber volume per ha* so that over-thinning starts having an effect at an earlier point in time and thus forest area is decreasing earlier. The lower *timber volume per ha* also decreases the *national annual increment*. Hence if the endogenous *national annual increment* is used to calculate the BC, the effect of the *proportion of firewood demand satisfied with green wood* on the BC is even larger because if the proportion of green firewood use increases, both the *forest land* area and the *national annual increment* decrease.

From these failed boundary adequacy tests it is concluded a) dead wood that should not be excluded from the model but also that b) the current structure is not sufficient to adequately model the full effect of dead wood collection. In reality, the *proportion of firewood demand satisfied with green wood* is not constant and it is not exogenous. It is reasonable to assume that in reality firewood demand is preferably realized by collecting dead wood and only if dead wood cannot be found in significant quantities green firewood is collected as this is much heavier to carry and needs to be stockpiled for drying. Hence the structure verification test failed and requires building extra structure including a dead wood stock and all its important flows. This task was begun in the project but could not be finished due to time constraints.

<u>Conversion of demands from mass to volumetric solid timber</u>

Since the *intended dead- and -green firewood extraction* still in units of kg year^{-1} they need to be converted to units of m^3 year^{-1}. For dead wood this is facilitated by division with the *weight of air-dry firewood per solid-m^3*. For green firewood the *weight of green firewood per solid-m^3* is used. The latter is calculated form the dry wood variable using the respective moisture contents but also taking care of the *proportional volumentric shrinkage when air-drying green wood*. The resulting variables are the *dead firewood harvest (solid-m^3)*, which does not influence the timber volume stock in any way as described above, and the *intended green fire wood harvest (solid-m^3)* which determines the *green firewood harvest*, an outflow to the *timber volume* stock.

Charcoal demand [kg] is converted to a *charcoal wood demand [m^3]* through multiplication with the variable *m^3 solid fuelwood per kg of charcoal*. This efficiency of the charcoal generation process was derived as follows:

The original formulation "wood needed for charcoal" in T21-Senegal34b (5kg wood per kg of charcoal) cannot be used directly because it converted kg of charcoal to kg of wood needed for charcoal. Dividing this variable with the *solid volume density of air-dry charcoal wood* yields a need of 7 m^3 of wood per t of charcoal. Many sources state a value of about 6 m^3/t (FAO Statistics Division, b; United Nations Economic Commission for Europe, 2009). FAO (1983) reveals, that these values stem from charcoal processing using steel or brick kilns. In Senegal however, the Casamance process using earth kilns is still in use which has much lower efficiencies (FAO, 1983/1987; USAID, 2008). The efficiency also depends on whether green or air-dry wood is used since in case of green wood part of the wood is burnt just to generate the heat which vaporizes the water in the wood (FAO, 1983). Estimates for air-dry wood range from 8.3 m^3 per t of charcoal (FAO, 1983/1987) to 10m^3/t, and for green wood up to 27m^3/t (FAO, 1983). As it is assumed that some green wood is used but the efficiency may on average be somewhat higher than the lowest possible a constant value of $10m^3/t$ ($0.01m^3/kg$) was chosen for the base-run of the model. The GFN2011 accounting methodology uses a value of $1m^3/t$ ($0.001m^3/kg$) (Global Footprint Network, 2011), which is unrealistic given that even a retort kiln will only go as low as 4.5 m^3/t (failed parameter verification test). GFN is planning to implement a value of $9.95m^3/t$ ($0.00595m^3/kg$) in the next edition of their accounting methodology and after discussions with their experts on the above sources found in this project are considering to use lower efficiencies for less developed countries as was implemented in this model (D. Moore, personal communication, 2012). Given the spread of the literature values a sensitivity analysis seems advisable. It is carried out in combination with the fraction of timber wasted in conversions as they both influence the residual timber demand (see further below).

Limitations of fuel conversions

It is possible that a technology diffusion of more efficient processes has taken place since the publishing of the above reports, which would indicate a dynamically sinking value of the *m^3 solid fuel wood per kg of charcoal* (efficiency increase of charcoal production), but no information on that was available. On the other hand the efficiency also depends on the type of wood used. Preferred charcoal wood species yield a much higher amount of charcoal than average tropical species (5.5 m^3 t^{-1} for preferred charcoal species and down to 3.5 m^3 t^{-1} for mangrove (FAO, 1983)). It is expected that preferred charcoal species are selectively logged first and only once these are not available any more the production should switch to less preferred species. Depending on the spatial pattern with which the thinning wave of selective logging of preferred charcoal species runs through the forests (Tappan et al., 2004) the drop in average efficiency could be more gradual or quite sudden. In future research the variable *m^3 solid fuel wood per kg of charcoal* could be endogenized. The former effect of technology diffusion could be made dependent on foreign direct investment assuming that technologies are imported. The latter effect of depletion of preferred charcoal species could be modeled either by introducing a separate stock for these, or (more crudely) by introducing a graph function that is linked to the *timber volume per ha* which assumes that at a certain forest density also a certain amount of preferred charcoal species are left. Due to time constraints and priorities of this thesis project the effects of these changes could not be analyzed yet.

Residual charcoal demand

But the charcoal wood demand m^3 does not directly translate into timber harvest because while researching to verify the structure it became apparent that besides the above-described fuel wood demand-pull mechanism there may also charcoal being pushed on the market. It results from two other drivers of timber extraction: Conversion of forest to agricultural land and to other use, esp. quarries and mines (FAO Forestry Department, 2010)(hereafter just addressed as conversion to mines). It is assumed that the timber in these converted forests is converted to charcoal, because it is not selective as is necessary for industrial timber extraction and it is too cumbersome and heavy to transport as firewood. The timber harvest from these conversions (*Charcoal timber harvested from conversion to agriculture [m^3]* and *charcoal timber harvested from conversion to mines [m^3]*) is considered to be pushed on the market. As a consequence charcoal timber demand is satisfied using this conversion related timber harvest as long as that is sufficient. If it is not, there is some *residual charcoal demand [m^3]* so that some charcoal timber is harvested just to satisfy demand. (This harvest can be carried out as selective logging or deforestation.)

The *Charcoal timber harvested from conversion to agriculture [m³]* and *charcoal timber harvested from conversion to mines [m³]* also constitute two more inputs to the *green timber harvest* and thus also to the *total timber harvest* that is fed into the EF calculation (see Figure 3).

Not all of the *timber cleared through conversion to cropland* or *-mines* is necessarily harvested. Some may be burnt to gain fertilizing ashes for example. The exogenous variable *fraction of timber wasted in conversions* is used to carry out a boundary adequacy test to determine if additional structure should be built to represent the mechanisms involving timber harvest vs. waste.

Limitations of residual charcoal demand

See Limitations of timber harvested form forest conversions, 6.5.6.

Combined sensitivity analysis of conversion timber waste fraction and charcoal efficiency

As both *residual wood demand* depends both on the *fraction of timber wasted in conversions* and the charcoal production efficiency (*m³ solid fuel wood per kg of charcoal*) a combined analysis of the sensitivity of the *residual wood demand* to the two variables is carried out: It can be seen in Figure 62 that the charcoal conversion efficiency only plays a role in increasing the *residual charcoal wood demand* if the efficiency is either very low (blue curves) or if much of the timber is wasted in conversion of forest land (bottom pane of the figure), because in case of a low waste percentage, the charcoal pushed on the market by forest conversion (over-)satisfies the demand.

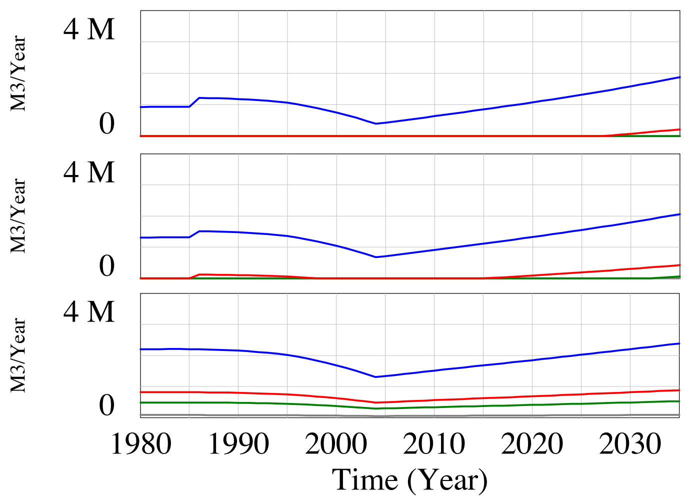

Figure 62: Sensitivity of the *charcoal wood demand [m³]* to the efficiency of the charcoal production process *m³ solid fuel wood per kg of charcoal* (technical conversion factor in GFN terminology) and the *fraction of timber wasted in conversions*.
***Timber wasted in conversions* at 0% (top), 30 % (middle), 100% (bottom). Blue: 27 m³ wood per t of charcoal (green wood, earth kiln), red: 10m³ t⁻¹ (base run value), green: 5.95m³ t⁻¹ (upcoming GFN TCF), grey: 1 m³ t⁻¹ (impossible GFN2010 TCF).**

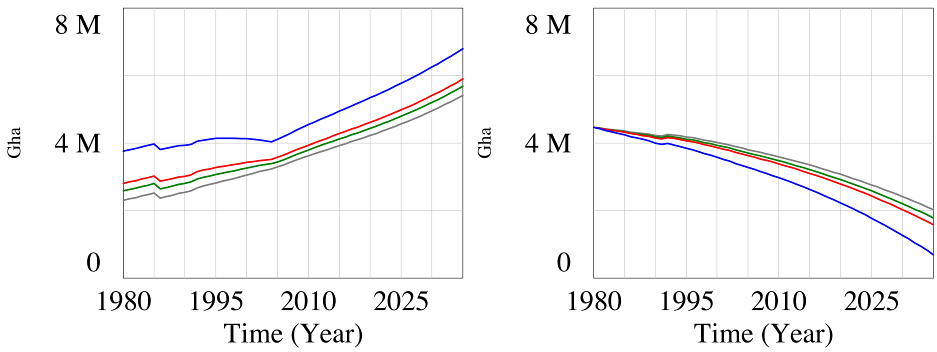

Figure 63: Sensitivity of the *forest EF of production* (left pane) and the *BC of forest land* (right pane) to the efficiency of the charcoal production process *m^3 solid fuel wood per kg of charcoal* assuming the *fraction of timber wasted in conversions* at 100%.
Blue: 27 m^3 wood per t of charcoal (green wood, earth kiln), red: 10m^3 t^{-1} (base run value), green: 5.95m^3 t^{-1} (upcoming GFN TCF), grey: 1 m^3 t^{-1} (impossible GFN2010 TCF).

Higher charcoal timber harvest due to lower charcoal conversion efficiency at high waste rates means higher EF and also indirectly lower BC (due to over-thinning) as can be seen in Figure 63.

<u>Limitations of the conversion timber waste structure</u>

Therefore, the sensitivity analysis shows that harvesting of timber form forest conversions should not be left outside the boundary of the model (boundary aqdequacy test failed). More information is necessary to build structure for the *fraction of timber wasted in conversions*. It is conceivable that this is not static but depends on the proportion of charcoal demand satisfied with conversion-related timber (via the charcoal price), thus closing a feedback loop that may lead to interesting dynamics.

Should the *fraction of timber wasted in conversions* turn out to be high, so that there is a significant *residual charcoal demand*, it would also be important to gather information to build structure that adequately models the *m^3 of fuelwood per kg of charcoal*. Note that the outcome of the above-mentioned sensitivity analysis is conditional on the assumed future development of demand. Therefore, for other scenarios of future demand this sensitivity analysis should also be revised.

6.4.2 Industrial wood demand

According to FAO data (FAO Statistics Division, a), there is also an increasing timber harvest that is not directed at a use as fuel but for industrial use (see Figure 3): “saw logs and veneer logs” and “industrial roundwood”, hereafter in sum called “industrial timber”.

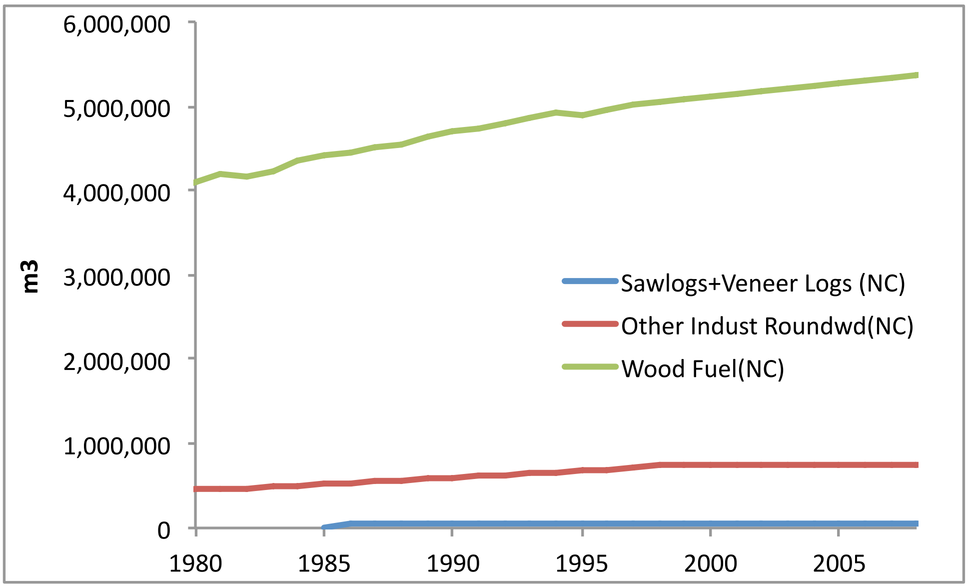

Figure 64: Forest production (primary products) according to FAO wood harvest data (NC=non-coniferous) (FAO Statistics Division, b)

Therefore, the boundary adequacy test of the structure in T21-Senegal34b was failed for the purpose of this project since it only contained demand for firewood and charcoal. Hence, *domestic industrial wood demand [m^3]* was also modeled. It is driven by the *Capital Industry* (that already existed in T21-Senegal34b) and a *timber demand per unit industrial capital*. Since no data on the latter variable was available, this value was calibrated to reproduce the reference mode (FAO harvest data, i.e. the sum of "saw logs and veneer logs" and "industrial roundwood"). Other FAO categories were not considered as they are derived products and are thus already included in these (except products based on imports which are treated in section 6.6). However, imports of industrial timber reduce this demand and exports increase it to yield the *residual industrial wood demand*. It can be switched off using the *switch industrial wood demand*.

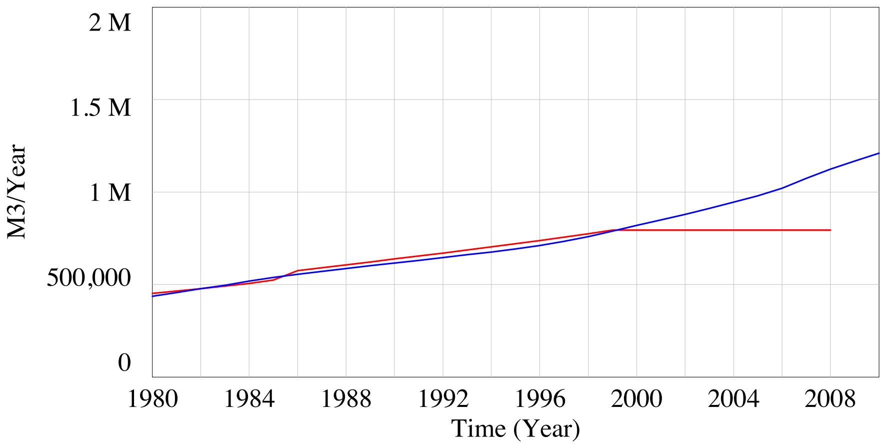

Figure 65: Industrial timer harvest FAO data (red) and simulation (blue) calibrated to fit the former.

It can be seen in Figure 65 that the value chosen for the *timber demand per unit industrial capital* ($4.1 \cdot 10^{-7}$ m^3 (CFA_{99} · year)$^{-1}$)[$] yields a very good fit before 2000 and not a

[$] note that the currency is measured in real terms i.e. deflated to the base year 1999 very good fit after that date. The exponential tendency and therefore increasing impact on the system calls for a sensitivity analysis of this variable.

Sensitivity analysis timber demand per unit industrial capital

Figure 66 shows that the EF and the BC are only somewhat sensitive to lower values of the *timber demand per unit industrial capital*. This makes sense because even at zero there are still other types of timber demand. They are however highly sensitive for values higher than the one used for the base run: Note that for the a value less than half an order of magnitude larger than the base run, the biocapacity almost reaches zero within the time horizon of the model.

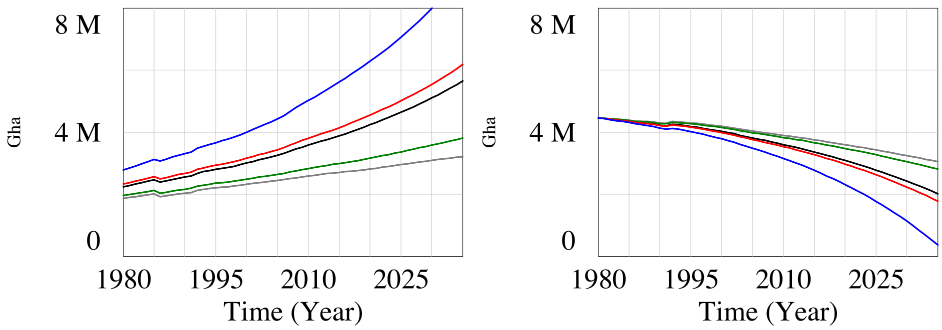

Figure 66: Sensitivity of the *forest EF of production* (left pane) and the *biocapacity* (right pane) to different *timber demands per unit industrial capital*. Black: base run with $4.1 \cdot 10^{-7}$ m^3 (CFA_{99} · year)$^{-1}$, Blue: $1 \cdot 10^{-6}$ m^3 (CFA_{99} · year)$^{-1}$, Red: $5 \cdot 10^{-7}$ m^3 (CFA_{99} · year)$^{-1}$, green: $1 \cdot 10^{-7}$ m^3 (CFA_{99} · year)$^{-1}$, grey: 0 m^3 (CFA_{99} · year)$^{-1}$,

While modeling the trade of EF (see section 6.6) it became apparent that domestic demand is not the only demand for industrial wood (failed boundary adequacy test): There is also foreign demand that is satisfied via exports of products that have been made from Selegalese timber. Hence the *demand embedded timber exports* was added to the domestic demand. But the *residual industrial wood demand* is also partly satisfied by *wood embedded in total imports of industrial wood-derived products.*

Limitations industrial timber

There are other problems besides the high sensitivity. As the simple model structure chosen cannot reproduce a sudden stabilization of an exponential trend, the boundary adequacy test is failed. Additional knowledge on the factors affecting the industrial wood harvest is necessary, esp. what led to the stabilization. By using an exponential trend that ignores the stabilization it is assumed that the data is flawed and that the trend actually continued, but that may be wrong. Unfortunately FAOstat does not link to the data sources. Other factors influencing the industrial timber harvest should be included in future elaborations of the model. This should also include turning the *timber demand per unit industrial capital* into a dynamic variable that may be influenced by different kinds of capitals. Political or administrative decisions (e.g. licenses for factories) may also play a role. Further research should analyze if future growth in the service sector, could even accelerate the growth of industrial demand due to pulp-demand.

6.5 Timber and forest land sector

In this section, the simplified core model is expanded to include the realism of the forestry Situation in Senegal. It simulates all important inputs for the EF and BC calculations, the *forest land* area and the *national annual increment* for the BC and the harvest for the EF. The harvest is no longer hypothesized as for the simplified core model analysis but is instead driven by the timber demand variables developed for Senegal in section 6.4.

While the structure has a lot more variables than the simplified core model, it does not have much dynamic structural complexity added. Only two additional feedback loops (R2a,b) are added (apart from quite a few local feedback loops which are mainly due to fuzzy min functions, s.b.). The rest of the model is essentially the same as the simplified core model but with a disaggregated harvest- and deforestation outflows. Some additional in- and outflows are added to take care of different types of deforestation and connected timber clearing which are not timber-demand-induced (fire, conversion to cropland or mines).

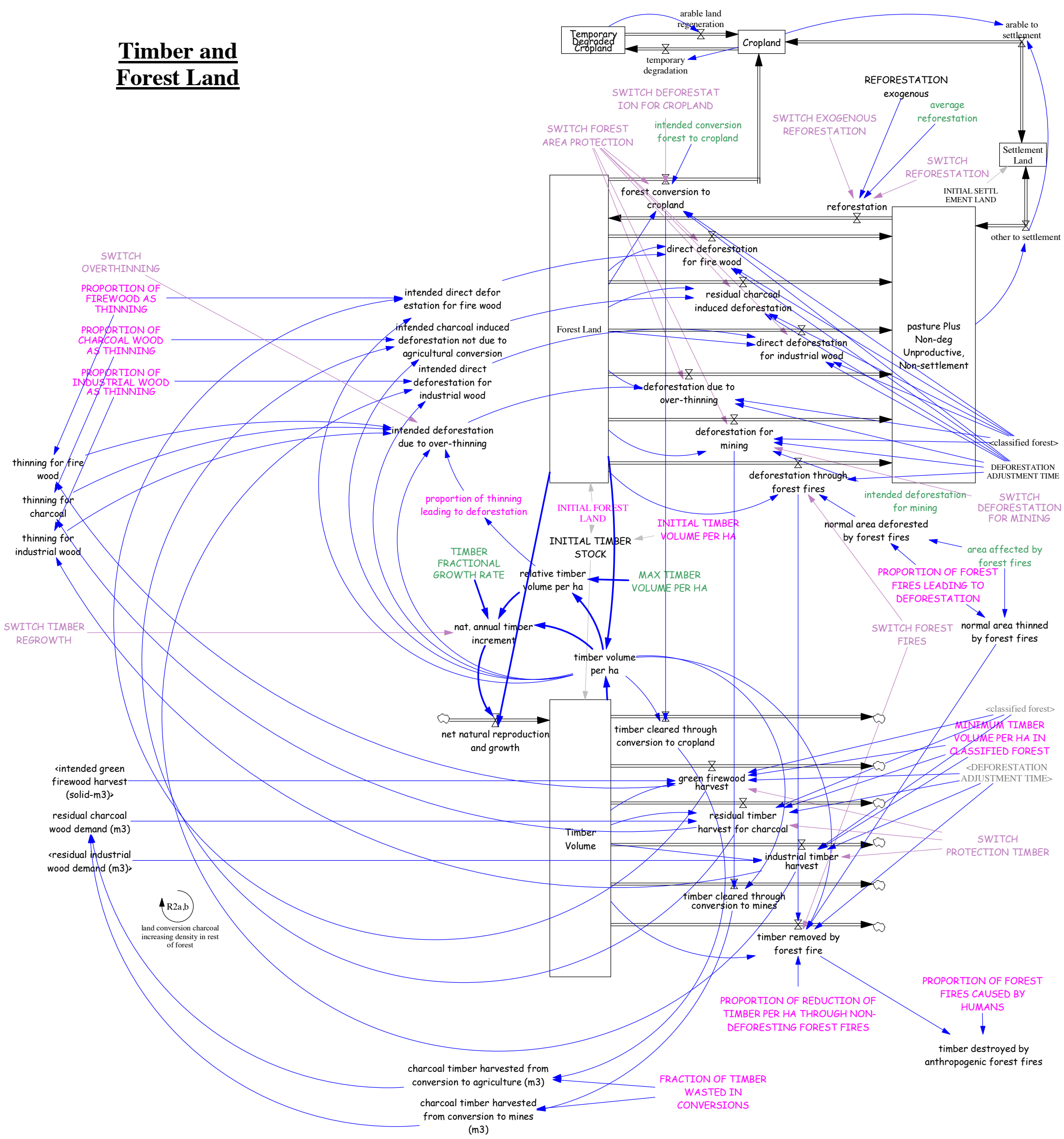

Figure 67: Timber and forest land sector.

Thick blue arrows trace simplified core model structure (compare Figure 8). Parameter values based on literature sources in green, parameters based on assumptions only in pink, switches in light purple. Variables derived form other model sectors carry < >, variables in Times New Roman were taken unchanged from T21-Senegal34, variables in Comic Sans MS were added or modified in this project. Please zoom in for details.

6.5.1 Harvest outflows

The three types of timber demand developed in section section 6.4. (*intended green firewood harvest, residual charcoal wood harvest, residual industrial wood harvest*) drive three harvest outflows from the timber stock: *green firewood harvest, residual timber harvest for charcoal* and *industrial timber harvest*. These flows are constrained by a fuzzy min function which i.a. makes sure that the stock runs empty smoothly and doesn't go negative (using the deforestation adjustment time of one year). It is important to note that the dead firewood extraction is excluded from the extraction outflow, as it does not affect standing timber extraction.

6.5.2 Harvest leading directly to deforestation

These three harvest flows govern three co-flows from the *forest land* stock: *direct deforestation for firewood, residual charcoal induced deforestation* and *direct deforestation for industrial wood.* But only if these harvests are to some degree carried out as <u>direct</u> deforestation as specified by the three variables *proportion of firewood as thinning, proportion of charcoal wood as thinning* and *proportion of industrial wood as thinning*. Harvest leading to <u>direct</u> deforestation is defined here as harvest is carried out as clear cuts AND that these clear cuts do not reforest themselves so that the forest is permanently lost. The latter is probably mostly the case as there is evidence for the non-existence of un-aided natural reforestation, animal exclosures are needed for natural forest spread (FAO Forestry Department, 2010) (see also section 6.5.9). Furthermore <u>direct</u> deforestation does not include deforestation due to over-thinning (see 6.5.3). Note that harvest carried out as deforestation reduces both the *forest land* stock and the *timber volume* stock, harvest carried out as thinning reduces only the latter directly.

Note also that T21-Senegal34b assumed that all harvest is carried out as direct deforestation, which seemed unreasonable given the evidence of the literature as described below (structure verification test failed by T21-Senegal34b). Also the purpose of this project which requires a *national annual increment* required a separate timber stock, which in turn requires differentiating thinning and direct deforestation (boundary adequacy test failed by T21-Senegal34bs approach for this project). Hence, T21-SenegalEFf1 considers selective harvest.

The base-run (10.1) is carried out with a *proportion of firewood as thinning* of 1, i.e. no direct deforestation on the following grounds: Firstly, from personal experience of the author, different kinds of firewood have different qualities (stem diameter, ease of felling and chopping, time it takes to dry out, tendency to cause skin irritations, thorns, tendency to smoke, energy content, short quick heat vs. long lasting heat, intensity of light-emission etc.) so that selective logging for firewood seems likely for non-commercial harvest. Secondly, while clear cuts could make sense for commercial firewood harvest, they do not appear very likely, because for transport purposes charcoal is more convenient. Thus the proportion of commercial firewood harvest is assumed to be very low (only 3%, see *share of informal and private firewood harvest* sector 20 section 0).

Smaller proportions of thinning should be explored in a sensitivity analysis.

For the base run a *proportion of charcoal wood as thinning* of 1 was chosen on the following grounds: In charcoal related logging species with high wood densities are preferred (FAO, 1983). Consequently (Tappan et al., 2004). Consequently describes charcoal-induced logging as a "wave of selective logging in all regions with significant wood resources". Note that selective logging only applies to the *residual timber harvest for charcoal* i.e. that which is not satisfied by charcoal production as a byproduct of conversion to agriculture and mines (see 6.4, Residual charcoal demand).

There may be some additional clear-cutting for charcoal wood e.g. around a earth kiln, to harvest small wood to put into spaces between the bigger pieces etc., so that smaller *proportions of charcoal wood harvest as thinning* should be explored in a sensitivity analysis.

The *proportion of industrial wood as thinning* was also set to 1 for the base-run, because industrial wood harvest can be regarded highly selective, as many uses require special species or diameters. There are however also some industrial timber uses (production of particle board or pulp) which may have a certain amount of discretion for which species to use, so that a sensitivity analysis seems advisable.

<u>Limitations direct harvest</u>

Note that above it is assumed that the dead wood that exists in forests that are deforested for charcoal or industrial wood production, is not utilized for satisfying any of the demands because the deforestation yields so much green wood, which is of better quality. This may in fact not be true for charcoal wood especially if the harvest is carried out as deforestation, because it is then likely, that all timber is used. A boundary adequacy test should explore if additional structures are necessary to take care of this.

The sensitivity analyses called for above could not be carried out due to time constraints.

6.5.3 Harvest indirectly leading to deforestation (over-thinning)

As described in detail in section 6.3.8, even if there is no direct deforestation continued thinning above the forests capacity to regrow may eventually lead to over-thinning which causes forest loss as an indirect form of deforestation. The afore-mentioned proportions of thinning multiplied with the respective harvests outflows yield the actual harvest quantities carried out as selective harvest (*thinning for fire wood, thinning for charcoal* and *thinning for industrial wood*).

The multiplication of the variables *thinning for fire wood, thinning for charcoal* and *thinning for industrial wood* with the *proportion of thinning leading to deforestation* yields the *intended deforestation due to over-thinning*. This variable drives the *deforestation due to over-thinning*. This outflow is hence not a simple co-flow to the harvest flows but depends on these in a highly non-linear fashion including the forest density as "switching agent" that determines the threshold after which over-thinning takes a strong effect.

The graph function *proportion of thinning leading to deforestation* could not be parameterized, the values are guesses while the shape follows the reasoning outlined in 6.3.8.

For the base run, the moderate curvature shown in Figure 34 was used, but a sensitivity analysis carried out in this more elaborate version of the model is advisable.

Limitations of over-thinning:

The above-mentioned sensitivity analysis could unfortunately not be carried out due to time constraints.

There may be two more causal mechanisms leading to over-thinning: Firstly there is also some definition threshold for forest in a country (e.g. defined by a minimum % crown-cover, minimum area and minimum tree height (e.g. ≥10%, ≥0.5ha, ≥5m World Resources Institute, 2003). Below that threshold, it is not considered forest any more and has thus disappeared because it does not meet the definition criteria. But the timber still exists, but outside the area defined as forest. Modeling this would thus require disaggregation into more stocks. Secondly, there may be some reinforcing feedbacks that lead to deforestation even if cutting was halted (e.g. caused by loss of stand climate, falling water tables because forest function of storing water ceases to work etc. What all these mechanisms have in common with the over-thinning introduced in this paper, is that they will start having a serious effect on forest area only at low forest densities i.e. they are all evoked by over-thinning.

Furthermore, once more information on over-thinning becomes available, that would enable parameterization it may turn out that the implementation as a graph function may have to be abandoned in favor of a more disaggregated structure.

There may also be some degree of indigenous knowledge-based management of forest resources to promote preferred species though. This may reduce the effect of depletion of preferred species and thus also the over-thinning effect.

6.5.4 Forest to cropland conversion and associated timber removal

Literature research revealed, that there is notable conversion of forest to agricultural land (FAO Forestry Department, 2010). Tappan et al. (2004) state that annualized total agricultural conversion from the periods 1965-1985 and 1986-2000 was at 27,715 ha year^{-1} and 20,573 ha year^{-1} respectively. These values were used in a graph function (*intended conversion forest to cropland,* see Figure 68).

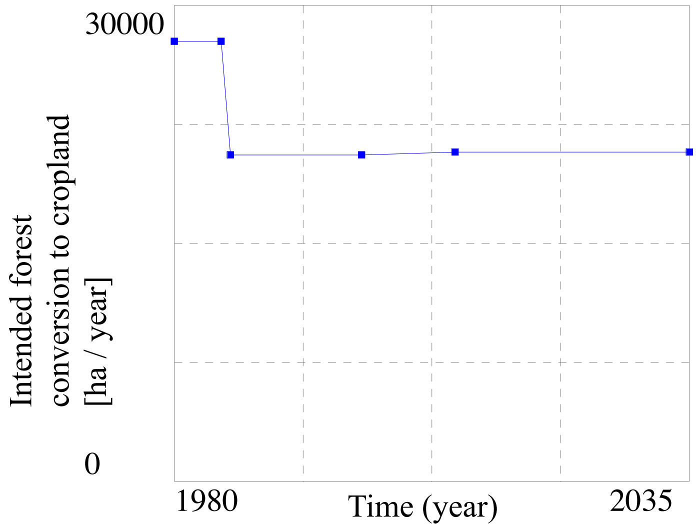

Figure 68: Graph function for the exogenous input *intended forest conversion to cropland*

While it was assumed for the base-run that this forest conversion rate stayed unchanged until 2010 and into the future, the graph function allows for sensitivity analysis of the effects of other future developments.

The *switch deforestation for cropland* allows for switching off and on the newly introduced flow to explore its implications.

Naturally, when forest is removed so is the timber in it, which is modeled as a co-flow *timber cleared through conversion to cropland*, using the *timber volume per ha.* Note that unlike for the harvest flows, the outflow of the *forest land* stock is the governing flow of the co-flow structure. Only the governing co-flow needs a fuzzy min function here, since there is no other variable influencing the co-flow.

<u>Limitations of *forest conversion to cropland*</u>

This flow is currently an exogenous input. Since it seems to be such an important determinant of the dynamics, this flow should definitely be endogenized. But that would require information on the causes for these conversions. Some of the reviewed literature (Wood, Tappan, & Hadj, 2004) suggests that it results from a lack of possibilities to intensify agriculture. But what are the constraining mechanisms on intensification? Poverty of farmers not allowing them to buy necessary inputs? High prices for necessary inputs, caused by imports? Are the soils the bottle-neck (nutrients, lack of fertilizer) or is it farming equipment? Is it the poverty of the buyers that preclude that farmers get decently paid for their produce or are the low world-market prices the problem?

Unfortunately, the sensitivity analysis of future cropland conversion rates could not be carried out due to time constraints.

One problem resulting from the additional conversion flow is that it would make the cropland stock increase, if there are no other changes made in the model. After updating the cropland area using new FAO data for the past two years, the reference mode seems to start catching up with the simulation though as can be seen in Figure 69.

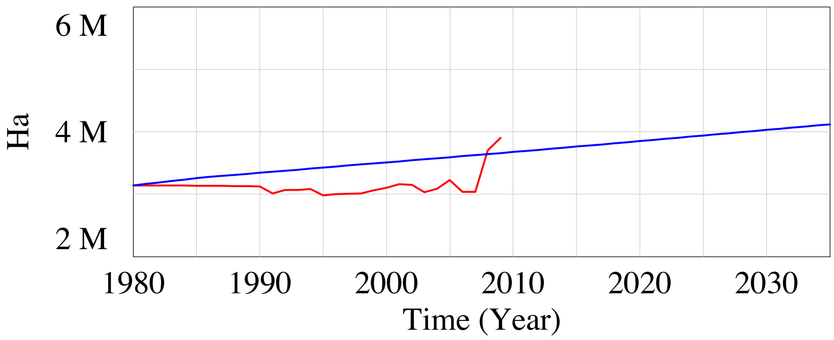

Figure 69: Development of cropland.
Red: reference mode data (FAO Statistics Division, a), blue: simulation

It may also be interesting to try to get data on the development of the temporary degraded land stock. Could loss of agricultural area be the cause, in other words is it the flow from cropland to degraded land that indirectly creates the need for the flow converting forest land into cropland? And is it actually be enough to have a temporarily degraded land stock, or is should there also be a stock of permanently degraded land (desert)?

6.5.5 Deforestation for mining and associated timber removal

Research also revealed, that there is notable conversion of forest to mines (FAO Forestry Department, 2010). The authors state that from 2005 to 2010, 12.5% of the assumed deforestation of 40,000ha/year constituted conversions to mines and similar uses. These 5000ha/year constitute the variable *intended deforestation for mining*, which is a graph function rather than a constant in order to facilitate sensitivity analysis of the effects of other future developments. The *switch deforestation for mining* allows for switching off and on the newly introduced flow to explore its implications.

Similar to the case of conversion to cropland, a co-flow to the *deforestation for mining the timber cleared through conversion to mines* ensures that the corresponding amount of timber of the forest is removed. Again contrary to the harvest flows, the flow out of the *forest land* stock is the governing one.

Limitations of *deforestation for mining*

Not quite as high as the cropland-demand-induced outflow but still substantial, it may be important to also endogenized this flow somewhat. T21-Senegal34b contains a sector on mining which considers the exploitation of gold and phosphates. Are these two or one of them the drivers of that deforestation? If so, one may expect that these mining activities drive deforestation. With depletion of these two resources deforestation may first go up (because lower quality ores may require larger amounts of land for the same output) and then gradually go down, as mining activity subsides, because it is no longer profitable.

6.5.6 Timber harvested from forest conversions

As already mentioned under 6.4, it is conceivable that some of the wood from the forests which are converted to cropland or to mines etc. is harvested and pushed on the market to yield additional income for the people converting it. In the model these amounts of wood (*Charcoal timber harvested from conversion to agriculture [m^3]* and *charcoal timber harvested from conversion to mines [m^3]*) are determined by the *fraction of timber wasted in conversions*. As there was no data on this variable it was assumed to be 30% for the base run, but a sensitivity analysis seems advisable. As already described under 6.4, all of this timber is assumed to be converted to charcoal for easier transport and marketing. Since this harvested timber reduces the *residual charcoal wood demand*, two additional feedbacks loops are closed (R2a,b). They are reinforcing as an increase in timber cleared through conversion leads to a further increase as follows: An increase in the *timber cleared through conversions* leads to an increase in *charcoal timber harvested from conversions* which reduces the *residual charcoal wood* demand, which means that the *residual timber harvest for charcoal* is lower than it would have been had there not been an increase in the *timber cleared through conversions*. This in turn means that the *timber volume* stock is higher than it would have been had the *residual charcoal wood demand* not been decreased. This also means though that the *timber volume per ha* is higher than it would have been, and this means that continuing timber clearing for conversions will also be higher than it would have been, had there not been an increase in this value a while ago. As the timber cleared through the conversions also itself constitutes an outflow to the timber stock it is by definition always experiences a higher the reduction of the residual timber harvest for charcoal discussed in R02 loops. Hence, these two reinforcing loops can never play out their reinforcing potential, since they are always weaker than the two local balancing feedback loops that are trying to empty the *timber volume* stock (timber volume, timber volume per ha, outflows of conversion timber, timber volume). The R02 loops should dampen the outflows of the two balancing feedback loops somewhat though.

<u>Sensitivity of the EF and BC to the *fraction of conversion timber wasted*</u>

As mentioned above, it seems advisable to explore the impact of the % of conversion timber wasted on the EF and BC. The left pane of Figure 70 is a bit counterintuitive at first sight: If no timber is wasted, the EF is highest.

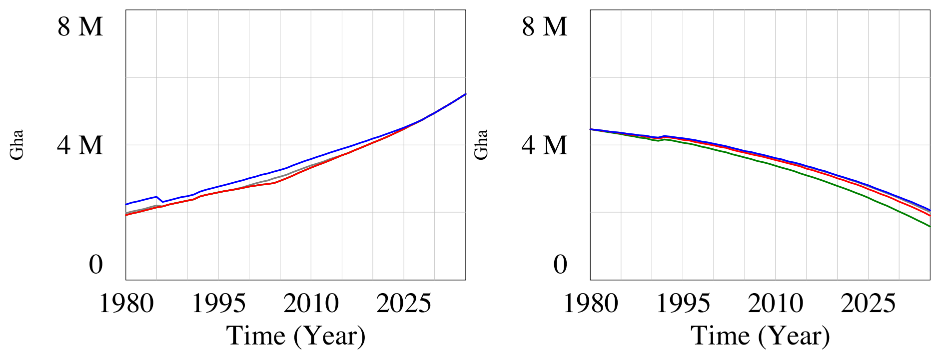

Figure 70: Sensitivity of the forestry consumption EF (left pane) and the forest BC (right pane) to the *fraction of timber wasted in conversions*.
Blue: 0% wasted, red: 50%, green (congruent with red): 100%, grey: 30%. All simulated with dynamic annual increment.

This makes sense though, considering that the EF is only considering the harvested part of the timber removed through conversions, and if no timber is wasted it means that all timber is harvested. It is also peculiar that the trajectories for 100% waste and 50% waste are congruent and that the 30% waste trajectory is only incongruent with the former two for part of the simulation. The reason is that if the timber harvested and converted to charcoal from conversions is below the total demand for charcoal (which is the case for high waste fractions) demand-driven and conversion-pushed charcoal together satisfy the demand (since the demand driven is defined as the residual demand). Hence the total charcoal harvest and hence the EF remains unchanged. Only if the supply of conversion-related charcoal production exceeds demand, the EF is consequently higher.

The development of the BC is more intuitive because it reacts to the total timber removed not only the harvest. If the waste fraction is high, the total timber removed will be higher because the residual charcoal harvest is higher and in sum with the unchanged timber removed through conversions leads to a faster decrease of the timber stock. This means though, that over-thinning-related deforestation gets more severe at an earlier point in time and thus the forest area decreases faster. Also due to the lower timber stock the timber volume per ha is lower, which also decreases the BC (simulation was done with dynamic annual increment).

Structure verification, sensitivity: Summing the wasted timber into the EF

Normally the wasted timber from conversions is not summed into the EF because it does not show up in the harvest statistics. This unintended exclusion is the cause for the counterintuitive graphs above. Furthermore, from a System Dynamics point of view the wasted timber is an outflow to the *timber volume* stock and thus – one may argue – should be considered. If we use the *switch waste conversion timber as part of EF* to sum the EF, we are basing the EF on the total timber removed from the timber stock and not just the part that was reported as harvest. Therefore the trajectories of the blue and red curves in Figure 71 where the timber wasted in conversions is factored into the EF is summed into the EF are much more intuitive: The more timber removed, the higher the EF.

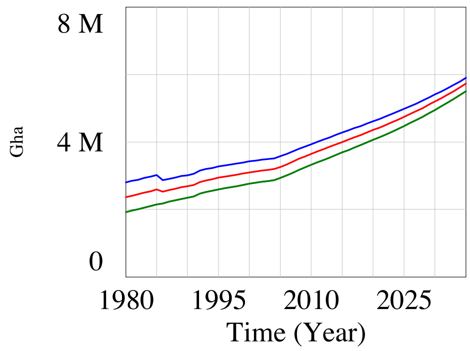

Figure 71: Sensitivity of the forest consumption EF to summing timber wasted in forest conversions into the EF.
Fraction of timber wasted in conversions: **Blue 100% waste summed into EF, red 50% factored into EF, green and grey 100% and 50% not factored into EF respectively)**

These trajectories are the “real” picture in terms of the outflow of the stock. The current way the EF is calculated (ignoring wasted timber) hides some of the anthropogenic outflows from the timber stock creating a skewed picture of what is sustainable. If there is a lot of conversion of forest to agriculture or mines going on where the timber is just burnt (e.g. to fertilize the land), this leads to the EF underestimating the actual timber removal.

Limitations of timber harvested form forest conversions

Firstly, the waste fraction may actually differ between conversions to mines vs. cropland. But since nothing was know about either of them, they were aggregated here.

A more important question is, what happens if the timber harvested form conversions is more than the demand for charcoal requires? There may be stocks of unsold charcoal building up or oversupply may result in an increasing waste fraction. This could be implemented in the model by letting a graph function connected to the fraction of charcoal demand satisfied with conversion timber specify an influence that would feed back on the waste fraction, which would become a stock.

6.5.7 Forest fires

Forest fires also affect notable forest land area (Ministre de l'Environment, de la Protection de la Natur, des Bassins de rétention et des Lacs Artificiels, 2009). The time series data from 1996 to 2006 in Figure 72 shows that the area affected by forest fires exhibits strong fluctuations.

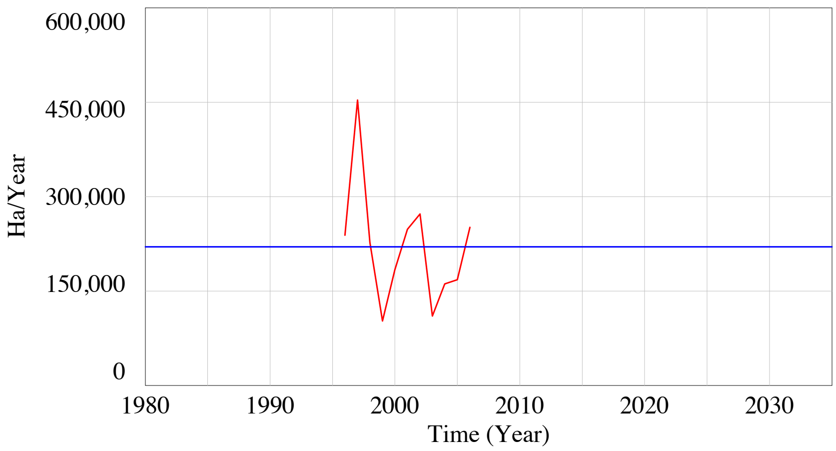

Figure 72: *Area affected by forest fires* simulation (blue) and reference mode data (red)

The time series is however too short to make meaningful assumptions about earlier or later developments. As a crude approach, the average of the available data has been used as *area affected by forest fires* hoping that it is at least in the right order of magnitude on the long run. The variable has been implemented as a graph function to allow for sensitivity analysis to explore higher or lower average values or even create large fluctuations. However, not every forest fire necessarily leads to deforestation. If the vegetation is adapted to fire "fire-climax" (Tappan et al., 2004), the *proportion of forest fires leading to deforestation* may be very low because trees protect themselves with thick barks and the ability to resprout after fires etc. The low crown cover in savannas may prevent fires from jumping from crown to crown, and ground fires likely do not burn hot enough to kill mature trees. Also only if a forest does not regrow after a forest fire can this really be considered deforestation. However, heavy grazing especially by goats may prevent reforestation to some degree. For the base run it was assumed that 10% of the area affected by forest fire is (permanently) deforested. Different assumptions on the *proportion of forest fires leading to deforestation* can be applied in a sensitivity analysis. The result of the multiplication of the *area affected by forest fires* with the *proportion of forest fires leading to deforestation* is the *normal area deforested by forest fires.* Of course when the stock runs very low, this normal area will not be realized anymore as there is not enough available to be burnt, which is taken care of by another fuzzy min function in the outflow *deforestation through forest fires*. The outflow from the timber stock called *timber removed by forest fires* of course is partly composed of the timber of these deforested areas.

But there is a second ingredient to this outflow because although some forest fires do not lead to deforestation, they always have an effect on the timber volume stock. As this is a thinning effect, the corresponding variable is the *normal area thinned by forest fires* is the residual of the total *area affected by forest fires* and the *normal area deforested by forest fires*. The degree of thinning is determined by the *proportion of reduction of timber per ha through non-deforesting forest fires*. In this case not only the outflow from the *forest land* stock but also the outflow from the *timber volume* stock contains a fuzzy min function because the latter has an additional component not governed by the other flow. The *switch forest fires* allows for turning off and on both of the flows to analyze their impacts.

Note that the thinning effect of forest fires implies that forest fires can also indirectly contribute to deforestation by contributing to over-thinning (see 6.5.3).

<u>Structure verification, sensitivity: Impact of anthropogenic forest fires on EF</u>

Of all of the forest fires, a large proportion of probably of human origin. None of the timber burnt in these fires shows up in harvest statistics, but it is an anthropogenic outflow from the *timber volume* stock, just like harvests. The *switch anthropogenic forest fires as part of EF* can be switched on to sum the *timber destroyed by anthropogenic forest fires* into the *total timber extracted*. Figure 73 shows that this actually makes a major difference for the EF. If all forest fires were started by humans, the forestry EF would already have been higher than the BC before 1980, whereas if only 50% of the forest fires were anthropogenic the EF would have surpassed the BC in the middle of the 1990s compared to 2012 for the case of 0% anthropogenic forest fires which is the than not factoring anthropogenic forest fires into the EF in the base run.

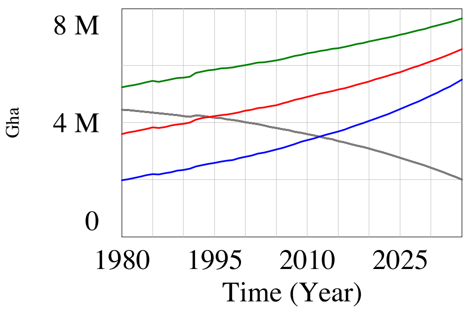

Figure 73: Sensitivity of the *forest EF of production* to of anthropogenic forest fires counted as part of the EF.
Forest fires never counted into EF (blue), 100% (green) and 50% (red) of forest fires anthropogenic and counted as part of the EF. *BC of forest land* (grey) calculated with dynamic *national annual increment*

Note that the relative potential contribution of the anthropogenic forest fires to the EF diminishes with time because the impact of fire stays the same wile the harvest impact is growing.

<u>Limitations of forest fires</u>

Forest fires should actually become less frequent as *timber volume per ha* goes down, not just due to fuzzy min but long before already. This is a significant limitation, since the way that the model is currently set up, the forest flows which are not affected by classified forest (see next section) empty the *forest area* and *timber volume* stocks. In reality, when forest becomes scarce, forest fires should also decrease in frequency. As a first approach, it may for example make sense to use a normal proportion of area affected by forest fires instead of a normal area affected by forest fires. Unfortunately, this conceptual error was detected to late to correct it. Better yet, both the *area affected by forest fires* and the *proportion of forest fires leading to deforestation* should be affected by the *timber volume per ha* and the *area affected by forest fires* should be affected by the *forest land* area.

The last remaining protected forest would probably either decline slowly, or not at all, because even if protected areas burn, measures would be taken to make the forest regrow so that it would not lead to deforestation.

Something a bit more difficult to implement in System Dynamics is that the occurrence of forest fires be influenced by spatial deforestation patterns. It may be necessary to use agent based modeling to explore this and then implement the aggregated results of that analysis on the SD-model.

Furthermore, unfortunately due to time constraints, the sensitivity analyses of the effect of the *proportion of forest fires leading to deforestation* and the *proportion of reduction of timber per ha through non-deforesting forest fires* on the EF &BC could not be carried out.

6.5.8 Forest protection

The described intended harvests and demands do not necessarily translate directly into harvest: Firstly, both the *forest land*- and the *timber volume* Stock can run out. Hence harvest stops at that point. It is assumed that this is not an abrupt stop but instead when stock levels get very low harvest gradually slows down using a fuzzy min-function with a *deforestation adjustment time* of 1 year. A convenient way to model forest protection as used in T21-Senegal34b is to let the stock not run to zero but to the area of *classified forest* instead. This is achieved by replacing the *forest land* stock in the fuzzy min function with the difference of the *forest land* and the *classified forest*. Note that *deforestation through forest fires* is not affected by the classified forest since forest fires do not abide by the borders of protected areas.

It may be difficult to prevent selective logging in protected areas, so there may be some selective timber harvest happening in classified forest, either because some lower protection statuses may allow to do so, or because enforcement of protected areas only becomes effective once degradation of protected areas surpasses a certain threshold. The model was initially implemented assuming that in classified forests there is no human interference and they are consequentially at a timber volume per ha of 250 m^3 ha^{-1}. But the resulting timber volume in classified forests would be more than is initially in all forests, so that assumption is clearly unrealistic (parameter verification test failed). Hence there <u>must</u> be thinning in classified forests. Here, this is modeled in by using a fuzzy min function with a difference as a goal again as above, but multiplying the classified forest area with the *minimum timber volume in classified forest.* Hence this balancing feedbacks in the outflows aim at this product, the total timber volume in classified forests. Note that again the flow *timber removed by forest fire* is not affected by classified forest.

Note that as stocks start to run low, harvest and deforestation flows start to diverge from their respective intended variables.

In T21-Sengal34b, the *classified forest* area is exogenous data for the past and a policy variable for the future, showing the development depicted in Figure 74.

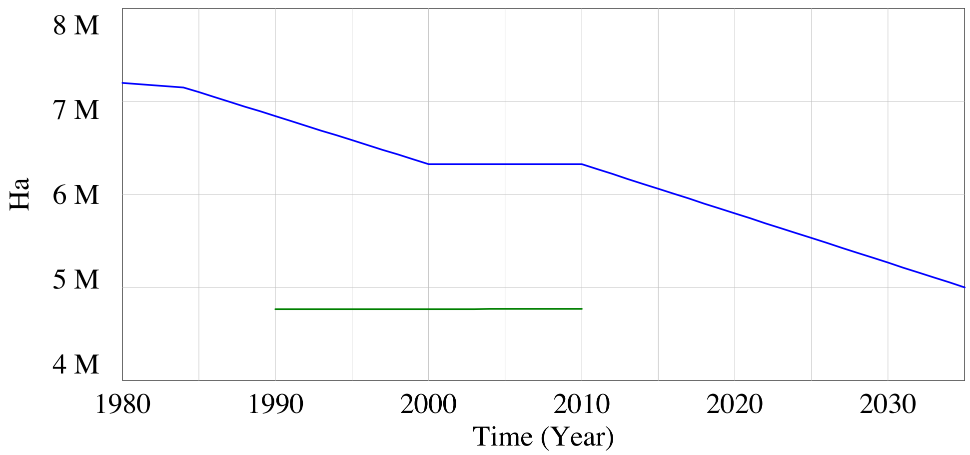

Figure 74: Development of exogenous variable *classified forest* area (blue) from T21-Senegal34b and total protected area in Senegal according to (IUCN & UNEP-WCMC, 2011)

Firstly, the development of the variable is peculiar in the because of the linear decreases of the classified forest area. Protecting an area is a legal act happening at a specified point in time so one should assume step-like behavior rather than ramps. Even if one interprets this variable as the effectively protected forest (including delays for implementation of enforcement or raising awareness among resource users) one should expect a development of exponential delays following a step-like changes. Hence the structure-behavior verification test of this data was failed. Since T21-Senegal34b is missing the documentation on the data source, the origin of the data could not be reviewed. The reasons for the decline remain unclear.

Furthermore Figure 75 shows that the *Proportion of forest land classified* calculated from the classified forest and the FAO data for forest land fluctuates tightly around 75% of the forest all the time. Tight protection from any use in these vast areas seems to be very unrealistic.

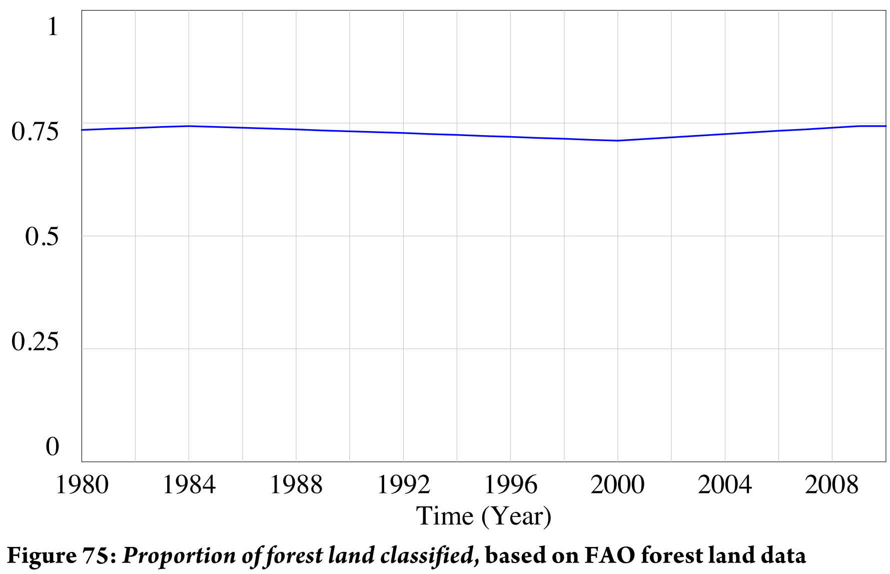

Figure 75: *Proportion of forest land classified*, based on FAO forest land data

The classified forest area given by (USAID, 2008) of 6.24 million ha is very similar to the 6.32 million ha for that time by the model. But the same source also states that this protection is hardly enforced: "*It is often aberrant to see a "classified forest" sign in a completely bare zone, following spontaneous colonization and unsustainable agriculture in formerly forested areas. This is the case of numerous classified forests situated in the department of Podor such as the "Ngaoulé Classified Forest." Other examples include: the city of Pire, which is located entirely within the classified forest of Pire; the "Corniche" classified forest in Dakar (100 ha); which is totally occupied by hotels; the Pata forest, which is 54% occupied by settlements and fields; and the Naere forest at Ross Bethio, Saint Louis region, which is 88% occupied by settlements and fields.*"

Note that the quote does not mention selective harvest in classified forests but actual deforestation and even conversion to cropland of classified forests.

That lack of enforcement may explain why (IUCN & UNEP-WCMC, 2011) considers less than 5 million ha of area protected in Senegal (see Figure 74), which includes not only forests but also coastal marshes, and other non-forest areas, so that the total protected forest area according to their classification may be even much lower.

As a result of the lack of enforcement, forest protection is completely ignored for the base run (*switch forest area protection* and *switch protection timber both turned off*). A sensitivity analysis with a small amount of protected forest seems advisable though.

<u>Limitations of protected areas</u>

As mentioned above the information on the amount of protected areas and on the actual enforcement were not sufficient to adequately model forest protection in Senegal. Ideally these to things should be kept separate, e.g. by modeling an enforcement effect on the amount *minimum timber volume in classified forest* and on an "effectively protected area". This enforcement could e.g. be dependent on the *timber volume per ha* and a "proportion of original forest remaining" because they express "how bad" the situation actually is (using a delay function to create a "perceived value", though). It may also be useful to disaggregate protected forest into different protection statuses that received different enforcement. Enforcement could of course also depend on environmental expenditure, but probably in a different manner than in T21-Senegal34b.

6.5.9 Reforestation

T21-Senegal34b did not contain any natural reforestation only deliberate anthropogenic reforestation. This approach is supported by sources stating that animal exclosures can allow for reforestation indicating that without protecting fences natural reforestation does not occur (FAO Forestry Department, 2010). Hence the T21-SenegalEFf1 also contains only deliberate reforestation.

The reference mode data used in T21-Senegal34b was not fitting data very well (see Figure 76). It had been dynamically modeled as being driven by the *relative accumulated public environment expenditure* (from sector 29) using a constant *elasticity of deforestation to relative forest stand* of 0.8. This value had been obtained through calibration by trying to make not only the simulated data for reforestation fit the a rising trend in the time series data, but also to make the deforestation simulation fit with its reference mode data (together with the accessibility loop described further below) (G. Züllich, personal communication, 2012). The reference mode had however only from 2001 to 2007 been made up of measured data, whereas from 1990-2000 the proportion of reforested area that are large plantations from 2001 had been applied to data series of large plantations to estimate a data series of total reforestation (see documentation in xls-data file of T21-Senegal34b).

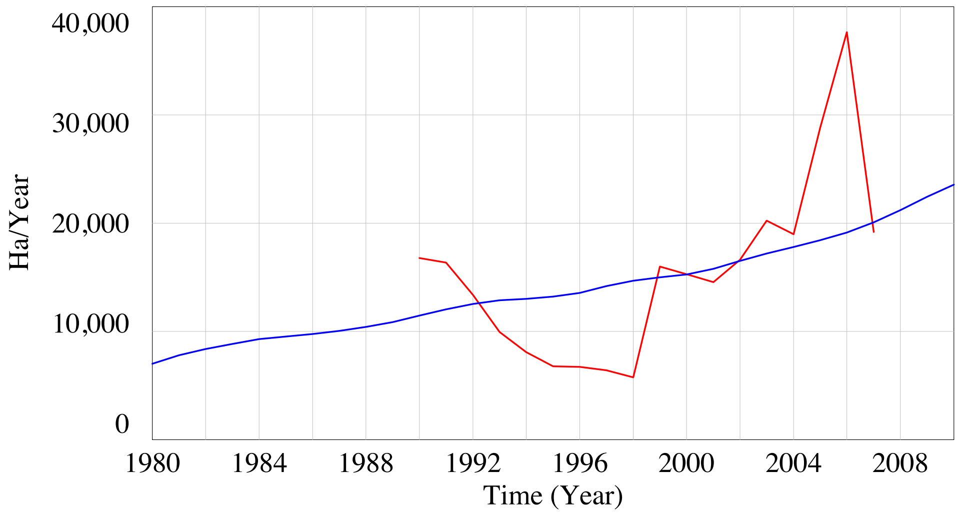

Figure 76: Reforestation as implemented in T21-Senegal34b. Reference mode data (red) and simulation (blue)

New reforestation data however makes a rising trend in reforestation much less plausible (see Figure 77, Ministre de l'Environment, de la Protection de la Natur, des Bassins de rétention et des Lacs Artificiels, 2009). Rather it seems that reforestation is fluctuating wildly, without a clear trend. Therefore the former structure involving an exponential trend using an elasticity was abandoned and in the face of lack of information on the causes of this variable, a constant value equal to the average of the years was used. To calculate that average, the two data series were synthesized as indicated by the black dots in Figure 77: data from) (Ministre de l'Environment, de la Protection de la Natur, des Bassins de rétention et des Lacs Artificiels, 2009) was used for data prior to 2001 and the preexisting data in T21-Senegal34b was used for the years 2001- 2007.

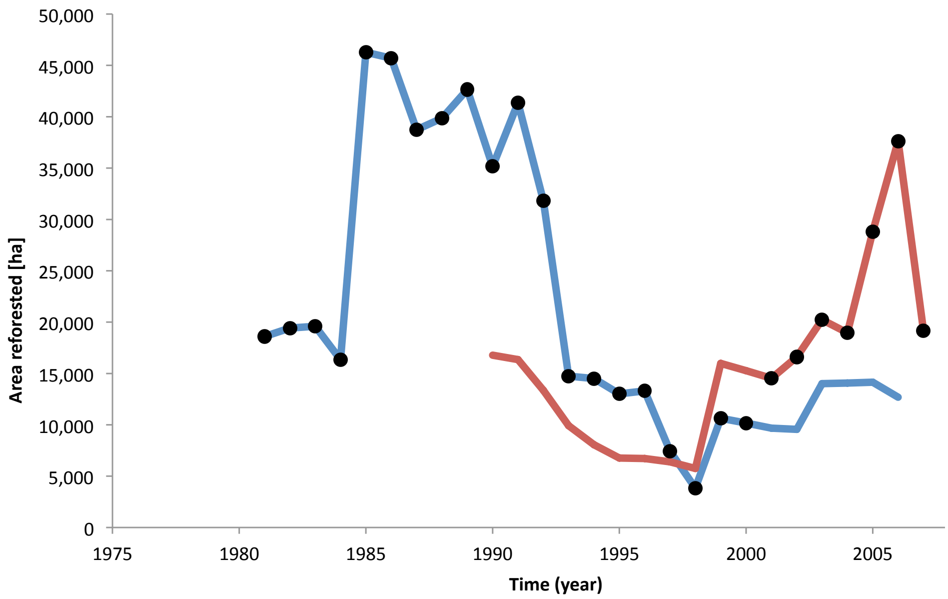

Figure 77: Comparison of old and new reforestation data with data and synthesis.
Red: reforestation data used in T21-Senegal34b, blue: reforestation data found in (Ministre de l'Environment, de la Protection de la Natur, des Bassins de rétention et des Lacs Artificiels, 2009) and reference mode data synthesized out of the two (black dots)

<u>Limitations reforestation</u>

Unfortunately, the recommended sensitivity could not be carried out due to the time constraints of a master thesis.

Using a constant average reforestation has the disadvantage that the effects of the large fluctuations are hidden. Future research should aim at obtaining a more complete data and information on the causes of reforestation to model this variable endogenously. These could e.g. be government decisions driven by the *relative timber volume per ha,* and the *proportion of forest remaining*, the delayed perceived values to be exact. Foreign aid may also play an important role here. But reforestation may also be driven by the need to combat desertification, which reiterates the need to properly model land degradation, possibly including a stock of permanently degraded land.

6.5.10 Deleted accessibility loop

In T21-Senegal34b, the harvest was constrained below the demand not only by forest protection but also by a balancing "accessibility loop". It assumed the most accessible forest will be logged first and that as the forest land shrinks, the more remote the remaining forest is, and thus the more supply should fall short of demand (see Figure 78).

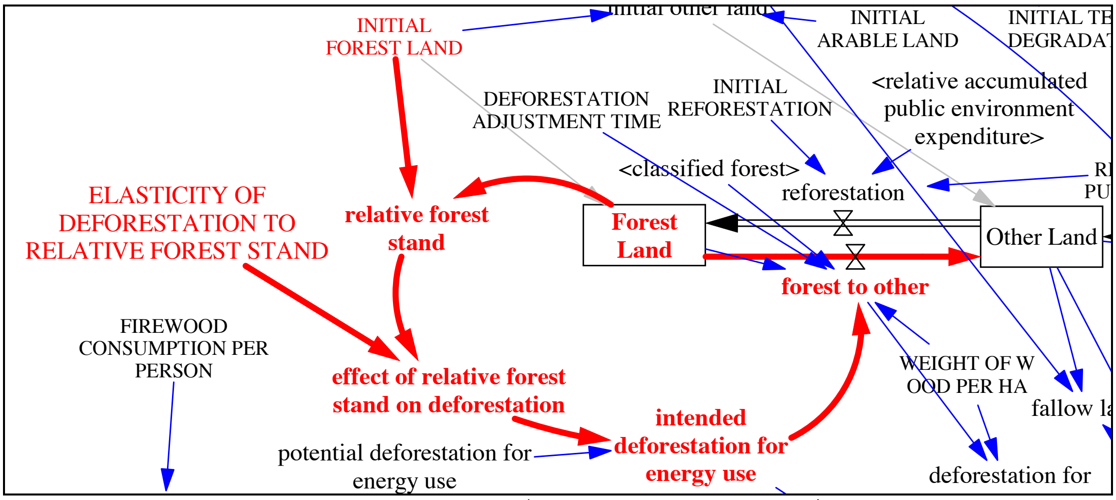

Figure 78: Accessibility loop in T21-Senegal34b (red, emphasized for clarity)

The "elasticity of deforestation to relative forest stand" was equal to one, which would mean that a halving of the forest would result in only half of the demand being satisfied with harvest due to remoteness of the forest. It is questionable if the accessibility loop is really that strong in reality and if it exists at all. One may argue that road density in forest areas may limit access of logging in some areas. But this effect is known from moist tropical forests which are impenetrable for vehicles before roads are built. While that may apply to some degree to Senegal's southernmost dry-deciduous forests, it does not likely apply to the vast Senegalese Savannas with its large interspaces between trees. Hence, timber transport may not need expensive road construction. Similarly, as long as trucks and gasoline are reasonably cheap, remoteness should not be a problem either. Therefore it is difficult to imagine costs for transport or road construction would rise so high that charcoal suppliers would not be able to cover those costs by increasing the price of charcoal somewhat. Furthermore since cooking is a basic necessity of life, the demand for firewood and charcoal wood is likely fairly inelastic to increasing prices for these fuels, which means suppliers know they can recuperate investments for increased access (unless there were government-imposed price restrictions on the resource, of which the author has not heard or read). In addition, the example of Haiti, a country that is already largely deforested, shows an acceleration rather than a slow-down of deforestation with progressing deforestation!

As a consequence this accessibility feedback loop was deleted from T21-SenegalEFf1.

6.5.11 Relative impact of outflows

One important question to ask is which outflows of the stocks contribute how much to their decline. Answering this question, allows for prioritization of policies.

Figure 79 shows that under base-run conditions, the *timber removed by forest fires* is actually the largest contribution for the timber stock decline. The only reason why it is going down so fast is the sinking *timber volume per ha* i.e. since the forest is less and less dense, less timber is lost by the same area affected by forest fires. This is based on the assumption that a fire removes 50% of the timber. It is clear that acquiring data on this variable is crucial.

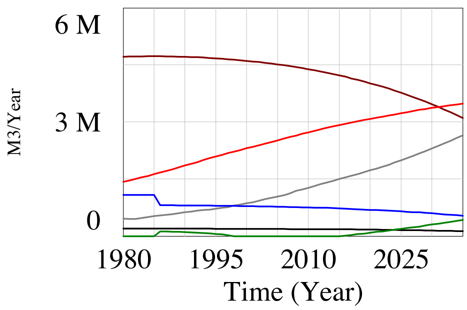

Figure 79: Comparison of the contributions of the different types of timber removal (base run). Blue: timber cleared through conversion to cropland, red: green firewood harvest, green: residual timber harvest for charcoal, grey: industrial timber harvest, black: timber cleared through conversion to mines, brown: timber removed by forest fire.

The second most important contributor to timber decline is the green firewood harvest. That is because in the base run it is assumed that all firewood is harvested green. That assumption is clearly unrealistic, some proportion, potentially a large one, may be collected as dead firewood. This highlights the importance of acquiring data on the *proportion of firewood demand satisfied with green wood*. It also highlights the importance of endogenzing the choice between green and dead wood in the model. It also stresses the importance of additional efforts to bring the butanization campaign or other substitutes into wide-spread use in rural areas.

Next in line, at least in recent years is actually already the industrial wood demand. As mentioned before (6.4.2) FAO data for industrial wood which shows a stabilization for the new millennium is not really measured data but only FAO estimates. It has therefore been ignored and the exponential trend from before was assumed to have continued. The potentially high future contribution of industrial wood demand stresses the importance of acquiring actual data on this variable and on the causes for it so that it can be endogenously modeled. The butanization campaign was heralded as a big success in urban areas. But if the assumptions underlying this model are remotely adequate its influence on the timber extraction is smaller than one would think, because the majority of the charcoal may be pushed on the market resulting from conversion to cropland and mines. This again makes it very important to find out if this hypothesized mechanism actually exists, or if all of the timber from converted land is wasted, in which case the green curve could increase in height substantially.

Figure 80 Shows that under base-run conditions there is no direct deforestation (red green and grey congruently =0, based on an assumption of selective harvest). Deforestation due to forest fires and due to conversion to cropland is at about the same level. Note that deforestation due to forest fires is based on the assumption, that 10% of the forest affected by forest fires is permanently destroyed. Since already 10% would have an effect comparable to the cropland-induced deforestation it seems very important to get information on this issue as the reality could be very different (even at 0% due to highly fire-adapted vegetation). This variable should also not stay exogenous but needs to be endogenized. Deforestation due to mines is at a lower but still notable level (5000 ha year^{-1}), so that better information on this variable seems important as well. In this model, over-thinning becomes the most important driver of deforestation already around the turn of the millennium. This is the result of several assumptions that are not backed by data: the *low initial timber volume per ha* (although necessary for the assumed decreasing development of the timber stock), that there is no direct deforestation (all demand-driven logging is selective) and the shape of the curve for the variable *proportion of thinning leading to deforestation* (see Figure 34). Recall from the analysis of the simplified core model that that the over-thinning only becomes effective once the *timber volume per ha* is already very low. The base run assumes that the development of forest thinning is already in an advanced stage and that forest densities were already reduced in pre-industrial maybe even in pre-colonial times. This is not a very unrealistic scenario because indigenous landscape management by using fire (in favor of savannahs rather than forests) may not be very unrealistic.

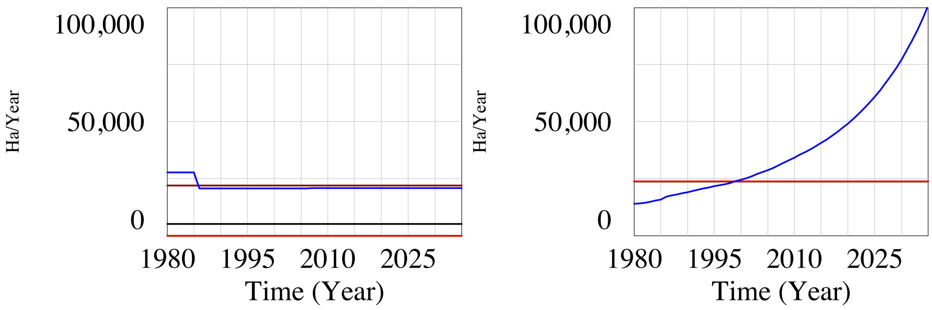

Figure 80: Comparison of the contributions of different types of deforestation (base run). Left pane: Blue: forest conversion to cropland, red: direct deforestation for fire wood, green: residual charcoal induced deforestation, grey: direct deforestation for industrial wood, black: deforestation for mining, brown: deforestation through forest fires. Right pane: Blue: deforestation due to over-thinning, red: reforestation (= negative deforestation but taken positive here for easy comparison)

Finally it also seems necessary to endogenize reforestation properly or turn it into a policy variable since it does seem to play an important role.

6.6 Forestry Trade sector

As already mentioned under 6.1, the EF is a consumption-based approach and hence any timber harvest that was used to produce exported products (timber “embedded” in these products) should be subtracted from the EF of forestry. Similarly, the timber that was harvested in other countries to produce imported products should be added to the EF of forestry. Division of the *embedded timber imports* and *embedded timber exports* with the *GFN constant forest increment world* and multiplication with the *equivalence factor forestry* yields the *forest EF embedded in imports* and *forest EF embedded in exports* respectively.

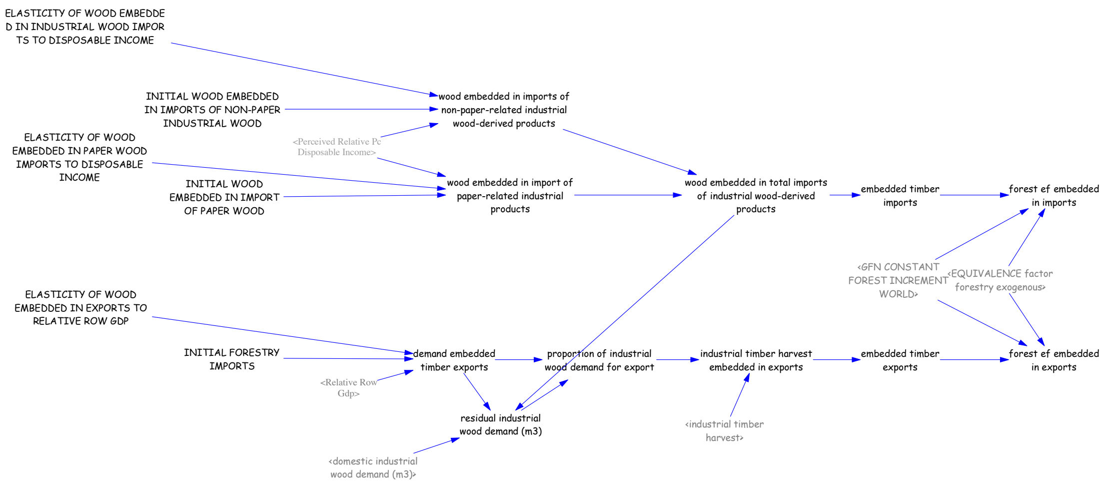

Figure 81: Forest trade sector calculating the forest EF "embedded" in wood-derived products imported or exported.

The GFN accounting methodology considers 33 different wood products, of which 19 actually played a role in Senegal during the period from 1980 to 2008. For the sake of simplicity this model, they were aggregated. Three different categories were seen in terms of their final use and demands:

- Wood-derived fuel products (firewood and charcoal)
- Paper- and pulp related products
- Wood derived industrial not related to pulp/paper

The imports in the first group are however so low (see Figure 82), that calibration would have been impossible (only three data points in the last three years), so they were neglected on grounds of their low impact for the model and only the second two groups were considered (see Figure 81).

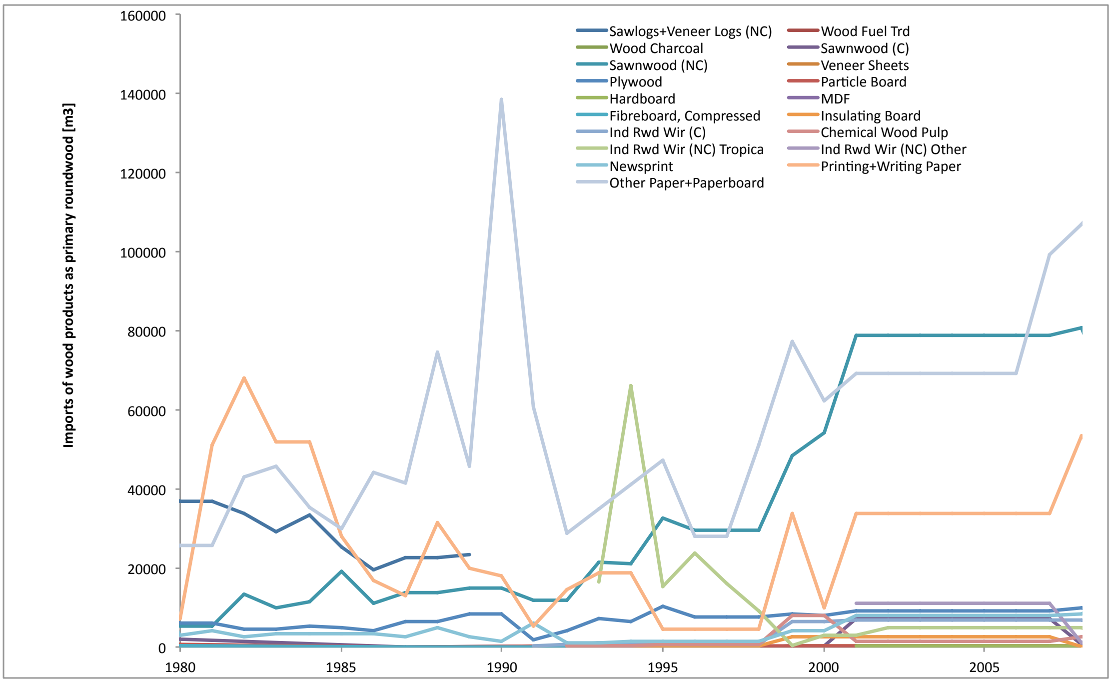

Figure 82: FAO data on imports of different wood-derived products to Senegal after conversion to primary round wood amounts using GFN Technical Conversion Factors

(**FAO Statistics Division, b; Global Footprint Network, 2011**)

Before the different data series can be aggregated however, they need to be converted to a common unit (e.g. kg of newsprint and m^3 of sawn wood). This is also necessary to calculate the amount of embedded timber. This is facilitated by multiplying the data series for imported / exported quantities with the respective GFN Technical Conversion Factors that express, how much of the primary product is needed to produce a certain quantity of the derived product (m^3 of roundwood per kg of newsprint). In order to keep the model lean, this conversion was done in Excel prior to import into Vensim.

There was no information available on what factors may influence imports of wood derived products. It appears reasonable however, to assume that higher disposable incomes lead to higher consumption which also lead to higher imports, especially of goods which are not produced domestically (M. Pedercini, personal communication, 2012). It was therefore decided to let the two categories (*wood embedded in imports of non-paper-related industrial wood-derived products* and *wood embedded in import of paper-related products*) be driven by the *perceived per capita disposable income* using respective elasticities and initial values. The elasticities were manually calibrated so that the simulation fits the data as best as possible (see further below). The two variables are then summed up in the *wood embedded in total imports of industrial wood-derived products* which equal to the *embedded timber imports* is as long as other wood categories do not matter.

In case of imports and exports there were fluctuations of which the nature is unclear. As described under 5.3.5, it was only attempted to reproduce the trend not the short-term fluctuations of the data.

Export demand is modeled in a way similar to imports but assuming that the economic productivity of the rest of the world (ROW) is the main driver of exports (variable *ROW GDP)*. However this driver does not directly drive exports but only a demand for exports, whereas the actual exports may be lower than the demand (the capacity to supply may be limited below the demand e.g. when the stock runs out). Based on the export data it is assumed that next to all wood products exported are for industrial use (hardly any fuel wood products exported, see Figure 83).

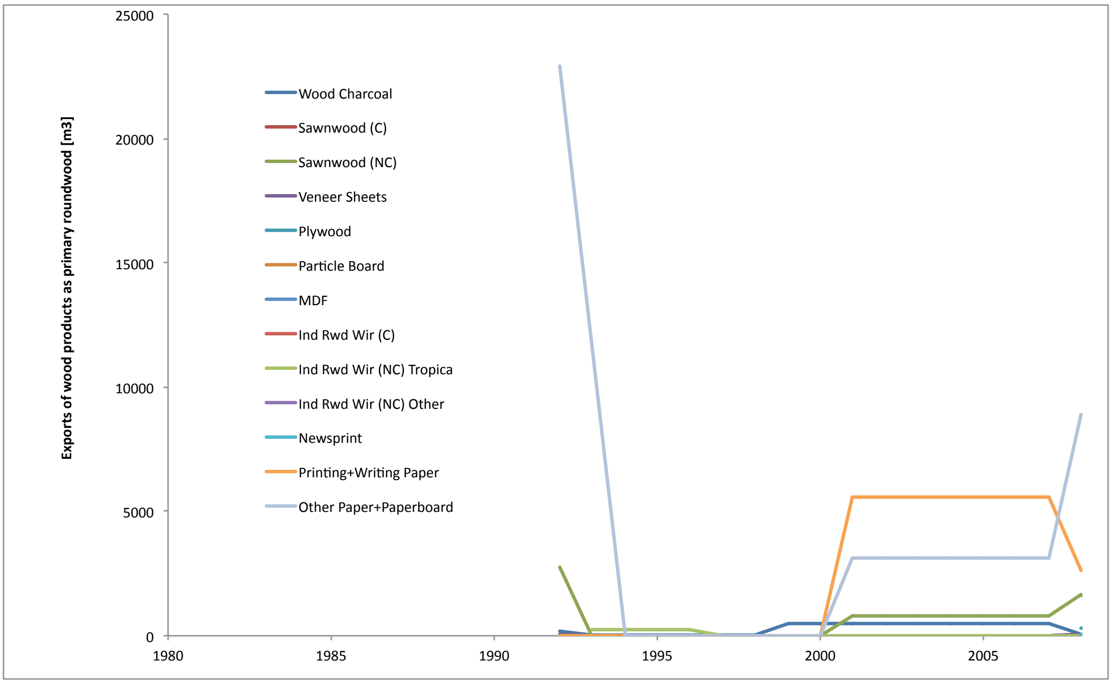

Figure 83 FAO data on exports of wood-derived products from Senegal after conversion to primary round wood amounts using GFN Technical Conversion Factors (FAO Statistics Division, b; Global Footprint Network, 2011)

Since the data on exports is very limited both in terms of the time period covered and the actual amounts traded, it does not seem reasonable to disaggregate it into product types. Hence the export demand forms part of the total *residual industrial wood demand (m*^{3}*)* together with the *domestic industrial wood demand (m*^{3}*)* as mentioned in section 6.3. Following the same logic, the *wood embedded in total imports of industrial wood-derived products* is subtracted from the *domestic industrial wood demand*. If the harvest is smaller than the total demand, the export demand is satisfied by the same proportion than it has in the total demand (assumption of non-existance of preference for satisfying domestic or foreign demand). The result is the *industrial timber harvest embedded in exports* which is equal to the *total embedded timber exports* as long as there are no other significant exports besides industrial wood-derived exports (e.g. no notable fuel-wood or charcoal exports).

The simulation was calibrated by manually adjusting the *elasticity of wood embedded in exports to relative row gdp* to make the *forest EF embedded in exports* fit to the historical data as best as possible. This historical data series was calculated by aggregating the exports of all products after conversion to primary products using GFN TCF.

It can be seen in Figure 84 that the data appears to fluctuate around some kind of mean during the 1980's and 1990's but starts rising in the new millennium. The result of the calibration of the variable *wood embedded in import of paper-related industrial products* roughly reproduces this trend.

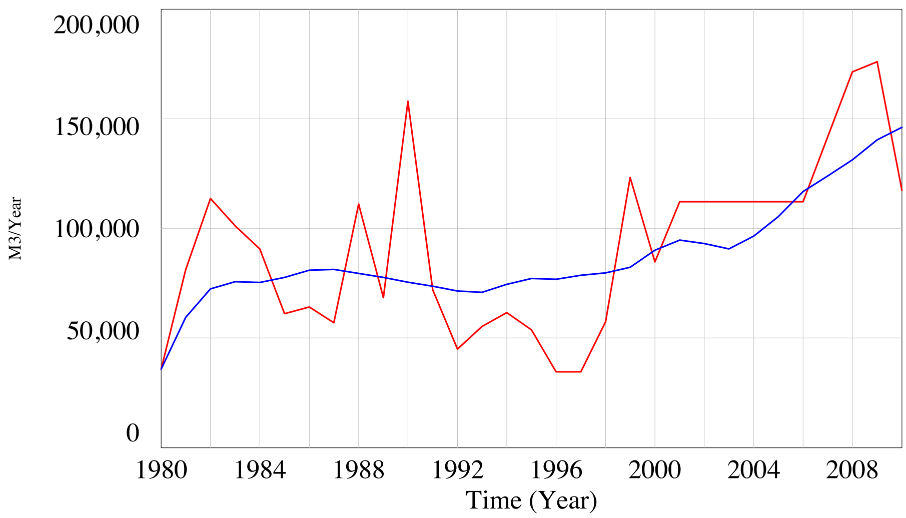

Figure 84: Calibration of *wood embedded in import of paper-related industrial products*. Data (red), simulation (blue)

The fit of the calibrated simulation with the data is less good for the variable *wood embedded in import of non-paper-related industrial products* (Figure 85). The simulation overestimates the data in the 1980's and underestimates it in the 2000's. The variable *perceived relative per capital disposable income* as the presumed driver of the variable to be calibrated here has a rise in the early 90's, which is simply not present in the data. And the presumed driver only seriously starts rising in 2004 whereas the variable starts rising already in 2001.

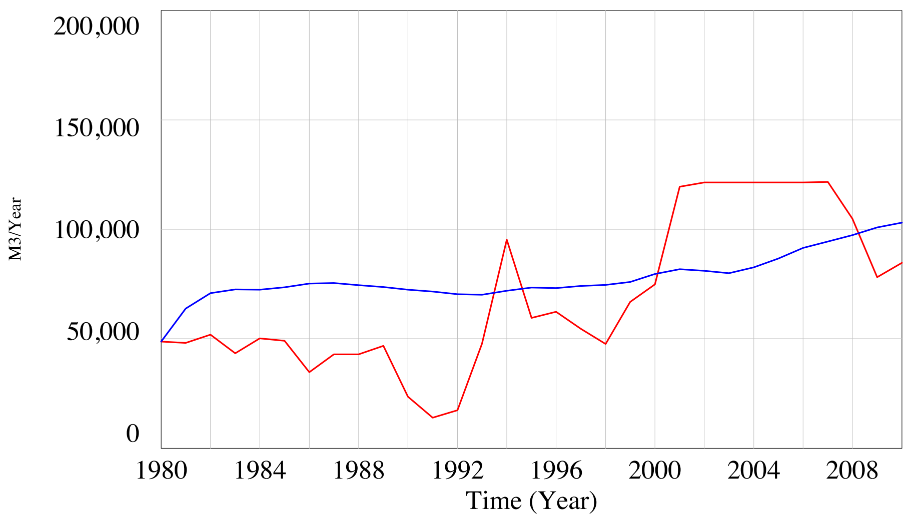

Figure 85: Calibration of *wood embedded in import of non-paper-related industrial products*. Data (red), simulation (blue)

Calibration attempts assuming a lower initial value than the actual data result in a somewhat better over-all fit but an honest assessment must conclude that the way that this variable is modeled has failed the reference mode reproduction test. Additional causal structure is needed to better reproduce the development of the variable in question. As this would however require additional knowledge and data not available to the modeler and could not be acquired in time the structure was still left as is. The impact of this inadequacy on the EF of consumption is confirmed to be still very low for past data as it is only one part of the EF embedded in imports and the EF embedded in imports itself is only small compared to the EF of production.

Figure 86 displays the simulation of the *Forest EF embedded in imports* and the Data on this variable from calculations of the GFN. Naturally, the fit is not as good as in Figure 84 but somewhat better than in Figure 85 as it results from a synthesis of the two and the two respective variables are in the same order of magnitude.

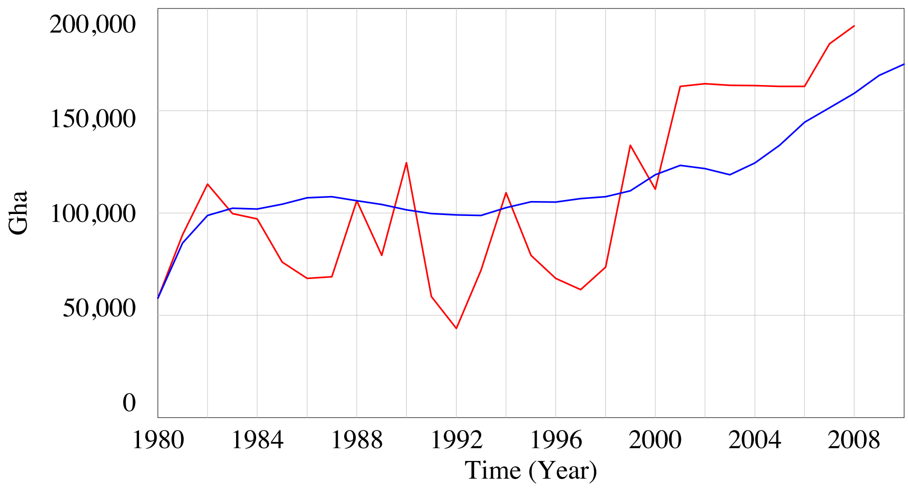

Figure 86: *Forest EF embedded in imports*. Data (red), simulation (blue)

Due to the inadequacy of reproducing the very recent rise of the EF embedded in imported products and the overestimation in the 1980s and 1990s, it remains in doubt whether the model projections based on the introduced model structure can be taken seriously, especially since small changes in elasticities can mean strong changes in far future developments.

Figure 87 shows that the available data for the *embedded timber exports* is very limited, the 1980's are missing completely. In addition the data has drastic jumps and stretches of constancy. It is impossible to get a good fit of this variable with a presumed driver (*rest of the world GDP*) that is rising and gently accelerating. In the calibration attempt more emphasis was given to reproduce more recent than older data. In addition it was assumed that demand for Senegalese timber products outside Senegal should be rising due to economic prosperity outside of the country.

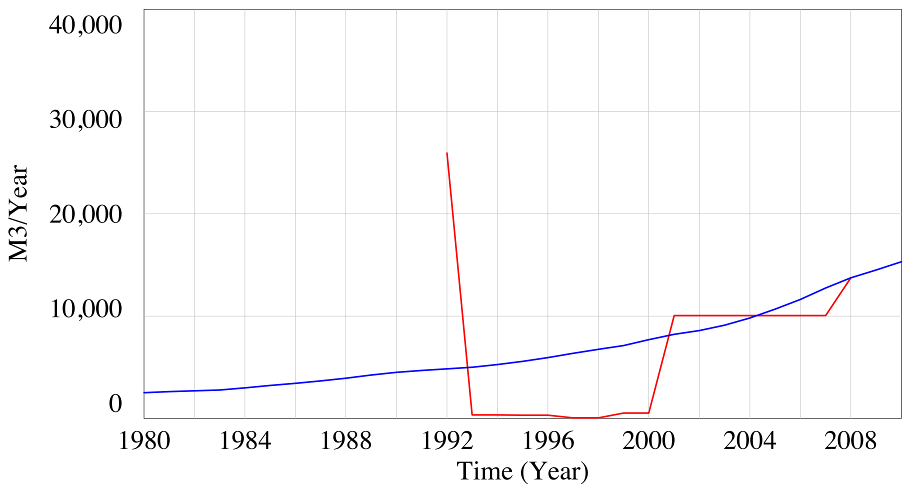

Figure 87: Calibration attempt of *embedded timber exports*. Data (red), simulation (blue)

Limitations of the forestry trade sector

This calibration structure for *embedded timber exports* has failed the reference mode reproduction test. Hence additional causal structure would be needed to adequately reproduce the development of the variable. Additional information about the factors influencing forestry product exports in Senegal is needed. The shape of the curve with its jumps and constant stretches could indicate that there may be strong political/administrative influence here (e.g. maybe an export bans was installed in the beginning of the 1990's and a quota in the new millennium whereas in the 1980s there was free trade?). The data should also be scrutinized. How was it derived, what are the sources? The calibration was used in spite of its inadequacy as no better approach was available.

An important question is whether modeling this sector with elasticities, is good enough or if it should be attempted to find out about the actual causal mechanisms responsible for imports and exports and model this as more disaggregated structure with more stocks etc. One problem with that is that we would leave one of the modeling boundaries, the country of Senegal. Also the question is if the potential impact, or the difference that the embedded imports make to the total footprint would justify the effort and complexity of additional structure. The left pane of Figure 88 shows that we can see from GFN-data that the impact of the cross-border EF flow is low in Senegal since the forestry EF of consumption is only slightly higher than that of production. The right pane of the same figure shows that the difference in the simulation is in the same order of magnitude which is a good sign that the above-mentioned inaccuracies may not have a big impact.

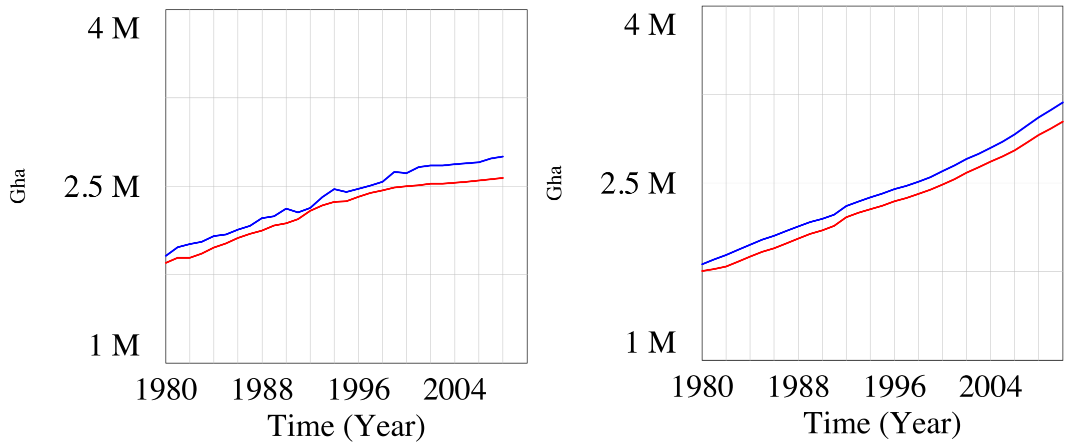

Figure 88: Impact of EF of forestry products embedded in trade on total forestry EF.
***Forestry EF of production* (red) and *Forestry EF of consumption* (blue); data (left pane) simulation (right pane)**

It can however also be seen in the data (left pane) that the impact of cross-border EF flow has increased in the new millennium compared to before and that this increase is lower in the simulated data. That indicates that overall the impact is too low in the simulation for recent years. If the trend continues, this inadequacy of the simulation compared to the data is likely to increase which is likely to decrease the accuracy of projections. So while overall, the simplified modeling approach taken for the forest trade sector makes sense for Senegal, but some caution should remain.

The sector assumes non-preference of satisfying domestic or foreign demand, which may easily not hold if prices differ, or there are governmental trade restrictions.

The exclusion of wood-derived fuel may become a problem if in the future imports or exports became significant. The development should be watched, as data on imported fuel wood appeared only in the most recent years. It is unclear if this is the beginning of a growing trend or if it will stay at low amounts or whether there was just no data available before (but existed).

6.7 Changes in the pre-existing Animal Husbandry and Forestry sector

Sector 20 “animal husbandry and forestry” estimated the economic contribution of forestry to total economic production in T21-Senegal34b (see Figure 89).

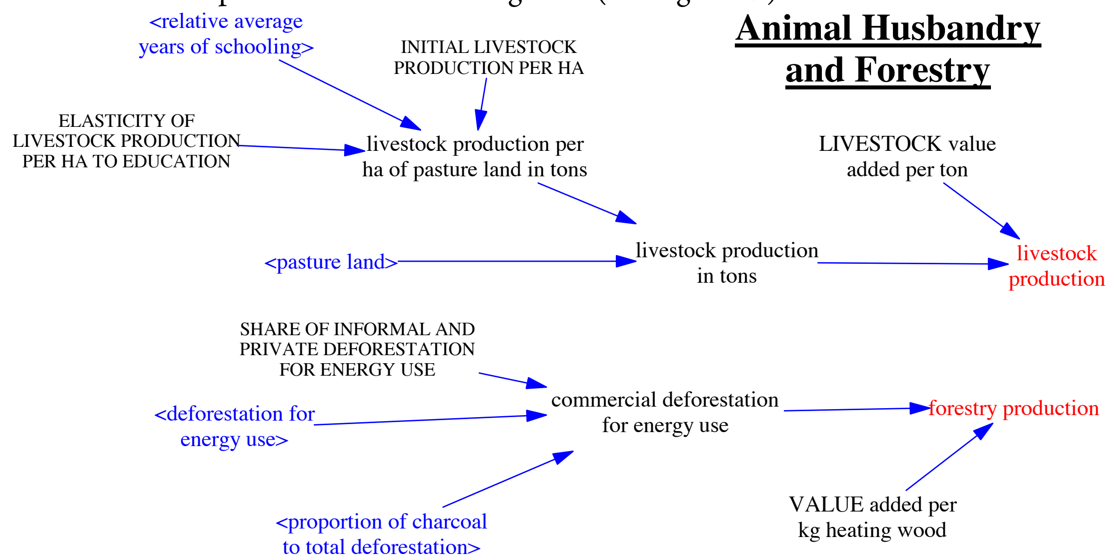

Figure 89: “Animal husbandry and forestry” sector in T21-Senegal34
The sector provided economic contribution of the forest sector to the agricultural sector and from there to GDP

In other sectors not depicted here, forestry production was part of agricultural production which in turn was part of total GDP. And GDP in turn fed back on forestry activities e.g. by influencing population, public expenditure for reforestation so that this sector closed 93 large feedback loops.

The new types of timber harvest are added to the sector in T21-SenegalEFf1 (see Figure 90) and due to the harvest unit change (from kg to m^3), the “value added per kg” of wood needs to be change to *value added per* m^3 *of harvested wood.*

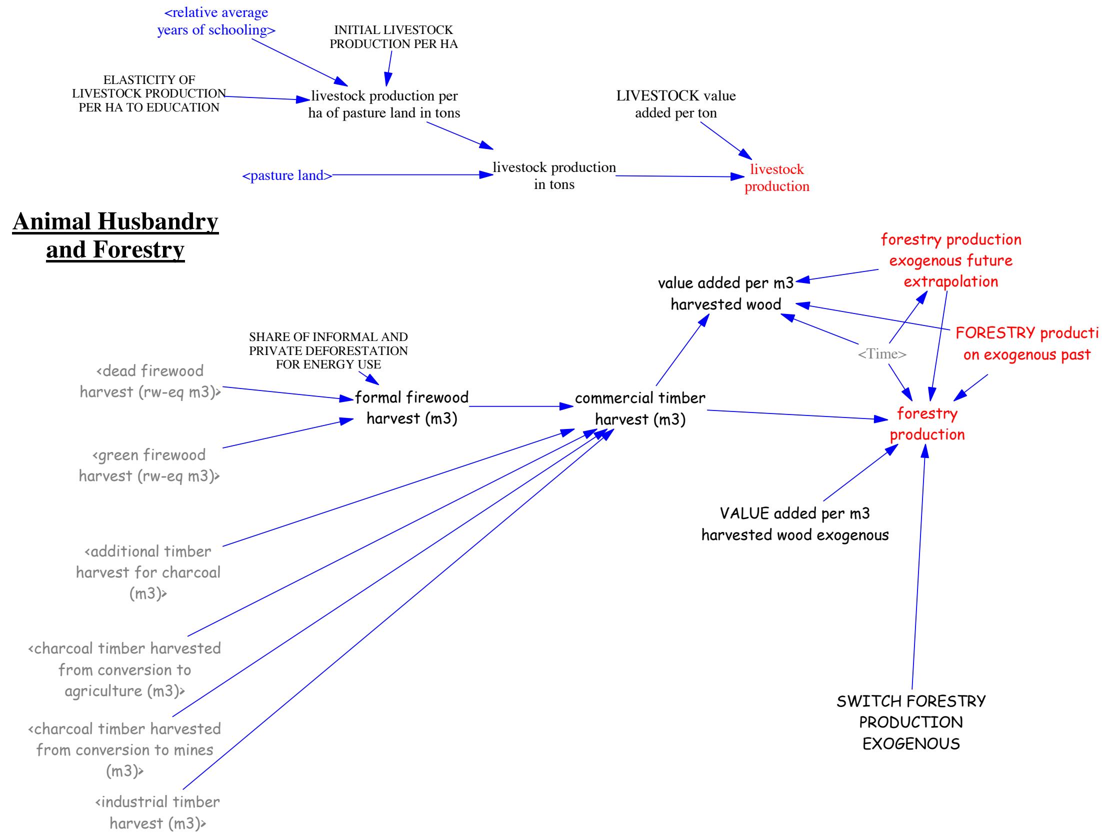

Figure 90: Changed Animal Husbandry and Forestry sector in T21-SenegalEFf1

In T21-Senegal34b, the *value added per kg of heating wood* was obtained by dividing known data for forestry production by the *commercial deforestation for energy use*. This effectively means that for the past, the loop is cut, or force-fit. Furthermore the *value added per kg of heating wood* was held constant at its 2010 value for the future, which appears unreasonable, given its past development which looks rather exponential.

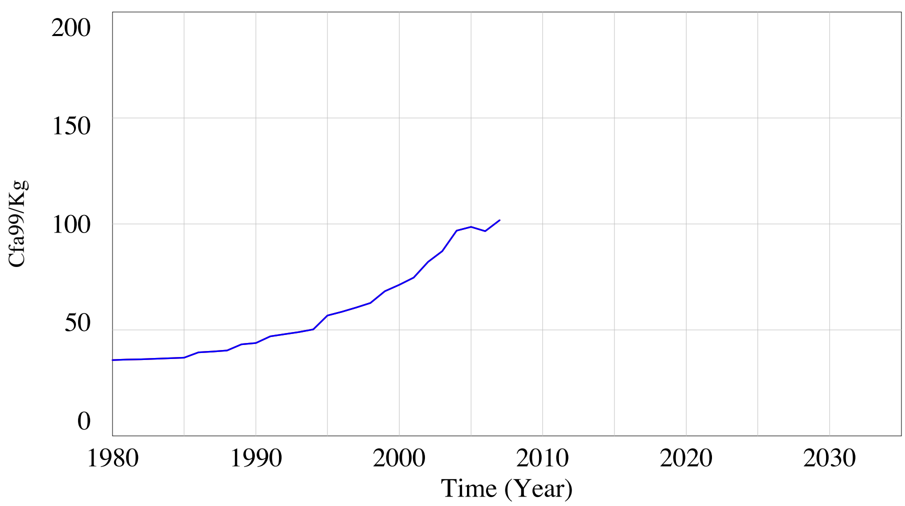

Figure 91: *Value added per kg heating wood* in T21-Senegal34b

This exponential development of the *value added per kg of heating wood* may in fact indicate a flaw in the model, because it is very unlikely to rise exponentially (it should be rather constant or may even decrease due to subsidized butane as an affordable and superior substitute and therefore sinking prices for firewood and charcoal). It appears more reasonable that the harvest is increasing exponentially.

As there was no data *on added value per m³ of harvested* available it was not possible to properly connect this sector to the rest of the model. It was therefore decided that the rest of the sector was fed with exogenous data (*forestry production exogenous past*). This means that partial model calibration is used and the model is not calibrated as a whole. This is effectively the same set-up as before for past data, but has the advantage that changes in the model do not affect the rest of the model for past data. For the future, the rest of the model was fed with an exponential extrapolation of the financial forest production data (*forestry production exogenous future extrapolation*). Compare Figure 92 and Figure 93 to see the changes in the behavior of the forestry production. The last few years seem to indicate an acceleration of the exponential growth, which cannot be reflected by a simple exponential regression though, as it treats all data points equally.

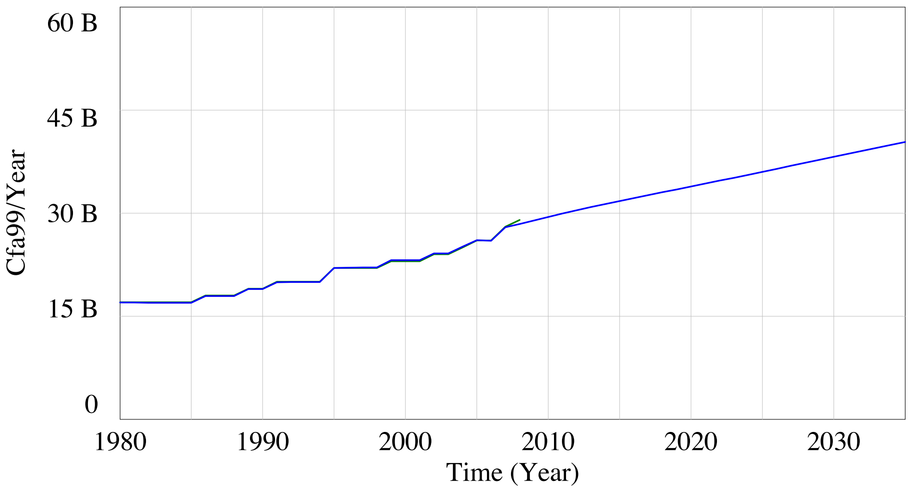

Figure 92: Forestry Production in T21-Senegal34b; simulation (blue), data (green)

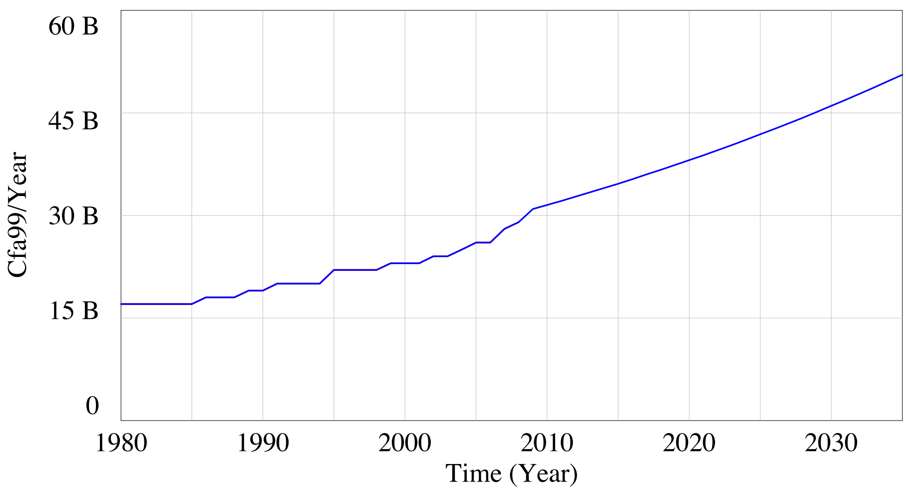

Figure 93: Forestry Production in T21-SenegalEFf1; simulation (blue), data (red)

The possibility of connecting the commercial harvest to the forestry production was retained and can be switched on by turning the *switch forestry production exogenous* to zero. This would however require data or some reasonable assumptions on the development of the *value added per m³ harvested wood exogenous*. It is very likely that different forest products have very different added value and thus the variable would need to be disaggregated accordingly.

The animal husbandry part of the sector remained unchanged.

6.8 Reference mode reproduction test of harvest and EF

A central test is whether the model structure can replicate past data of the EF. In order to grow confidence that it does so for the right reasons it is also necessary to test if the model reproduces the reference mode for the harvest data. While the reference mode for the EF is given by GFN data the reference mode for the harvest needs to be derived from FAO data first. Each of the component harvests should also be checked for fit with its own reference mode.

Figure 94 shows the charcoal production data from FAO (FAO Statistics Division, b). The causes for the fluctuations from 1980 to 1996 are unclear. After 1996 the data series does not consist of measured data any more is an FAO estimate.

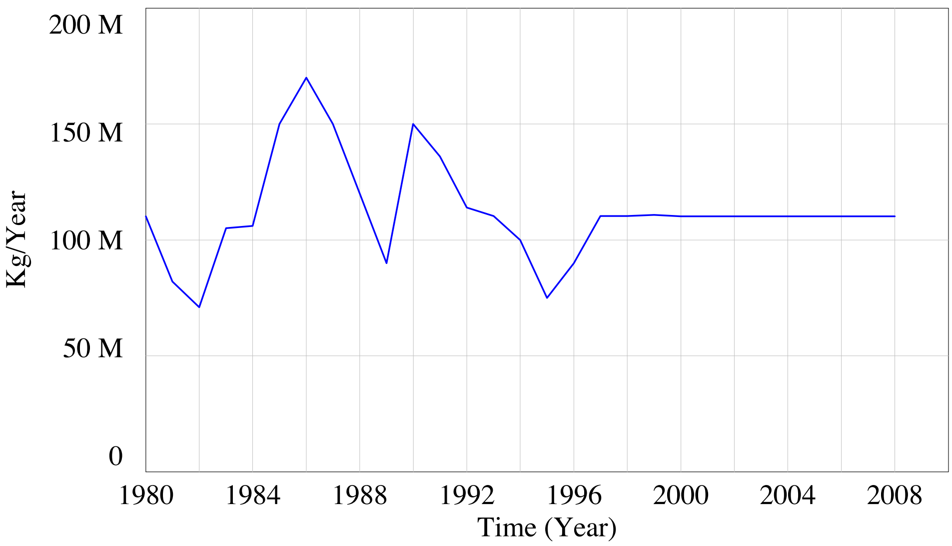

Figure 94: Charcoal production data FAO (FAO Statistics Division, b)

In the light of the butanization campaign, which was quite successful especially in urban areas where charcoal is used (see Figure 58), one would expect a sinking charcoal production. Even if most of the charcoal was pushed on the market due to land-conversion, an increasing number of butane users would create stockpiles of charcoal and sinking charcoal prices that would at some point disincentivize production of charcoal from land-conversion related timber. Hence it is probable that FAO simply kept the last data value since they did not get any new data. Therefore this FAO data series can probably not be trusted and should be used with care.

The FAO category "wood fuel, non-coniferous" however, includes charcoal (FAO, Eurostat, ITTO, & UNECE, 2011):

"WOOD FUEL (INCLUDING WOOD FOR CHARCOAL)

Coniferous

Non-Coniferous

Roundwood that will be used as fuel for purposes such as cooking, heating or power production. It includes wood harvested from main stems, branches and other parts of trees (where these are harvested for fuel) and wood that will be used for charcoal production (e.g. in pit kilns and portable ovens). The volume of roundwood used in charcoal production is estimated by using a factor of 6.0 to convert from the weight (mt) of charcoal produced to the solid volume (m3) of roundwood used in production. It also includes wood chips to be used for fuel that are made directly (i.e. in the forest) from roundwood. It excludes wood charcoal. It is reported in cubic metres solid volume underbark (i.e. excluding bark)."

Therefore this data could also be biased by the bad charcoal data. But, looking at Figure 95 it seems unlikely that wood fuel has been calculated as the sum of charcoal wood calculated using a conversion factor of 6 m^3 t^{-1} because if it had, the fluctuations of the charcoal wood curve should show up more prominently in the wood fuel curve. There are some similarities in the fluctuations of the wood fuel curve but of much lower amplitude, but it seems more likely that firewood production and charcoal production have been affected by similar factors than that firewood production should be countercyclical to charcoal wood production smoothing out the fluctuations of charcoal in the combined curve.

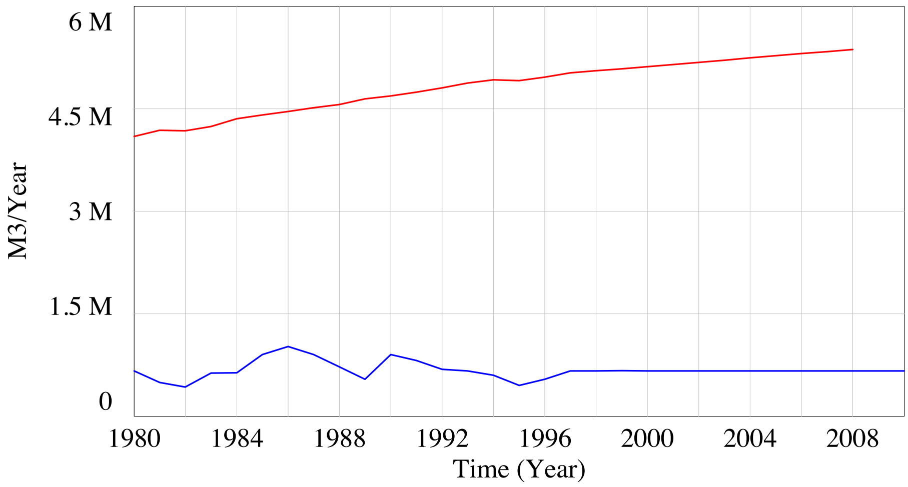

Figure 95: Wood fuel data (FAO, red) and charcoal wood production (blue) calculated from FAO charcoal production data using FAO's conversion factor of 6m^3 t^{-1} (FAO Statistics Division, b)

It therefore seems more likely that FAO wood fuel data was reported to FAO using an unknown estimation method which includes charcoal wood from the start and which was different from the method used to estimate charcoal production.

GFN methodology uses a TCF for converting derived harvest data of wood fuel into primary wood fuel data. The latter should be in solid m^3 $year^{-1}$. Since however FAO wood fuel harvest data is reported in this unit already (see citation above (FAO et al., 2011)), it is unclear why such a conversion factor is needed at all. Hence one of the reference modes used is simply the unaltered FAO wood fuel (NC) data. This is meaningful since the model does not contain any conversion factor for wood fuel.

Since however GFN uses this method and it can only expect to reproduce the EF and harvest reference mode simultaneously if the same methodology is used to derive harvest data, one harvest reference mode was calculated using this standard approach.

A third reference mode was derived because as mentioned the model uses a different conversion factor for charcoal than FAO or GFN data. First charcoal wood was calculated using the FAO charcoal efficiency subtracted from the FAO wood fuel production to yield the supposed firewood harvest. Then charcoal wood was calculated using the lower efficiency of $10m^3\ t^{-1}$ used in the model and added to the firewood harvest again to gain a "corrected" wood fuel harvest. Figure 96 shows that the base run simulation is fairly close to the GFN-reference mode of harvest data of wood derived fuels (charcoal wood and firewood). The discrepancy grows in the recent years though. Interestingly it was also found that the increasing discrepancy of the simulation from the reference mode is due to the fact that as the gains of the butanization programs experience diminishing returns in recent years, its effect is overpowered by population growth. The butanization program does not reduce the percentages using firewood and charcoal to zero. Instead the charcoal percentage is already stabilizing.

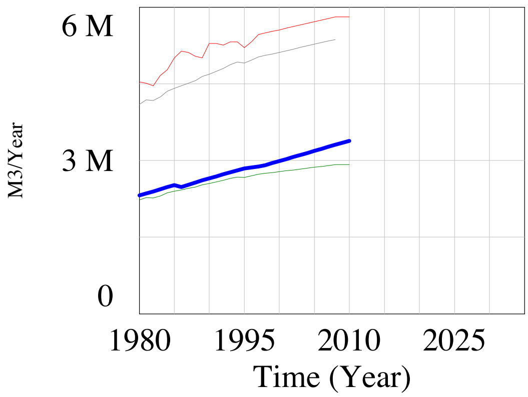

Figure 96: Comparison of the base run simulation (thick blue) to three reference modes. Reference mode calculated using 2010GFN-methodology (green), Unaltered FAO data (grey), correcting FAO wood fuel data for different charcoal conversion factor used in this model (red)

What is strange about this good fit though, is that GFN experts (D. Moore, personal communication, 2012) stated that the calculation of this reference mode is based on bad data for the TCF of wood fuel which is supposed to be changed from 0.543478 to 0.913993 in the next edition of the GFN methodology. That would bring the reference mode much closer to the grey line (unaltered FAO data TCF=1, which seems most reasonable choice any way as outlined above). If the data is corrected for the much lower charcoal conversion efficiency ($10m^3\ t^{-1}$) used by the model than for the reference mode ($6m^3\ t^{-1}$), the discrepancy grows even larger (red line).

It can be a useful exercise to attempt to calibrate the simulation to fit the data using the available uncertain parameters:

If one attempts to fit the simulation even better to the base run (eliminating the discrepancy in recent years), that is not possible by using just the uncertain parameters. The *proportion of timber wasted in conversions* moves the curve down only slightly, even if put to 100%. The charcoal efficiency only moves the whole curve down so that a better fit in recent years automatically results in a worse fit in early years. The graph functions for the shares of the population using firewood and charcoal would allow for a good fit, but that would mean significantly more successful butanization program, which is unlikely.

But as outlined further above the GFN-reference mode is most likely not accurate any way, and reality is likely somewhere around the unaltered FAO data (grey line in Figure 96). Calibrating to make the simulation fit with that data. Again calibration using the *proportion of timber wasted in conversions* did not work. The only ways that the *energy wood harvest* could be as high as the unaltered FAO data are:

a) Charcoal efficiency is much lower than assumed. (although even the value of $27m^3\ t^{-1}$ did not bring the simulation up all the way to the grey curve)

b) The charcoal consumption per person and/or the firewood consumption per person are much higher than assumed

c) the butanization program is much less successful than assumed.

d) The population is much higher than assumed

Some model runs exploring the above can be seen in Figure 97.

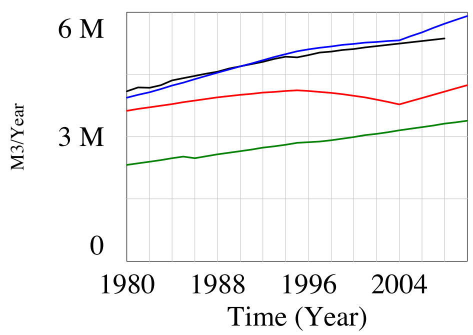

Figure 97: Calibration attempts to the higher FAO reference mode of *Wood harvest for energy use*. Grey: FAO data, green: base run (with const. GFN forest increment), red: charcoal efficiency $27m^3\ t^{-1}$, blue: *charcoal consumption per person* at 65kg (person year)$^{-1}$, *firewood consumption per person* 550 kg (person year)$^{-1}$, black: unaltered aggregated FAO data

If any of the assumptions a) to d) were true, that would mean though, that the current EF and BC calculations by GFN underestimate the actual situation as shown in Figure 98.

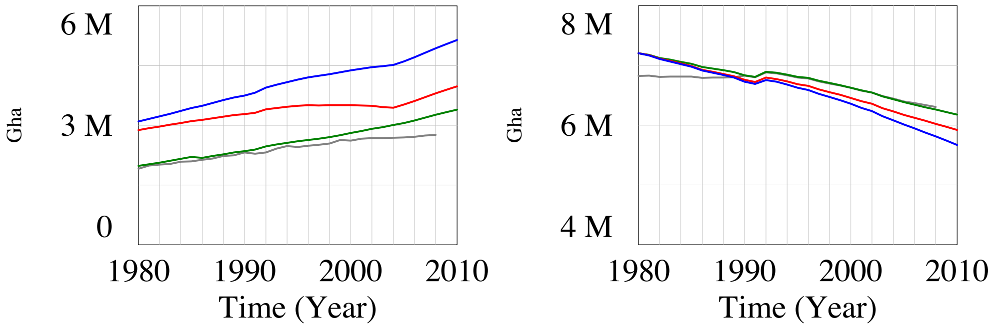

Figure 98: *Ecological footprint of consumption of forestry* and *Biocapacity of forest land* under the harvest scenarios explored in Figure 97.
Green: base run (with const. GFN forest increment), red: charcoal efficiency 27m^3 t^{-1}, blue: *charcoal consumption per person* at 65kg (person year)$^{-1}$, *firewood consumption per person* 550 kg (person year)$^{-1}$, Grey: GFN data

It should be noted that of course the FAO data could easily be wrong too.

6.9 Reference mode reproduction test of Forest Land and Biocapacity

It was already mentioned that the FAO forest land has a data gap before 1990. While looking into the different extrapolation methods, I stumbled over a peculiar fact that the development is extremely linear. The data stated that from 1990 to 2005 exactly 45,000 ha of forest were lost every year (in the years 1994 and 1995 45,200 and 44,800 ha year^{-1} were lost, but on average that is still 45,000 ha year^{-1}). From 2006 to 2008 40,000 ha were lost annually, again a linear decline. From the previous analysis of the simplified core model one would expect a trajectory that is curved in some way, the actual data appeared too linear to be true measurement data. Intrigued by the peculiarity research found the original report, which the Senegalese government sent to the FAO reporting this data (FAO Forestry Department, 2010). It turns out that this data series is based on only one maybe two actual measurement points: There was a forest assessment for the year 2004. Even this data point however was used for the year 2005 instead. This may be because these reports get sent to FAO every 5 years and thus they just used the available value for the year 2005. The above-mentioned rate of change of the forest is an estimation based on a regression of the 2004 forest assessment with the data used in the 2000 report that the Senegalese government sent to the FAO. We can speculated that the year 2000 report may have based its data on another forest assessment which was carried out in 1999, which is mentioned but not directly used in (FAO Forestry Department, 2010) because the forest definitions in that assessment were too different from the definitions in the 2004 assessment (the former had ecological forest category definitions and the latter used economic ones). Sill using the value from the 2000 report to the FAO most probably violates the same principle. This means that the rate of loss may be quite wrong. The value used for the later years also still carries the same bias as the value of 45,000 ha year^{-1} was simply adjusted to 40,000 ha year^{-1} in (FAO Forestry Department, 2010) because experts felt that the situation had improved in some areas. Since the one to two measurement data that this data series is built upon are from 2004 and likely from 1999 and the annual loss is probably wrong, the initial forest area in T21 of 1980 which is as mentioned based on backwards extrapolation of false data over a data gap is very likely also quite wrong. The suspicion that the forest land area data may be wrong is supported by information on the website of the ministry of ecology and conservation of Senegal (Ministry of Ecology and Nature Protection, Senegal, 2009) which states an average forest loss of

80,000 ha year-1 from 1980 to 1990 with the values for the two years being 12.7 and 11.9 million ha, respectively. The latter figure is in stark contrast to FAOs figure for the same year of 9,3 million ha. The difference between these two values (2.6 million ha) is the equivalent to 65 or 32 years of forest loss (depending on whether you trust the 40,000 ha year-1 or the 80,000 ha year-1 value. It is hard to conceive (though possible) that the difference of this magnitude is due to different forest definitions (national vs. FAO). Since the *forest land* area also takes part in the dynamics of the core model it also influences the *timber volume* stock and its run-out time and the *national annual increment* the simulations of the latter two variables in the base run are almost certainly also biased if not wrong. The same consequently holds for the forest BC, including model runs with a dynamic *national annual forest increment.*

But if the data on forest area is almost certainly quite off reality, then what about the good fit of the simulation with the reference mode (see Figure 99)?

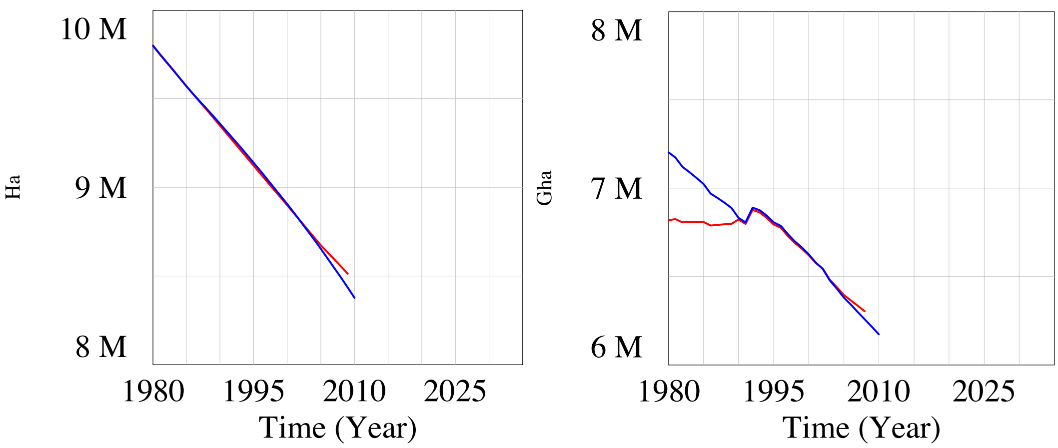

Figure 99: Reference mode reproduction test of Forest land (left pane) and BC (right pane). Simulation (blue) with data (red). Data is FAO data for forest area (plus backward extrapolation) and GFN data for BC. Simulation is a modified base-run assuming constant GFN annual forest increment.

It means that this simulation must also be wrong. The reason is that the information based about the system is so thin that there are so many degrees of freedom of the parameters of the model that it is possible to find a base-run (which appears reasonable from its parameterization) that fits a wrong reference mode. As a consequence, one should not only try to find better reference mode data but one should also endogenize the model further to reduce the degrees of freedom (reduce the amount of pink constants, either by turning them into green constants using values from measurements, literature etc. or by making them dependent on other variables (esp. for exogenous data series and time dependent graph functions).

It appears important to not only look the simulation of the past but also at the future development: Interestingly, the forest area decline seems to accelerate its decline. As can be seen in Figure 100, this is due to over-thinning, as discussed under (6.5.3) and due to the fact that the accessibility loop that was present in T21-Senegal34b was deleted (see 6.5.10)

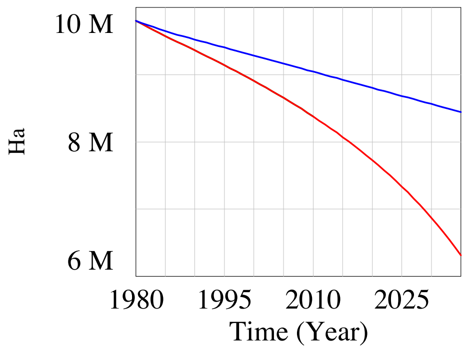

Figure 100: Development of *Forest land* area base run (red) and over-thinning deactivated (blue)

6.10 Implications of dynamic annual increment for the forestry footprint of production and forest biocapacity (full model)

The GFN EF&BC accounting framework assumes a constant annual forest increment due to lack of time series data on this variable. The switch *endogenous national timber growth* allows for switching between GFN's assumption of constancy (*GFN constant forest increment world*) and a dynamically simulated annual increment delivered by other model sectors (*nat. annual timber increment (m*^{3}*)*). This is a sensitivity/boundary adequacy test to the assumption of constancy of the annual increment. A similar test was already carried out for the simplified core model (6.3.12) and is now repeated for the full model.

Figure 101 shows just like in the simplified core model case that there is no influence of switching to a dynamic annual increment for the EF. But there is one on the BC: the calculation with the dynamic annual increment suggests a much lower BC than in case of using standard GFN methodology.

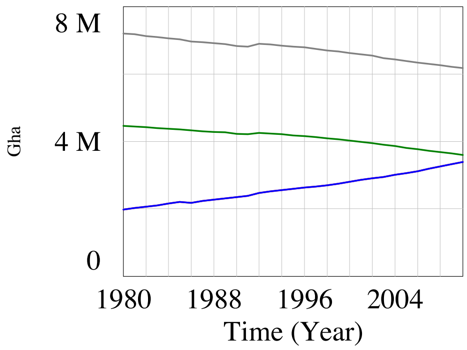

Figure 101: Constant vs. dynamic annual increment in the full model: past development of the EF & BC *BC of forest land* calculated with GFN constant forest increment (grey) and dynamic national annual increment (green) and the *forestry EF of consumption* (blue and red for const. and dynamic annual increments)

The reason can be seen in Figure 102: the dynamic annual increment is much lower than the constant GFN forest increment. Moreover, it is sinking!

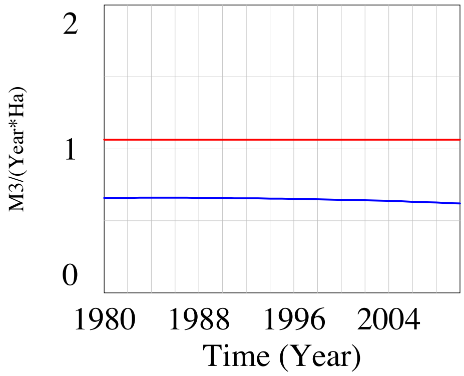

Figure 102: Development of the dynamic *national annual increment*.
Red: GFN constant forest increment, blue: dynamic national annual increment

Recall from Figure 11 that the maximum national annual increment is actually higher than the *GFN constant annual forest increment* but that it depends on the *timber volume per ha*. As can be seen in Figure 103, the latter has peaked in 1985 has since been sinking. Recall from Figure 11 that the maximum national annual increment is at 125m^3 ha^{-1}. Even 1980 the *timber volume per ha* was already below 40 m^3 ha^{-1}. At this continued timber removal at the same rate means that not only is the forest land and the timber stock decreasing but also the potential of the forest to compensate for selective harvest.

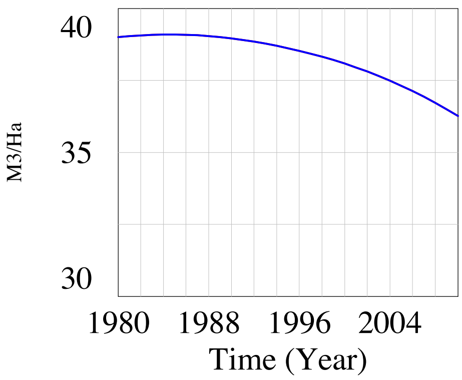

Figure 103: Development of the *timber volume per ha*

What are the implications of the difference in Figure 101? Such figures are used by GFN to raise awareness of current or coming over-use situations. Over-use occurs as soon as the EF is higher than the BC. As Figure 104 shows, when using the constant GFN annual increment, that point in time not before 2030, when using the dynamic annual increment it that point is reached NOW in 2012!

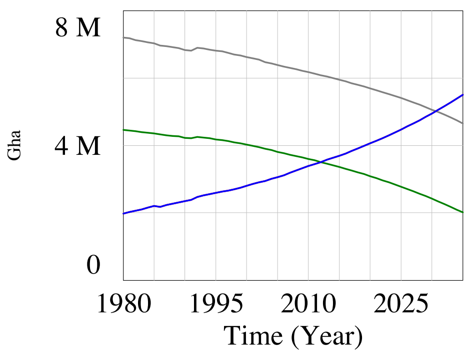

Figure 104: Constant vs. dynamic annual increment in the full model: future development of the EF & BC.
Development (including base-run future projection) of the *BC of forest land* calculated with: Grey: GFN constant forest increment, green: dynamic national annual increment. *Forestry EF of consumption* (blue and red for const. and dynamic annual increments are congruent)

7 Discussion of the most important results

The analysis of the simplified core model firstly yielded that the EF is hardly influenced by its dynamics while the BC is strongly influenced by its dynamics, especially when using the dynamic annual timber increment. It could be seen that the forest land and timber can experience very different developments, including sudden shifts / thresholds depending on initial conditions and harvest rates and the way in which the harvest is carried out (thinning vs. deforestation). Some of these sudden shifts may be hard to anticipate without the use of modeling. For example, the more thinning, the faster the rise of annual increment will be but also the faster the fall following the rise. Hence, if policies for less deforestation are effective but harvest is still high (i.e. more thinning), forest managers may be lured to believe that everything is going wonderful if they see the annual increment go up, but if harvest is too high, collapse will still occur and it can be a very rapid one. This would also mean that forest biocapacity would initially rise and then collapse if calculated using the dynamic annual timber increment. It was found that for the development of the BC it can may a strong difference whether a constant or dynamic annual increment is used for calculation. It can also be concluded however, that from a pure yield maximization perspective, it can make sense to have the EF exceeding the BC for a while to stimulate the growth of the resource. Depletion of forest resources in Senegal however are already far past the point where that would make sense.

The realization that in a country like Senegal, where forest does not spread naturally, a forestry system involving deforestation can never sustainable, should not come as a surprise. But in fact a number of other conditions have to be met, and importantly they have to be met in time. The harvest needs to be stabilized below the systems ability to regrow. If deforestation is halted, this ability can initially be increased as stated, but if the causes for the harvest increase cannot be reduced in time, it can easily grow beyond the systems capacity to regrow. If it is allowed to let the forests degrade very much, the final sustainable state may be at a much lower level than could be possible if the degradation is halted earlier, or the harvest would need to be decreased even lower to let the forest recover first, so it could sustain a higher harvest again. This may actually be something worth considering in Senegal. If it was possible to dramatically reduce the harvest, the remaining forests could recover. So when the butane finally gets more expensive again, due to rising world market prices they would have recovered more and would be able to sustain a higher harvest. Similarly if deforestation is reduced quickly enough, the larger remaining forest area would also be able to sustain a larger harvest. Importantly though, the above-described measures are not enough for a sustainable forest system because over-thinning may lead to a situation, where locally, selective harvest is no longer possible due to depletion of preferred species. This loss of selectivity causes an indirect over-thinning-induced deforestation. It was shown that this can take effect very abruptly and that how abrupt this happens may depend on the spatial pattern of deforestation: the more spatially homogenous the thinning the more abrupt the onset of over-thinning-induced deforestation may be. Since these spatial effects were modeled in a very aggregated manner though, the conclusions that were drawn should be viewed with some reservation and should instead encourage a more spatially disaggregated model, based on Senegalese reality.

The analysis of the timber demand sector stressed the importance to further develop the model to endogenize the influence of the butanization campaign (currently exogenous policy variable) because there may be important feedbacks, which may hamper its ultimate success. Sensitivity analysis furthermore cast doubt on weather this successful policy may still work, should world-market prices of butane rise a lot, which can be expected as fossil energy resource run out.

Furthermore it could be shown that it makes a big difference if part of the firewood harvest is collected as dead wood, which seems reasonable, given that this is more convenient. This later also raised the issue whether or not dead wood harvest should considered part of the EF at all, since it does not constitute an outflow to the timber stock. Therefore, dead wood collection should be modeled as a separate structure in the future. Preliminary experiences in doing this (not included in this thesis) suggest, that there are important additional dynamics to be found there.

Research on the efficiency of turning wood into charcoal concluded that the GFN accounting methodology and to a lesser degree also T21-Senegal overestimate the efficiency of charcoal production in Africa.

If however, a large part of the timber removed from forest land converted to cropland is pushed on the market as charcoal, the charcoal efficiency doesn’t play much of a role, because most of the demand is satisfied or even over-satisfied with such charcoal from forest conversions. Importantly, this also implies that the effectiveness of the campaign to make people switch to butane as an alternative fuel may stay limited since charcoal production is not demand-driven but is instead pushed onto the market.

If the forest-conversion-related timber removal is not harvested but instead burnt for gaining fertilizing ashes or wasted otherwise, it hides itself form the harvest statistics and is therefore also over-looked when calculating the EF. Depending on the proportion wasted, this was found to potentially notably increase the EF.

In addition, industrial wood demand may start to rival other drivers of depletion of forest resources some decades from now if exponential growth driven by industrial capital continues.

When analyzing the timber and forest land sector, it was found that some major drivers of deforestation had been missing in T21-Senegal34b: forest conversion to agriculture and to some degree also to mines and other uses. Furthermore since the area of forest land affected by fires is very high, it was found that even if only a small proportion of these fires lead to deforestation (10%) this could have a major impact on forest area at about the same level as conversion to agriculture. Similarly, the effect on timber stock could also be quite large. More information on all of these drivers is necessary and should be modeled endogenously in future model editions. Importantly, as the EF calculation is based on harvest statistics, it is blind for the timber removal by anthropogenic forest fires.

Furthermore, forest protection as modeled in T21-Senegal34b turned out to be very overstated. The only information on forest protection in Senegal found stated that it is largely ineffective.

New data on reforestation led to abandonment of the previous way that this was modeled. The present structure not properly endogenized yete though, due to lack of better information on causal structures.

Furthermore a feedback loop limiting deforestation as soon as the resource becomes scarcer has been abandoned completely, as it is believed that for several reasons accessibility will not limit deforestation.

When analyzing the forestry trade sector it was found that its virtual EF-flows embedded in im- or exported wood derived products does not play a major role yet compared to the EF caused by domestic production. The imports are much higher than the exports though. Overall that sector was not endogenized to a great extent though, due to lack of information and bad data quality.

While trying to implement changes in the preexisting animal husbandry and forestry sector, it was found that that sector was not properly connected to the other economical sectors. While that is not a problem for past model behavior, it means that the contribution of the forestry sector to the economic sectors was wrong for future projections. This could not be fundamentally fixed within the scope of this thesis.

Analyzing the fit of the simulations of the EF to the reference mode, it was found that a) the reference modes are not accurate and likely underestimate reality due to wrong technical conversion factors for wood fuel and charcoal. Similarly, analyzing the reference mode for the forest land it was found that the data is to a large degree based on guestimates and likely only one to two actual measurements, which were not even reported for the right year. As a consequence also the reference mode for the BC likely over-estimates the actual BC. Hence the situation is likely worse than BC and EF data had been showing so far.

Another even worse source of underestimation of the severity of the forest overuse in Senegal is assuming a constant national annual increment instead of a variable one. The BC is almost halved, when switching to the dynamic annual timber increment and the point in time when the EF surpasses the biocapacity is no longer around 2030 but now, in 2012! It is therefore highly recommended to try implementing a dynamic annual increment in the GFN accounting framework.

8 Conclusion

AT its outset this thesis asked to what degree it could be possible to introduce a model sector of the Ecological Footprint and the Biocapacity in the T21-model of Senegal that is sufficiently congruent in its core meaning and behavior to be considered quasi-identical with the static accounting ecological footprint of forestry.

“Sufficiently congruent in its core meaning”?:

It was found that the implementation of the GFN accounting methodology in Vensim is principally not a problem. It is arithmetic and thus can be implemented in Vensim. The only issue here may be that the GFN accounting methodology often works at a very disaggregated level in terms of the data inputs to the calculation structure. This is not principally limited by Vensims maximum number of 8 subscripts to a variable, since a larger number could be implemented by modeling explicit structure instead of subscripting. So there is really no principal limitation in terms of converting the endogenously derived data into the EF and BC.

But T21 generally works at a more aggregated level than the GFN methodology, since due to its broader scope it is more complex already even at this high aggregation level. Therefore from a T21 implementation perspective, the structures should be as lean as possible and still produce “the right behavior for the principally right reasons”. In this thesis, data inputs (harvest, forest land and annual increment data) were often aggregated compared to the GFN methodology (e.g. just “industrial wood” summing all the different FAO types of wood products for industrial uses). This is strictly speaking not congruent with GFN methodology any more. At the same time the model created in this thesis is at an aggregation level that may already be quite low for T21 purposes.

“Sufficiently congruent in past behavior”?:

In the course of this research it was shown several times that without enough information about the real system, there is the danger to make the model behavior congruent with *wrong* past behavior. If the reference mode data is of very bad quality (which was found to be the case for forest land data) it is still possible to make the simulation fit fairly well, given that due to lack of information there is a lot of freedom in setting parameters and graph functions.

“Meaningful future projections”?

These obvious shortcomings in causal structure cast a shadow of doubt on the models third desired capability: to make meaningful future projections. For that to be possible would require much more information from Senegal. Instead of speculating from the modelers desk, there needs to be contact to some knowledgeable people working in Senegal who know the system well, and who know and have access to relevant documents that may not be available online.

Also the time available for this thesis precluded proper analysis of some model parts which may have allowed for elaborating more important feedback loops e.g. modeling a separate dead wood stock or modeling rebound effects in the butanization efforts.

What benefits does a dynamic ecological footprint deliver to GFN, MI & T21 and other possible users?

This research has already delivered a number of unexpected benefits so far. The first is **assessment of data quality**. Unlike pure accounting as used by the GFN methodology, that takes data “as is”, the causal structures modeled here allow for finding inconsistencies in data. If unreasonable assumptions, are necessary to reproduce the desired data series, the modeler starts questioning the data as well as his causal structures. While in many cases the causal structures may turn out to be erroneous, so can the data. Here, that was the case for forest land data and the technical conversion factor for charcoal. Interestingly this also holds not only for the GFN methodology but also for the preexisting T21-model. The structures added to T21 had a different additional purpose than the original model. Therefore it is only logical that additional structures that are needed for the new purpose introduce more realism into the already existing parts (e.g. the *timber volume* stock). But the research also found some issues that have to be considered inadequate even for the preexisting model purpose. T21-Senegal34b did not have the flow *forest conversion to cropland*, which turned out to be very important. Similarly forest conversion to mines and the influence by forest fires have to be introduced into the original model even if the EF&BC is not introduced.

In addition the research **suggests methodological improvements** to the GFN methodology. So far, the forestry EF is based only on harvest data. But harvest data does not cover all of the outflows from the timber volume stock. Timber that is wasted in forest conversions to agriculture or other uses such as mines and that is either burnt or left to decay is just as much of a problem for forest sustainability than harvested timber. Similarly, anthropogenic forest fires also constitute a removal of some timber. Excluding both of these flows likely leads to a notable underestimation of the EF. On the other hand, this research suggests that it may sense to exclude dead wood harvest from the EF calculation, as its harvest does not influence the stock of living timber. This may mitigate or even over-compensate some of the underestimation mentioned above. Since GFN always strives to be conservative in their estimations (under- rather than over-estimate the EF and the opposite for the BC), the dead-wood issue could be even more important for GFN to look into. A number of improvements have also been suggested for the existing T21-model: The connection of the forestry sector to the economical production for example really needs improvement since it currently cannot be expected to lead to meaningful future projections of the forestry's contribution to GDP. Even more important from a resource perspective is the addition of a flow describing forest conversion to cropland and potentially also the influence of forest fires.

It was also shown that a dynamic EF / BC can help GFN to **assess the importance of different kinds of methodological improvements**:

The second most important improvement suggested is the inclusion of timber stock information: It became clear that the GFN-methodology which essentially focuses on the in and outflows of the timber stock and the forest area stock neglects the timber stock. This stock information is important additional information in terms of sustainability management for two reasons:

1) collapse point anticipation

2) yield maximization

By (1) it is meant that the stock level (together with the outflows) gives an indication of how far the stock depletion likely is. Naturally this should not just be extrapolated but simulated but even an extrapolation is already better than just the two BC / EF trajectories that tell only the degree of over-use but seem to continue endlessly. By (2) it is meant that from a management perspective, stock depletion including an EF higher than BC can make sense for a while because this can increase yield (see analysis simplified core model). But it is important to not reduce the density / forest area below threshold points after which decline accelerates under continued extraction or even becomes selfaccelerating. To estimate these kind of thresholds a dynamic model including a rich feedback structure is helpful if not essential.

It therefore appears recommendable to think about if there is a way to also transmit information about stock levels alongside the EF & BC information in a meaningful manner.

The most important methodological improvement is the introduction of a dynamic national annual increment: It also became clear that the constant annual increment is a severe shortcoming as the real dynamic annual increment is suggested to be much lower. It could not be clarified what the constant forest increment that GFN uses is based upon. But since it is close to the theoretical maximum of the dynamic annual increment of the forests in Senegal, that it is based assessments of the principal capability of a forest in Senegal, it may be based on considerations of the principal potential of forests in this climatic zone. In reality however thinning of the forest stands can change the annual increment. It was shown that at the very low values of stand density in Senegal today, the annual increment is likely much lower than GFNs constant value. Thus this variable is suggested as a priority for GFN to improve in their methodology by getting time series data on it instead of using a constant. If the modeling approach taken here is roughly correct (growth of the forest stand is intrinsically density dependent) time series data could be gained from the following data:

1) functional relationship between the annual forest increment as dependent on the stand density

2) time series data on stand densities

If the assumptions of this research are correct, these are the two determining factors. (1) is necessary since the actual functional relationship is likely not a simple logistic growth assumed here but will likely still be hump-shaped (first rising to a peak, then decreasing). This data may already be available. Even if not, forestry experts can probably make pretty good guesses on this. Since Senegal spans all the way from desert over bush savannahs to forest savannahs to dry-deciduous tropical forest, some disaggregation into different forest types may be necessary if the have very different functional relationships of the annual increment to stand density. As a first approximation, until better data is available, the logistic growth could be used, ideally utilizing parameter estimations from experts.

It may be somewhat more difficult to get (2), as such data may not be readily available in a country without long a long tradition of institutionalized forest management. But there may be two ways to circumvent these problems which should ideally both be used to cross-check each other: a) remote sensing data could be analyzed to extract data on stand densities. One problem with this approach will be that the measurement instruments and their sensitivities change with time so that some tinkering would be required to eliminate the resulting biases. But these hurdles generally can be overcome. Another way would be to b) use indigenous knowledge. One could ask village people including elders around the country what the forests looked like in their childhood. Pictures of forests with different stand densities could be used. Asking people for information at different points in their lives may contain more error than asking people with different ages for their childhood memories, as we usually have a very good memory of our childhood days and using the age of the people to locate these memories in time.

If both are not available, dynamic modeling could be an alternative way to determine the annual forest increment. But this would need proper parameterization of the model in close communication with experts from the country in question. It could also conveniently be done as a side-product of implementation of the EF&BC in the T21-models already in use in many developing countries.

If however a dynamic annual increment was implemented in the EF & BC accounting methodology, one may also seriously question the constancy of the *GFN constant forest increment world*. Keeping the global one constant but making the national one dynamic is clearly inconsistent, unless there is evidence that the global one indeed does stay constant. In the face of world-wide deforestation and forest degradation (with a few countries being exceptions) it is very unlikely that the global annual increment would stay the same. For the BC it would mean that if the global annual forest increment sinks faster than the national one, that would mitigate the decline of the BC, while the BC decline would be reinforced if the national annual increment decline was faster than the global one. Any decline in global annual increment however would lead to an increase of the speed at which the EF is rising. As a result, a falling global annual increment may still lead to an increase in resource overuse as measured by the difference of EF and BC, even if it dampens the fall of the BC. As far as implementation of a global dynamic annual forest increment is concerned that is not a problem any more as soon as the national dynamic annual increment is has been calculated for all countries, since the global one could be calculated as an area-weighted average (using the areas of the forests not of the nations).

There are however, some implementation issues of a dynamic national annual increment: As much sense as a dynamic national annual increment may make from a modeling and natural resources perspective, its introduction to the EF BC may bring up a potential problem: One of the main virtues of the EF&BC concept is that it is understandable to lay-men. *"EF>BC=bad, BC>EF=good"* is the simple message of the graphs. It states whether or not we are living within the limits of sustainability. But with a dynamic annual increment things can get a bit more tricky to understand: Imagine e.g. a country with a large stock of some natural renewable resource (e.g. forests, fisheries) has just started to industrially exploit a resource. This may lead to an increase of the BC (assuming only selective harvest for forest). So both curves, the EF and the BC would be increasing. The different speeds would depend on how much the system reacts to the release of internal competition. In addition there may be fairly sudden regime shifts that cannot be anticipated just by looking at the past behavior of the two curves. The question this is if the EF would loose some of its ease of understanding by introducing the dynamic annual increment.

For the Millennium Institute, even the current version of the model asks for potential revisions of past political strategies. In order to halt forest decline a butanization campaign was initialized in the 1970s. It was very successful in towns, replacing charcoal, less so in rural areas, but even there firewood may recently have lost its status as primary fuel. The observed effect of these policies on the forest area decline however, were small (although as discussed the forest area data is probably wrong). The reason appears to be that a large part of the deforestation is actually not demand-driven but caused by agricultural expansion. If this turns out to be correct, other policies could become necessary to turn the tides. The model needs to be enlarged for the causal structure of the conversion to agriculture. Wood (2004) suggests that it results from a lack of possibilities to intensify agriculture. Should Senegal uses its phosphate reserves for fertilizing their own crops instead of exporting it even though the short-term return on the latter option is higher? Would this allow for intensification of agriculture that could stop forest area decline?

These questions and many others could better answered if the model was brought from its current somewhat limbless state to the point where it could provide meaningful future projections. This should allow for estimates when the forest resources (timber stock, area) would run out and also anticipate important thresholds. Most importantly it would allow for testing different kinds of policies on their impact on the natural resources (here forests). Alternative future scenarios could be analyzed. The question of whether there is a danger of a reverse-butanization when world-market prices for fossil fuels like butane increase was already briefly analyzed in this research, but the model structure used was still too exogenous. Not only the effectiveness of different policies suggested to mitigate resource overuse could be assessed but potential side effects of other policies not primarily targeted at resource management could be explored. This could give valuable insights to the government as to what are the most efficient policies or where different kinds of policies are in conflict with each other in terms of some of their more or less intended effects. A good model should answer questions like: When will it be how hard to turn around current developments, i.e. is there an accumulation of inertia involved (e.g. industries creating a constant or increasing demand)? Or: How likely are different kinds of policies to exhibit path dependence (e.g. are there self-reinforcing tendencies to either export raw materials or create value inside of the country)?

Future projections could also be interesting for the increasing number of users utilizing the EF&BC. The WWF for example uses the EF&BC in their living planet reports (WWF International, 2012). These reports also contain future projections of the EF&BC but these are limited to simple scenario analysis with ad-hoc assumptions of future scenarios. A dynamic EF&BC would allow for much more sophisticated analysis and could help actors with good connections to governments like the WWF to recommend well-tested policies.

Rolling out the EF / BC to T21, not only for the forestry but also for the other partial footprints so that the total EF and BC could have several positive effects on the model as a whole. It could help answer the question how useful or how sustainable the transfer of biocapacity from one type to the other may be. If e.g. forest is converted to cropland and cropland has a higher equivalence factor, will that make the over-all biocapacity rise? This could potentially shed an interesting light on the interesting issue of substitutability of natural resources. Is it meaningful to deplete some stocks somewhat to develop? What dangers do such policies hold (e.g. underestimating thresholds)?

Furthermore the EF&BC is a “natural resource umbrella indicator”. Unlike many other models, T21 already contains some important natural resources (e.g. for Senegal: fisheries, drinking water) but in terms of long-term importance natural resources are still underrepresented. The EF&BC due to its umbrella nature would be like a “natural resources boost” for the model. In the application of these models in developing countries more focus would come to the proper management of natural resources. The indicators used by practitioners would of course not just be the umbrella-indicators EF & BC but the structures introduced to derive them would yield many of the indicators necessary for implementation of policies.

But precisely because of that umbrella nature of the EF&BC concept the causal structures needed for its calculation are likely quite copious. What is good in terms of added understanding as outlined in the paragraph above may be a problem when it comes to finding the financial and personal resources for such an endeavor. Not only will the backbone of the EF&BC require copious causal structure, but rolling it out to the national

T21-implementations in different countries may require heavy customization needing additional resources. Take for example the assumption that forest does not spread naturally in Senegal due to heavy grazing by animals. That assumption may not hold for other countries. The result would be an additional (density depended?) growth of the forest area, which may significantly increase the dynamic complexity of the forestry system. The question thus is if GFN and MI, both being small NGOs with limited resources, can summon the necessary resources.

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10 Appendices

10.1 Base run settings

Variable	Value in base run
Fraction of timber demand wasted in conversions	0.3
Initial timber volume per ha	$39m^3$ ha^{-1}
intended conversion forest to cropland	graph function (see Figure 68)
intended deforestation for mining	5000 ha $year^{-1}$
m3 solid fuel wood per kg charcoal	0.01 m3 kg^{-1}
max timber volume per ha	$250m^3$ ha^{-1}
Minimum timber volume per ha in classified forest	$30m^3$ ha^{-1}
proportion of bush fires caused by humans	0.9
proportion of bush fires leading to deforestation	0.1
Proportion of charcoal wood as thinning	1
Proportion of firewood as thinning	1
Proportion of firewood demand satisfied with green wood exogenous	1
Proportion of industrial wood as thinning	1
proportion of reduction of timber per ha through non-deforesting forest fires	0.5
Proportion of thinning leading to deforestation	Graph function see (Figure 34)
switch anthropogenic bush firs as part of EF	0 (off)
switch dead firewood harvest as part of EF	1 (on)
switch deforestation for cropland	1 (on)
switch deforestation for mining	1 (on)
switch endogenous national timber growth	1 (on)
switch exogenous data input	0 (off)
switch forest fires	1 (on)
Switch forest protection	0 (off)
Switch GFN forest data	0 (off)
Switch over-thinning	1 (on)
Switch protection timber	0 (off)
Switch reforestation	0 (on)
switch timber regrowth	1 (on)
switch waste of conversion timber as part of ef	0 (off)
swtich industrial wood demand	1 (on)
timber demand per unit industrial capital	$4.1 \cdot 10^{-7}$ m^3 $(CFA_{99} \cdot year)^{-1}$

timber fractional growth rate	0.02 $year^{-1}$

10.2 Table of figures

10.3 Equations

Due to the fact that I am bound to a non-disclosure agreement with the Millennium Institute and that this thesis will be publicly available in the library, I do not cite all of the equations of the full model. Instead I only provide the equations for the model sectors which were changed in the T21-model. The equations are provided by sector and in alphabetical order for quick search. Note also that Vensim's "capitalization by type" may ease your search further:

- CONSTANTS ARE ALWAYS WRITTEN IN ALL CAPS (note that for Vensim switches are also constants)
- TIME series data (exogenous) are always written with all caps in the first word
- all other variables are written in small letters

10.3.1 Equations of the simplified core model

```
actual thinning = intended thinning - "deforestation due to over-
       thinning" · timber volume per ha
       Units: M3 / Year

biocapacity of forest land = Forest Land · "nat. to world increment
       ratio" · CONST EQUIVALENCE FACTOR FORESTRY
       Units: Gha

CONST EQUIVALENCE FACTOR FORESTRY = 1.26249
       Units: Gha / Wha

deforestation = direct deforestation + "deforestation due to over-
       thinning"
       Units: Ha / Year

DEFORESTATION ADJUSTMENT TIME = 1
       Units: Year

"deforestation due to over-thinning" = SWITCH OVERTHINNING ·
       proportion of thinning leading to deforestation · intended
       thinning / timber volume per ha
       Units: Ha / Year

direct deforestation = SWITCH DIRECT DEFORESTATION · timber
       extraction / timber volume per ha · PROPORTION OF HARVEST AS
       DIRECT DEFORESTATION
       Units: Ha / Year

ecological footprint of production of forest land = timber extraction
       / GFN CONSTANT FOREST INCREMENT WORLD · CONST EQUIVALENCE
       FACTOR FORESTRY
       Units: Gha

exp harvest = INITIAL HARVEST · EXP(EXP HARVEST GROWTH RATE · Time)
       Units: M3 / Year [0,1.5e + 007,100000]

EXP HARVEST GROWTH RATE = 0.04
       Units: 1 / Year

Forest Land= INTEG ( - deforestation,INITIAL FOREST LAND)
       Units: Ha
```

"GFN CONSTANT FOREST INCREMENT NATIONAL (M3)" = 1.0635
Units: M3 / (Year · Ha)
Source: (Global Footprint Network, 2011)

GFN CONSTANT FOREST INCREMENT WORLD = 1.81878
Units: M3 / (Year · Wha)
Source: (Global Footprint Network, 2011)

INITIAL FOREST LAND = 9.8e + 006
Units: Ha
Source: Backward - extrapolation (linear) over data gap of FAOstat data
{FaoStatisticsDivisionaComment: Most likely wrong! There is a much lower initial value on p 75 and 76 (76 and 77pdf) (Ministre de l'Environment, de la Protection de la Natur, des Bassins de rétention et des Lacs Artificiels, 2009): a total of 3 456 600, sum of regions 2.5million ha.There is a much lower initial value on p 75 and 76 (76 and 77pdf) : a total of 3 456 600, sum of regions 2.5million ha. But forest definitions may be different there. Therefore not used

INITIAL HARVEST = 1
Units: M3 / Year [0,1e + 007,100000]

INITIAL TIMBER STOCK= INITIAL(INITIAL FOREST LAND · INITIAL TIMBER VOLUME PER HA)
Units: M3

INITIAL TIMBER VOLUME PER HA = 250
Units: M3 / Ha [0,250,1]

intended thinning = timber extraction · (1 - PROPORTION OF HARVEST AS DIRECT DEFORESTATION)
Units: M3 / Year

linear harvest = INITIAL HARVEST + LINEAR HARVEST GROWTH RATE · Time
Units: M3 / Year [0,1.5e + 007,100000]

LINEAR HARVEST GROWTH RATE = 60000
Units: M3 / (Year · Year) [0,1e + 006,10000]

MAX TIMBER VOLUME PER HA = 250
Units: M3 / Ha [144,488,1]
Source: see parameterization of core model

"nat. annual timber increment" = IF THEN ELSE((timber volume per ha · TIMBER FRACTIONAL GROWTH RATE · (1 - relative timber volume per ha))<"ZERO CUT - OFF VALUE",0,(timber volume per ha · TIMBER FRACTIONAL GROWTH RATE · (1 - relative timber volume per ha)))
Units: M3 / (Year · Ha)

"nat. to world increment ratio" = (1 - SWITCH ENDOGENOUS NATIONAL TIMBER GROWTH) · "GFN CONSTANT FOREST INCREMENT NATIONAL (M3)" / GFN CONSTANT FOREST INCREMENT WORLD + SWITCH ENDOGENOUS NATIONAL TIMBER GROWTH · "nat. annual timber increment" / GFN CONSTANT FOREST INCREMENT WORLD
Units: Wha / Ha

net natural reproduction and growth = Forest Land · "nat. annual timber increment"
Units: M3 / Year

PROPORTION OF HARVEST AS DIRECT DEFORESTATION = 0.1
Units: Dmnl [0,1,0.01]

proportion of thinning leading to deforestation= WITH LOOKUP (relative timber volume per ha,([(0,0) -

```
        (1,1)],(0,1),(0.05,0.5),(0.2,0.2),(0.5,0.05),(1,0) ))
        Units: Dmnl

relative timber volume per ha = IF THEN ELSE (timber volume per ha /
        MAX TIMBER VOLUME PER HA>(1 - "ZERO CUT - OFF VALUE"),1,timber
        volume per ha / MAX TIMBER VOLUME PER HA)
        Units: Dmnl

SWITCH DIRECT DEFORESTATION = 1
        Units: Dmnl [0,1,1]

SWITCH ENDOGENOUS NATIONAL TIMBER GROWTH = 0
        Units: Dmnl [0,1,1]

SWITCH EXP HARVEST = 0
        Units: Dmnl [0,1,1]

SWITCH OVERTHINNING = 1
        Units: Dmnl [0,1,1]

timber extraction = MIN(MAX(0,Timber Volume / DEFORESTATION
        ADJUSTMENT TIME), (1 - SWITCH EXP HARVEST) · linear harvest +
        SWITCH EXP HARVEST · exp harvest)
        Units: M3 / Year

timber extraction per ha = timber extraction / Forest Land
        Units: M3 / (Ha · Year)

TIMBER FRACTIONAL GROWTH RATE = 0.02
        Units: 1 / Year [0.014,0.028,0.001]
        Source: (IPCC, 2006) (see also details about parameterization
        of core model in text)
        Comment: Values from Ghana indicate it could be as high as 3%
        (Inventory of Wood Resources, Ghana, Year 2000, n.d.)

Timber Volume= INTEG (net natural reproduction and growth - timber
        extraction,INITIAL TIMBER STOCK)
        Units: M3

timber volume per ha = IF THEN ELSE(Forest Land=0,0,Timber Volume /
        Forest Land)
        Units: M3 / Ha

"ZERO CUT - OFF VALUE" = 0.0001
        Units: M3 / Year [0,0.1]
```

10.3.2 Equations of the Timber and forest land sector

```
arable land regeneration = Temporary Degraded Cropland / TIME TO
        RECOVER ARABLE LAND
        Units: Ha / Year

arable to settlement = MIN(Cropland / SETTLEMENT LAND ADJUSTMENT
        TIME, required settlement land adjustment - other to
        settlement)
        Units: Ha / Year

area affected by forest fires= WITH LOOKUP (Time,([(1980,0) -
        (2035,40000)],(1980,220000),(1996,220000),(2006,220000),(2010,
        220000),(2035,220000) ))
        Units: Ha / Year
        Source: (Ministre de l'Environment, de la Protection de la
        Natur, des Bassins de rétention et des Lacs Artificiels, 2009)

average reforestation= WITH LOOKUP (Time,([(1980,0) -
        (2035,40000)],(1980,23673),(2010,23673),(2035,23673) ))
        Units: Ha / Year
        Source: two data series were synthesized: (Ministre de
        l'Environment, de la Protection de la Natur, des Bassins de
```

rétention et des Lacs Artificiels, 2009) was used for data prior to 2001 and the preexisting data in T21 - Senegal34b was used for the years 2001 - 2007 (see text for details).

"charcoal timber harvested from conversion to agriculture (m3)" = timber cleared through conversion to cropland · (1 - FRACTION OF TIMBER WASTED IN CONVERSIONS)
Units: M3 / Year

"charcoal timber harvested from conversion to mines (m3)" = timber cleared through conversion to mines · (1 - FRACTION OF TIMBER WASTED IN CONVERSIONS)
Units: M3 / Year

"charcoal wood demand (m3)" = "charcoal demand (kg)" · M3 SOLID FUELWOOD PER KG OF CHARCOAL
Units: M3 / Year

classified forest = IF THEN ELSE(Time<2011, CLASSIFIED forest past,CLASSIFIED forest future)
Units: Ha
Source: original T21 - Senegal34b

Cropland= INTEG (arable land regeneration + forest conversion to cropland - arable to settlement - temporary degradation,INITIAL CROPLAND LAND)
Units: Ha

DEFORESTATION ADJUSTMENT TIME = 1
Units: Year

"deforestation due to over-thinning" = MIN(MAX(0, (Forest Land - classified forest · SWITCH FOREST AREA PROTECTION) / DEFORESTATION ADJUSTMENT TIME),"intended deforestation due to over-thinning")
Units: Ha / Year

deforestation for mining = SWITCH DEFORESTATION FOR MINING · MIN(MAX(0, (Forest Land - classified forest · SWITCH FOREST AREA PROTECTION) / DEFORESTATION ADJUSTMENT TIME),intended deforestation for mining)
Units: Ha / Year

deforestation through forest fires = SWITCH FOREST FIRES · MIN(MAX(0, Forest Land / DEFORESTATION ADJUSTMENT TIME), normal area deforested by forest fires)
Units: Ha / Year
Source: (FAO Forestry Department, 2010), 10,000ha / year in the period 2005 - 2010 (25% of the total deforestation of 40,000ha / year

direct deforestation for fire wood = MIN(MAX(0, (Forest Land - classified forest · SWITCH FOREST AREA PROTECTION) / DEFORESTATION ADJUSTMENT TIME),intended direct deforestation for fire wood)
Units: Ha / Year

direct deforestation for industrial wood = MIN(MAX(0, (Forest Land - classified forest · SWITCH FOREST AREA PROTECTION) / DEFORESTATION ADJUSTMENT TIME),intended direct deforestation for industrial wood)
Units: Ha / Year

ELASTICITY OF TEMPORARY DEGRADATION TO OVERUSE = 1
Units: Dmnl

forest conversion to cropland = SWITCH DEFORESTATION FOR CROPLAND · MIN(MAX(0, (Forest Land - classified forest · SWITCH FOREST AREA PROTECTION) / DEFORESTATION ADJUSTMENT TIME),intended

```
        conversion forest to cropland)
        Units: Ha / Year [0,10000,5000]

Forest Land= INTEG (reforestation - "deforestation due to over-
        thinning" - deforestation for mining - deforestation through
        forest fires - direct deforestation for fire wood - direct
        deforestation for industrial wood - forest conversion to
        cropland - residual charcoal induced deforestation,INITIAL
        FOREST LAND)
        Units: Ha

FRACTION OF TIMBER WASTED IN CONVERSIONS = 0.3
        Units: Dmnl [0,1,0.1]
        Source: wild guess
        Comment: This is actually not a constant (failed boundary
        adequacy test). It is part of feedbacks, e.g.: if the wood
        harvested from conversion is more than the demand, this
        fraction is likely to go up, until demand = supply. Not
        implemented here because time for a Master thesis is limited.

green firewood harvest = MIN (MAX(0,(Timber Volume - SWITCH
        PROTECTION TIMBER · classified forest · MINIMUM TIMBER VOLUME
        PER HA IN CLASSIFIED FOREST) / DEFORESTATION ADJUSTMENT
        TIME),"intended green firewood harvest (solid - m3)")
        Units: M3 / Year

industrial timber harvest = MIN (MAX(0,(Timber Volume - SWITCH
        PROTECTION TIMBER · classified forest · MINIMUM TIMBER VOLUME
        PER HA IN CLASSIFIED FOREST) / DEFORESTATION ADJUSTMENT
        TIME),"residual industrial wood demand (m3)")
        Units: M3 / Year

INITIAL CROPLAND LAND = 3.141e + 006
        Units: Ha

INITIAL FOREST LAND = 9.8e + 006
        Units: Ha

"initial pasture plus non - deg unproductive, non - settlement" =
        total land area - INITIAL CROPLAND LAND - INITIAL FOREST LAND
        - INITIAL SETTLEMENT LAND - INITIAL TEMPORARY DEGRADED LAND
        Units: Ha

INITIAL SETTLEMENT LAND = 112500
        Units: Ha

INITIAL TEMPORARY DEGRADATION RATE = 0.03
        Units: Dmnl / Year

INITIAL TEMPORARY DEGRADED LAND = 270000
        Units: Ha

INITIAL TIMBER STOCK= INITIAL(INITIAL FOREST LAND · INITIAL TIMBER
        VOLUME PER HA)
        Units: M3

INITIAL TIMBER VOLUME PER HA = 39
        Units: M3 / Ha [1,488,1]
        Source: no source found. See parameterization

intended charcoal induced deforestation not due to agricultural
        conversion = (1 - PROPORTION OF CHARCOAL WOOD AS THINNING) ·
        residual timber harvest for charcoal / timber volume per ha
        Units: Ha / Year

intended conversion forest to cropland= WITH LOOKUP (Time,([(1980,0)
        -
        (2035,30000)],(1980,27715),(1985,27715),(1986,20573),(2000,205
        73),(2010,20753),(2035,20753) ))
```

Units: Ha / Year
Source: (Tappan et al., 2004). He does state that this conversionto agriculture was also to some degree from savannas (which depending on definition can be considered pasture land or forests), so that maybe some of this flow should instead actually go from pasture land, but thats a samaller part. I take the whole value here to explore the implications. Values for 2010 and 2035 based on assumption that nothing changes

"intended deforestation due to over-thinning" = SWITCH OVERTHINNING · proportion of thinning leading to deforestation · (thinning for green fire wood + thinning for charcoal + thinning for industrial wood) / timber volume per ha
Units: Ha / Year

intended deforestation for mining= WITH LOOKUP (Time,([(1980,0) - (2035,6000)],(1980,5000),(2005,5000),(2010,5000),(2035,5000)))
Units: Ha / Year
Source: (FAO Forestry Department, 2010)
Comment: 5,000ha / year in the period 2005 - 2010 (12.5% of the total deforestation of 40,000ha / year). Due to lack of other data I assume the same for 1980 and 2035.

intended direct deforestation for fire wood = (1 - PROPORTION OF FIREWOOD AS THINNING) · green firewood harvest / timber volume per ha
Units: Ha / Year

intended direct deforestation for industrial wood = (1 - PROPORTION OF INDUSTRIAL WOOD AS THINNING) · industrial timber harvest / timber volume per ha
Units: Ha / Year

"intended green firewood harvest (solid - m3)" = "intended green firewood extraction (green kg)" / "weight of green firewood per solid - m3"
Units: M3 / Year

MAX TIMBER VOLUME PER HA = 250
Units: M3 / Ha [144,488,1]
Source: see parameterization of core model

MINIMUM TIMBER VOLUME PER HA IN CLASSIFIED FOREST = 30
Units: M3 / Ha [0,150,1]
Source: guesstimate pretty low since otherwise hardly any harvest would take place.

"nat. annual timber increment" = SWITCH TIMBER REGROWTH · timber volume per ha · TIMBER FRACTIONAL GROWTH RATE · (1 - relative timber volume per ha)
Units: M3 / (Year · Ha)

net natural reproduction and growth = Forest Land · "nat. annual timber increment"
Units: M3 / Year

normal area deforested by forest fires = area affected by forest fires · PROPORTION OF FOREST FIRES LEADING TO DEFORESTATION
Units: Ha / Year
Source: (FAO Forestry Department, 2010) 10,000ha / year in the period 2005 - 2010 (25% of the total deforestation of 40,000ha / year

normal area thinned by forest fires = (1 - PROPORTION OF FOREST FIRES LEADING TO DEFORESTATION) · area affected by forest fires
Units: Ha / Year

```
other to settlement = MIN(required settlement land
       adjustment,"pasture Plus Non - deg Unproductive, Non -
       settlement" / SETTLEMENT LAND ADJUSTMENT TIME)
       Units: Ha / Year

overuse = relative average years of schooling^ELASTICITY OF OVERUSE
       TO EDUCATION · relative rural population ^ ELASTICITY OF
       OVERUSE TO RURAL POPULATION
       Units: Dmnl

"pasture Plus Non - deg Unproductive, Non - settlement"= INTEG
       ("deforestation due to over-thinning" + deforestation for
       mining + deforestation through forest fires + direct
       deforestation for fire wood + direct deforestation for
       industrial wood + residual charcoal induced deforestation -
       other to settlement - reforestation,"initial pasture plus non
       - deg unproductive, non - settlement")
       Units: Ha

PROPORTION OF CHARCOAL WOOD AS THINNING = 1
       Units: Dmnl [0,1,0.1]
       Source: (Tappan et al., 2004) states that a wave of charcoal-
       related thinning swept over the country. Hence assumption that
       all non-conversion related charcoal production is selective
       harvest. See more details in text

PROPORTION OF FIREWOOD AS THINNING = 1
       Units: Dmnl [0,1,0.1]
       Source: assumption based on the fact that some wood es better
       firewood that other. Hence harvest should be selective

PROPORTION OF FOREST FIRES CAUSED BY HUMANS = 0.9
       Units: Dmnl [0,1,0.1]
       Source: wild guess (see more in text)

PROPORTION OF FOREST FIRES LEADING TO DEFORESTATION = 0.1
       Units: Dmnl [0,1,0.1]
       Source: wild guess

PROPORTION OF INDUSTRIAL WOOD AS THINNING = 1
       Units: Dmnl [0,1,0.1]
       Source: Assumption based on the fact that many industrial wood
       uses have preferred species and or diameters so that it is
       likely that this harvest is selective.

"PROPORTION OF REDUCTION OF TIMBER PER HA THROUGH NON - DEFORESTING
       FOREST FIRES" = 0.5
       Units: Dmnl [0,1,0.1]

proportion of thinning leading to deforestation= WITH LOOKUP
       (relative timber volume per ha,([(0,0) -
       (1,1)],(0,1),(0.05,0.5),(0.2,0.2),(0.5,0.05),(1,0) ))
       Units: Dmnl

reforestation = SWITCH REFORESTATION · (SWITCH EXOGENOUS
       REFORESTATION · REFORESTATION exogenous + (1 - SWITCH
       EXOGENOUS REFORESTATION) · average reforestation)
       Units: Ha / Year

REFORESTATION exogenous
       Units: Ha / Year

relative forest stand = Forest Land / INITIAL FOREST LAND
       Units: Dmnl

relative timber volume per ha = timber volume per ha / MAX TIMBER
       VOLUME PER HA
       Units: Dmnl
```

```
required settlement land adjustment = MAX(0, (required settlement
       land - Settlement Land) / SETTLEMENT LAND ADJUSTMENT TIME)
       Units: Ha / Year

residual charcoal induced deforestation = MIN(MAX(0, (Forest Land -
       classified forest · SWITCH FOREST AREA PROTECTION) /
       DEFORESTATION ADJUSTMENT TIME),intended charcoal induced
       deforestation not due to agricultural conversion)
       Units: Ha / Year

"residual charcoal wood demand (m3)" = MAX (0,"charcoal wood demand
       (m3)" - "charcoal timber harvested from conversion to
       agriculture (m3)" - "charcoal timber harvested from conversion
       to mines (m3)")
       Units: M3 / Year

"residual industrial wood demand (m3)" = (1 - SWITCH EXOGENOUS
       INDUSTRIAL WOOD HARVEST) · MAX(0,("domestic industrial wood
       demand (m3)" + demand embedded timber exports - "wood embedded
       in total imports of industrial wood - derived products")) +
       SWITCH EXOGENOUS INDUSTRIAL WOOD HARVEST · industrial wood
       harvest exo
       Units: M3 / Year
       Source: (FAO Statistics Division, a)

residual timber harvest for charcoal = MIN (MAX(0,(Timber Volume -
       SWITCH PROTECTION TIMBER · classified forest · MINIMUM TIMBER
       VOLUME PER HA IN CLASSIFIED FOREST) / DEFORESTATION ADJUSTMENT
       TIME),"residual charcoal wood demand (m3)")
       Units: M3 / Year

Settlement Land= INTEG (arable to settlement + other to
       settlement,INITIAL SETTLEMENT LAND)
       Units: Ha

SETTLEMENT LAND ADJUSTMENT TIME = 1
       Units: Year
       Source: Original T21-Senegal34b

SWITCH DEFORESTATION FOR CROPLAND = 1
       Units: Dmnl [0,1,1]

SWITCH DEFORESTATION FOR MINING = 1
       Units: Dmnl [0,1,1]

SWITCH EXOGENOUS REFORESTATION = 0
       Units: Dmnl [0,1,1]

SWITCH FOREST AREA PROTECTION = 0
       Units: Dmnl [0,1,1]

SWITCH FOREST FIRES = 1
       Units: Dmnl [0,1,1]

SWITCH OVERTHINNING = 1
       Units: Dmnl [0,1,1]

SWITCH PROTECTION TIMBER = 0
       Units: Dmnl [0,1,1]

SWITCH REFORESTATION = 1
       Units: Dmnl [0,1,1]

SWITCH TIMBER REGROWTH = 1
       Units: Dmnl [0,1,1]

temporary degradation = INITIAL TEMPORARY DEGRADATION RATE · Cropland
       · overuse^ELASTICITY OF TEMPORARY DEGRADATION TO OVERUSE
       Units: Ha / Year
```

Temporary Degraded Cropland= INTEG (temporary degradation - arable land regeneration,INITIAL TEMPORARY DEGRADED LAND)
Units: Ha

thinning for charcoal = PROPORTION OF CHARCOAL WOOD AS THINNING · residual timber harvest for charcoal
Units: M3 / Year

thinning for green fire wood = PROPORTION OF FIREWOOD AS THINNING · green firewood harvest
Units: M3 / Year

thinning for industrial wood = PROPORTION OF INDUSTRIAL WOOD AS THINNING · industrial timber harvest
Units: M3 / Year

timber cleared through conversion to cropland = forest conversion to cropland · timber volume per ha
Units: M3 / Year

timber cleared through conversion to mines = deforestation for mining · timber volume per ha
Units: M3 / Year

timber destroyed by anthropogenic forest fires = timber removed by forest fire · PROPORTION OF FOREST FIRES CAUSED BY HUMANS
Units: M3 / Year

TIMBER FRACTIONAL GROWTH RATE = 0.02
Units: 1 / Year [0.014,0.028,0.001]

Source: (IPCC, 2006) (see also details about parameterization of core model in text)
Comment: Values from Ghana indicate it could be as high as 3% (*Inventory of Wood Resources, Ghana, Year 2000,* n.d.)

timber removed by forest fire = SWITCH FOREST FIRES · MIN (Timber Volume / DEFORESTATION ADJUSTMENT TIME,(deforestation through forest fires · timber volume per ha + normal area thinned by forest fires · timber volume per ha · "PROPORTION OF REDUCTION OF TIMBER PER HA THROUGH NON - DEFORESTING FOREST FIRES"))
Units: M3 / Year
Comment: Conceptual mistake should not be normal area but normal proportion of area affected. Could not be fixed within the time available for thesis since discovered very late.

Timber Volume= INTEG (net natural reproduction and growth - residual timber harvest for charcoal - green firewood harvest - industrial timber harvest - timber cleared through conversion to cropland - timber cleared through conversion to mines - timber removed by forest fire,INITIAL TIMBER STOCK)
Units: M3

timber volume per ha = Timber Volume / Forest Land
Units: M3 / Ha

TIME TO RECOVER ARABLE LAND = 3
Units: Year

10.3.3 Equations of the Forestry footprint and biocapacity

biocapacity of forest land = (1 - SWITCH EXOGENOUS DATA INPUT) · Forest Land · "nat. to world increment ratio" · EQUIVALENCE factor forestry exogenous + SWITCH EXOGENOUS DATA INPUT · (1 - SWITCH GFN FOREST DATA) · FOREST land exogenous · "nat. to world increment ratio" · EQUIVALENCE factor forestry exogenous + SWITCH EXOGENOUS DATA INPUT · SWITCH GFN FOREST DATA · FOREST land exogenous gfn · "nat. to world increment ratio" ·

EQUIVALENCE factor forestry exogenous
Units: Gha

"charcoal timber harvested from conversion to agriculture (m3)" = timber cleared through conversion to cropland · (1 - FRACTION OF TIMBER WASTED IN CONVERSIONS)
Units: M3 / Year

"charcoal timber harvested from conversion to mines (m3)" = timber cleared through conversion to mines · (1 - FRACTION OF TIMBER WASTED IN CONVERSIONS)
Units: M3 / Year

conversion timber wasted = FRACTION OF TIMBER WASTED IN CONVERSIONS · (timber cleared through conversion to cropland + timber cleared through conversion to mines)
Units: M3 / Year

"dead firewood harvest (solid - m3)" = "intended dead firewood extraction (kg)" / "WEIGHT OF AIR - DRY FIREWOOD PER SOLID - M3"
Units: M3 / Year

ecological footprint of consumption of forest land = ecological footprint of production of forest land + forest ef embedded in imports - forest ef embedded in exports
Units: Gha

ecological footprint of production of forest land = (1 - SWITCH EXOGENOUS DATA INPUT) · total timber extracted / GFN CONSTANT FOREST INCREMENT WORLD · EQUIVALENCE factor forestry exogenous + SWITCH EXOGENOUS DATA INPUT · "TIMBER harvest (m3) exogenous" / GFN CONSTANT FOREST INCREMENT WORLD · EQUIVALENCE factor forestry exogenous
Units: Gha

embedded timber exports = industrial timber harvest embedded in exports
Units: M3 / Year

EMBEDDED timber exports exogenous
Units: M3 / Year
Source:

embedded timber imports = "wood embedded in total imports of industrial wood - derived products"
Units: M3 / Year

EMBEDDED timber imports exogenous
Units: M3 / Year
Source:

EQUIVALENCE factor forestry exogenous
Units: Gha / Wha
Source: (Global Footprint Network, 2011)

forest biocapacity pc = biocapacity of forest land / total population
Units: Gha / Person

forest ef embedded in exports = (1 - SWITCH EXOGENOUS DATA INPUT) · embedded timber exports / GFN CONSTANT FOREST INCREMENT WORLD · EQUIVALENCE factor forestry exogenous + SWITCH EXOGENOUS DATA INPUT · EMBEDDED timber exports exogenous / GFN CONSTANT FOREST INCREMENT WORLD · EQUIVALENCE factor forestry exogenous
Units: Gha

forest ef embedded in imports = (1 - SWITCH EXOGENOUS DATA INPUT) · embedded timber imports / GFN CONSTANT FOREST INCREMENT WORLD · EQUIVALENCE factor forestry exogenous + SWITCH EXOGENOUS

DATA INPUT · EMBEDDED timber imports exogenous / GFN CONSTANT FOREST INCREMENT WORLD · EQUIVALENCE factor forestry exogenous
Units: Gha

forest footprint pc = ecological footprint of consumption of forest land / total population
Units: Gha / Person

Forest Land= INTEG (reforestation - "deforestation due to over-thinning" - deforestation for mining - deforestation through forest fires - direct deforestation for fire wood - direct deforestation for industrial wood - forest conversion to cropland - residual charcoal induced deforestation,INITIAL FOREST LAND)
Units: Ha

FOREST land exogenous
Units: Ha
Source: (FAO Statistics Division, a)

FOREST land exogenous gfn
Units: Ha
Source: (Global Footprint Network, 2011)

"GFN CONSTANT FOREST INCREMENT NATIONAL (M3)" = 1.0635
Units: M3 / (Year · Ha)
Source: (Global Footprint Network, 2011)

GFN CONSTANT FOREST INCREMENT WORLD = 1.81878
Units: M3 / (Year · Wha)
Source: (Global Footprint Network, 2011)

green firewood harvest = MIN (MAX(0,(Timber Volume - SWITCH PROTECTION TIMBER · classified forest · MINIMUM TIMBER VOLUME PER HA IN CLASSIFIED FOREST) / DEFORESTATION ADJUSTMENT TIME),"intended green firewood harvest (solid - m3)")
Units: M3 / Year

green timber harvest = industrial timber harvest + green firewood harvest + "charcoal timber harvested from conversion to mines (m3)" + "charcoal timber harvested from conversion to agriculture (m3)" + residual timber harvest for charcoal
Units: M3 / Year

industrial timber harvest = MIN (MAX(0,(Timber Volume - SWITCH PROTECTION TIMBER · classified forest · MINIMUM TIMBER VOLUME PER HA IN CLASSIFIED FOREST) / DEFORESTATION ADJUSTMENT TIME),"residual industrial wood demand (m3)")
Units: M3 / Year

"nat. annual timber increment" = SWITCH TIMBER REGROWTH · timber volume per ha · TIMBER FRACTIONAL GROWTH RATE · (1 - relative timber volume per ha)
Units: M3 / (Year · Ha)

"nat. to world increment ratio" = (1 - SWITCH ENDOGENOUS NATIONAL TIMBER GROWTH) · "GFN CONSTANT FOREST INCREMENT NATIONAL (M3)" / GFN CONSTANT FOREST INCREMENT WORLD + SWITCH ENDOGENOUS NATIONAL TIMBER GROWTH · "nat. annual timber increment" / GFN CONSTANT FOREST INCREMENT WORLD
Units: Wha / Ha

residual timber harvest for charcoal = MIN (MAX(0,(Timber Volume - SWITCH PROTECTION TIMBER · classified forest · MINIMUM TIMBER VOLUME PER HA IN CLASSIFIED FOREST) / DEFORESTATION ADJUSTMENT TIME),"residual charcoal wood demand (m3)")
Units: M3 / Year

```
SWITCH ANTHROPOGENIC FOREST FIRES AS PART OF EF = 0
       Units: Dmnl [0,1,1]

SWITCH DEAD FIREWOOD HARVEST AS PART OF EF = 1
       Units: Dmnl [0,1,1]

SWITCH ENDOGENOUS NATIONAL TIMBER GROWTH = 1
       Units: Dmnl [0,1,1]

SWITCH EXOGENOUS DATA INPUT = 0
       Units: Dmnl [0,1,1]

SWITCH GFN FOREST DATA = 0
       Units: Dmnl [0,1,1]

SWITCH WASTE OF CONVERSION TIMBER AS PART OF EF = 0
       Units: Dmnl [0,1,1]

timber destroyed by anthropogenic forest fires = timber removed by
       forest fire · PROPORTION OF FOREST FIRES CAUSED BY HUMANS
       Units: M3 / Year

"TIMBER harvest (m3) exogenous"
       Units: M3 / Year
       Source: aggregated data from (FAO Statistics Division, a)

total population = SUM(Population[sex!,age!])
       Units: Person

total timber extracted = total timber harvest + SWITCH WASTE OF
       CONVERSION TIMBER AS PART OF EF · conversion timber wasted +
       SWITCH ANTHROPOGENIC FOREST FIRES AS PART OF EF · timber
       destroyed by anthropogenic forest fires
       Units: M3 / Year

total timber harvest = green timber harvest + SWITCH DEAD FIREWOOD
       HARVEST AS PART OF EF · "dead firewood harvest (solid - m3)"
       Units: M3 / Year
```

10.3.4 Equations of the Timber demand sector

```
Capital Industry= INTEG (industry gross capital formation -
       depreciation industry,INITIAL CAPITAL INDUSTRY)
       Units: Cfa99
       Comment: This variable represents the stock of installed
       production capital in the industry sector. It accumulates in
       the flow of industry investment and the negative flow of
       depreciation.

CHARCOAL CONSUMPTION PER PERSON = 40
       Units: Kg / (Year · Person)
       Source: (Thomas et al., 2003, p.16)

"charcoal demand (kg)" = total population · share of population using
       charcoal · CHARCOAL CONSUMPTION PER PERSON
       Units: Kg / Year

charcoal timber harvest = residual timber harvest for charcoal +
       "charcoal timber harvested from conversion to agriculture
       (m3)" + "charcoal timber harvested from conversion to mines
       (m3)"
       Units: M3 / Year

"charcoal timber harvested from conversion to agriculture (m3)" =
       timber cleared through conversion to cropland · (1 - FRACTION
       OF TIMBER WASTED IN CONVERSIONS)
       Units: M3 / Year
       Comment: I assume all conversion related harvested timber to
       be turned into charcoal. The reason is that people cannot use
```

as much firewood themselves as they are producing through the conersion. Hence they likely turn the part that they do harvest into charcoal.

"charcoal timber harvested from conversion to mines (m3)" = timber cleared through conversion to mines · (1 - FRACTION OF TIMBER WASTED IN CONVERSIONS)
Units: M3 / Year
Comment: s.o.

"charcoal wood demand (m3)" = "charcoal demand (kg)" · M3 SOLID FUELWOOD PER KG OF CHARCOAL
Units: M3 / Year

conversion timber wasted = FRACTION OF TIMBER WASTED IN CONVERSIONS · (timber cleared through conversion to cropland + timber cleared through conversion to mines)
Units: M3 / Year

"dead firewood harvest (solid - m3)" = "intended dead firewood extraction (kg)" / "WEIGHT OF AIR - DRY FIREWOOD PER SOLID - M3"
Units: M3 / Year

demand embedded timber exports = INITIAL FORESTRY IMPORTS · Relative Row Gdp^ELASTICITY OF WOOD EMBEDDED IN EXPORTS TO RELATIVE ROW GDP
Units: M3 / Year

"domestic industrial wood demand (m3)" = Capital Industry · TIMBER DEMAND PER UNIT INDUSTRIAL CAPITAL
Units: M3 / Year
Source: (for data to be calibrated against) (FAO Statistics Division, a)

FIREWOOD CONSUMPTION PER PERSON = 300
Units: Kg / (Person · Year)
Source: taken unchanged from T21-Senegal34b. Cited there is that the data is provided by a three - year Senegal Survey Project starting in 1979, under sponsorship of Peace Corps / Senegal and the Ministries of Promotion Humaine and Research scientific of the Government of Senegal. The following url doesn't work any more: http://nzdl.sadl.uleth.ca/cgi-bin/library?e=d-00000-00---off-0envl--00-0----0-10-0---0---0direct-10---4-------0-1l--11-en-50---20-about---00-0-1-00-0-0-11-1-0utfZz-8-00&a=d&c=envl&cl=CL3.25&d=HASH01f73b67a4d349512ff39b7f.5.2.3.3
Comment: This variable represents the per capita firewood consumption in rural areas per year.

"firewood demand (air - dry kg)" = total population · share of population using wood · FIREWOOD CONSUMPTION PER PERSON
Units: Kg / Year

firewood harvest = "dead firewood harvest (solid - m3)" + green firewood harvest
Units: M3 / Year

FRACTION OF TIMBER WASTED IN CONVERSIONS = 0.3
Units: Dmnl [0,1,0.1]
Source: Wild guess
Comment: This is actually not a constant (failed boundary adequacy test). It is part of feedbacks, e.g.: if the wood harvested from conversion is more than the demand, this fraction is likely to go up, until demand = supply. Not implemented here because time for a Master thesis is limited.

green firewood harvest = MIN (MAX(0,(Timber Volume - SWITCH PROTECTION TIMBER · classified forest · MINIMUM TIMBER VOLUME PER HA IN CLASSIFIED FOREST) / DEFORESTATION ADJUSTMENT TIME),"intended green firewood harvest (solid - m3)")
Units: M3 / Year

green timber harvest = industrial timber harvest + green firewood harvest + "charcoal timber harvested from conversion to mines (m3)" + "charcoal timber harvested from conversion to agriculture (m3)" + residual timber harvest for charcoal
Units: M3 / Year

industrial timber harvest = MIN (MAX(0,(Timber Volume - SWITCH PROTECTION TIMBER · classified forest · MINIMUM TIMBER VOLUME PER HA IN CLASSIFIED FOREST) / DEFORESTATION ADJUSTMENT TIME),"residual industrial wood demand (m3)")
Units: M3 / Year

industrial wood harvest exo = "SAWLOGS + VENEER log (nc) harvest exo" + "OTHER indust roundwd(nc) harvest exo"
Units: M3 / Year

"intended dead firewood extraction (kg)" = "firewood demand (air - dry kg)" · (1 - PROPORTION OF FIREWOOD DEMAND SATISFIED WITH GREEN WOOD EXOGENOUS)
Units: Kg / Year

"intended green firewood extraction (green kg)" = "firewood demand (air - dry kg)" · PROPORTION OF FIREWOOD DEMAND SATISFIED WITH GREEN WOOD EXOGENOUS · (1 - MOISTURE CONTENT OF AIR DRY FUELWOOD) / (1 - MOISTURE CONTENT OF GREEN WOOD)
Units: Kg / Year

"intended green firewood harvest (solid - m3)" = "intended green firewood extraction (green kg)" / "weight of green firewood per solid - m3"
Units: M3 / Year

M3 SOLID FUELWOOD PER KG OF CHARCOAL = 0.01
Units: M3 / Kg
Source: (FAO, 1983)
Comment: Range 3 to 27m3 per t charcoal, depending on mosture content, species used, and efficiency of chosen process. Could be dynamically sinking due to depletion of preferred species. See more details in text

MOISTURE CONTENT OF AIR DRY FUELWOOD = 0.13
Units: Dmnl
Source: (FAO, 1983)
Comment: wet basis corresponds to 15% in the dry.

MOISTURE CONTENT OF GREEN WOOD = 0.5
Units: Dmnl
Source: (FAO, 1983)

PROPORTION OF FIREWOOD DEMAND SATISFIED WITH GREEN WOOD EXOGENOUS = 1
Units: Dmnl [0,1,0.1]
Comment: this should actually be dynamic. The green wood should be residual if harvest of dead wood cannot satisfy the firewood demand.

"PROPORTIONAL VOLUMETRIC SHRINKAGE WHEN AIR - DRYING GREEN WOOD" = 0.04
Units: Dmnl
Source: (Hernández & Pontin, 2006 figure 2, at 15% Equillibrium Moisture Content (in the dry) the volumentric shrinkage is around 4%) (FAO, 1983) states 5%

"residual charcoal wood demand (m3)" = MAX (0,"charcoal wood demand (m3)" - "charcoal timber harvested from conversion to agriculture (m3)" - "charcoal timber harvested from conversion to mines (m3)")
Units: M3 / Year

"residual industrial wood demand (m3)" = (1 - SWITCH EXOGENOUS INDUSTRIAL WOOD HARVEST) · MAX(0,("domestic industrial wood demand (m3)" + demand embedded timber exports - "wood embedded in total imports of industrial wood - derived products")) + SWITCH EXOGENOUS INDUSTRIAL WOOD HARVEST · industrial wood harvest exo
Units: M3 / Year

residual timber harvest for charcoal = MIN (MAX(0,(Timber Volume - SWITCH PROTECTION TIMBER · classified forest · MINIMUM TIMBER VOLUME PER HA IN CLASSIFIED FOREST) / DEFORESTATION ADJUSTMENT TIME),"residual charcoal wood demand (m3)")
Units: M3 / Year

share of population using butane = 1 - (share of population using charcoal + share of population using wood)
Units: 1

share of population using charcoal= WITH LOOKUP (Time,([(1980,0) - (2035,1)],(1980,0.36),(1995,0.215),(2004,0.109),(2010,0.109),(2035,0.11)))
Units: Dmnl
Source: Taken from T21-Senegal34b but with some modifications. Data points 1995 and 2004 from (Ministere De L'economie, Des Finances Et Du Plan - Direction De La Prevision Et De La Statistique, 1997; Ministere De L'economie, Des Finances Et Du Plan - Direction De La Prevision Et De La Statistique, 2004), rest: estimations (see text)

share of population using wood= WITH LOOKUP (Time,([(1980,0) - (2035,1)],(1980,0.58),(1995,0.555),(2004,0.515),(2010,0.49),(2035,0.4)))
Units: Dmnl
Source: Taken from T21-Senegal34b but with some modifications. Data points 1995 and 2004 from (Ministere De L'economie, Des Finances Et Du Plan - Direction De La Prevision Et De La Statistique, 1997; Ministere De L'economie, Des Finances Et Du Plan - Direction De La Prevision Et De La Statistique, 2004), rest: estimations (see text)

SWITCH DEAD FIREWOOD HARVEST AS PART OF EF = 1
Units: Dmnl [0,1,1]

SWITCH EXOGENOUS INDUSTRIAL WOOD HARVEST = 0
Units: Dmnl [0,1,1]

timber cleared through conversion to cropland = forest conversion to cropland · timber volume per ha
Units: M3 / Year

timber cleared through conversion to mines = deforestation for mining · timber volume per ha
Units: M3 / Year

TIMBER DEMAND PER UNIT INDUSTRIAL CAPITAL = 4.1e - 007
Units: M3 / Cfa99 / Year [1e - 010,1e - 009]
Source: value obtained through calibration to data before stabilization (since data after is only FAO estimate not measurement)
Comment: This should better not be constant but endogenized.

```
total population = SUM(Population[sex!,age!])
       Units: Person

total timber harvest = green timber harvest + SWITCH DEAD FIREWOOD
       HARVEST AS PART OF EF · "dead firewood harvest (solid - m3)"
       Units: M3 / Year

"WEIGHT OF AIR - DRY FIREWOOD PER SOLID - M3" = 719.424
       Units: Kg / M3
       Source: (FAO, 1983)
       Comment: may actually be dynamically going down as preferred
       species are depleted

"weight of green firewood per solid - m3" = "WEIGHT OF AIR - DRY
       FIREWOOD PER SOLID - M3" · (1 - MOISTURE CONTENT OF AIR DRY
       FUELWOOD) / (1 - MOISTURE CONTENT OF GREEN WOOD) · (1 -
       "PROPORTIONAL VOLUMETRIC SHRINKAGE WHEN AIR - DRYING GREEN
       WOOD")
       Units: Kg / M3

"wood embedded in total imports of industrial wood - derived
       products" = "wood embedded in import of paper - related
       industrial products" + "wood embedded in imports of non -
       paper - related industrial wood - derived products"
       Units: M3 / Year

wood harvest for energy use = firewood harvest + charcoal timber
       harvest
       Units: M3 / Year
```

10.3.5 Equations of the Forestry trade sector

```
demand embedded timber exports = INITIAL FORESTRY IMPORTS · Relative
       Row Gdp^ELASTICITY OF WOOD EMBEDDED IN EXPORTS TO RELATIVE ROW
       GDP
       Units: M3 / Year

"domestic industrial wood demand (m3)" = Capital Industry · TIMBER
       DEMAND PER UNIT INDUSTRIAL CAPITAL
       Units: M3 / Year
       Source: calibration data from (FAO Statistics Division, a)

ELASTICITY OF WOOD EMBEDDED IN EXPORTS TO RELATIVE ROW GDP = 1.8
       Units: Dmnl [0,2,0.1]
       Source: obtained through calibration

ELASTICITY OF WOOD EMBEDDED IN INDUSTRIAL WOOD IMPORTS TO DISPOSABLE
       INCOME = 1.6
       Units: Dmnl
       Source: obtained through calibration

ELASTICITY OF WOOD EMBEDDED IN PAPER WOOD IMPORTS TO DISPOSABLE
       INCOME = 3
       Units: Dmnl [0,5,0.1]
       Source: obtained through calibration

embedded timber exports = industrial timber harvest embedded in
       exports
       Units: M3 / Year

EMBEDDED timber exports exogenous
       Units: M3 / Year
       Source: Data from (FAO Statistics Division, a) aggregated and
       where necessary GFN Technical conversion factors applied to
       convert derived amounts into primary amounts
```

embedded timber imports = "wood embedded in total imports of industrial wood - derived products"
Units: M3 / Year

EMBEDDED timber imports exogenous
Units: M3 / Year
Source: Data from (FAO Statistics Division, a) aggregated and where necessary GFN Technical conversion factors applied to convert derived amounts into primary amounts

EQUIVALENCE factor forestry exogenous
Units: Gha / Wha
Source: (Global Footprint Network, 2011)

forest ef embedded in exports = (1 - SWITCH EXOGENOUS DATA INPUT) · embedded timber exports / GFN CONSTANT FOREST INCREMENT WORLD · EQUIVALENCE factor forestry exogenous + SWITCH EXOGENOUS DATA INPUT · EMBEDDED timber exports exogenous / GFN CONSTANT FOREST INCREMENT WORLD · EQUIVALENCE factor forestry exogenous
Units: Gha

forest ef embedded in imports = (1 - SWITCH EXOGENOUS DATA INPUT) · embedded timber imports / GFN CONSTANT FOREST INCREMENT WORLD · EQUIVALENCE factor forestry exogenous + SWITCH EXOGENOUS DATA INPUT · EMBEDDED timber imports exogenous / GFN CONSTANT FOREST INCREMENT WORLD · EQUIVALENCE factor forestry exogenous
Units: Gha

GFN CONSTANT FOREST INCREMENT WORLD = 1.81878
Units: M3 / (Year · Wha)
Source: (Global Footprint Network, 2011)

industrial timber harvest = MIN (MAX(0,(Timber Volume - SWITCH PROTECTION TIMBER · classified forest · MINIMUM TIMBER VOLUME PER HA IN CLASSIFIED FOREST) / DEFORESTATION ADJUSTMENT TIME),"residual industrial wood demand (m3)")
Units: M3 / Year

industrial timber harvest embedded in exports = industrial timber harvest · proportion of industrial wood demand for export
Units: M3 / Year

industrial wood harvest exo = "SAWLOGS + VENEER log (nc) harvest exo" + "OTHER indust roundwd(nc) harvest exo"
Units: M3 / Year

INITIAL FORESTRY IMPORTS = 2500
Units: M3 / Year
Source: obtained through calibration, since there is no initial value in the data which is from (FAO Statistics Division, a)

INITIAL WOOD EMBEDDED IN IMPORT OF PAPER WOOD = 35780.8
Units: M3 / Year
Source: Data from (FAO Statistics Division, a) aggregated and where necessary GFN Technical conversion factors applied to convert derived amounts into primary amounts

"INITIAL WOOD EMBEDDED IN IMPORTS OF NON - PAPER INDUSTRIAL WOOD" = 48669.5
Units: M3 / Year
Source: Data from (FAO Statistics Division, a) aggregated and where necessary GFN Technical conversion factors applied to convert derived amounts into primary amounts

Perceived Relative Pc Disposable Income = SMOOTH N(relative pc disposable income ,TIME TO PERCEIVE CHANGES IN PC INCOME , 1 , 1)

Units: Dmnl
Source: taken unchanged from T21-Senegal34b
Comment: This variable represents the influence of income on a consumer's decision - making process regarding water consumption. It is calculated as a first order delay of relative per capita disposable income.

proportion of industrial wood demand for export = demand embedded timber exports / "residual industrial wood demand (m3)"
Units: Dmnl

Relative Row Gdp= INTEG (row gdp net growth,1)
Units: Dmnl
Source: taken unchanged from T21-Senegal34b
Comment: This stock represents relative Gross Domestic Product (GDP) of the Rest Of the World (ROW), relative to its initial value. For definition, the initial value of this stock is 1, and it accumulates in the net flow "ROW GDP net growth".

"residual industrial wood demand (m3)" = (1 - SWITCH EXOGENOUS INDUSTRIAL WOOD HARVEST) · MAX(0,("domestic industrial wood demand (m3)" + demand embedded timber exports - "wood embedded in total imports of industrial wood - derived products")) + SWITCH EXOGENOUS INDUSTRIAL WOOD HARVEST · industrial wood harvest exo
Units: M3 / Year
Source: (of data) (FAO Statistics Division, a)

SWITCH EXOGENOUS DATA INPUT = 0
Units: Dmnl [0,1,1]

SWITCH EXOGENOUS INDUSTRIAL WOOD HARVEST = 0
Units: Dmnl [0,1,1]

"wood embedded in import of paper - related industrial products" = Perceived Relative Pc Disposable Income^ELASTICITY OF WOOD EMBEDDED IN PAPER WOOD IMPORTS TO DISPOSABLE INCOME · INITIAL WOOD EMBEDDED IN IMPORT OF PAPER WOOD
Units: M3 / Year

"wood embedded in imports of non - paper - related industrial wood - derived products" = Perceived Relative Pc Disposable Income^ELASTICITY OF WOOD EMBEDDED IN INDUSTRIAL WOOD IMPORTS TO DISPOSABLE INCOME · "INITIAL WOOD EMBEDDED IN IMPORTS OF NON - PAPER INDUSTRIAL WOOD"
Units: M3 / Year

"wood embedded in total imports of industrial wood - derived products" = "wood embedded in import of paper - related industrial products" + "wood embedded in imports of non - paper - related industrial wood - derived products"
Units: M3 / Year

10.3.6 Equations of the Calculations Sector

"10M3 SOLID FUELWOOD PER T OF CHARCOAL" = 0.01
Units: M3 / Kg
Comment: see "M3 SOLID FUELWOOD PER T OF CHARCOAL". This is just a replication of that variable but it does not change if the other one is changed for sensitivity analysis

CHARCOAL production exo
Units: Kg / Year
Source: (FAO Statistics Division, a)

charcoal timber harvest = residual timber harvest for charcoal + "charcoal timber harvested from conversion to agriculture

(m3)" + "charcoal timber harvested from conversion to mines (m3)"
Units: M3 / Year

charcoal wood pr exo 10m3eff = CHARCOAL production exo · "10M3 SOLID FUELWOOD PER T OF CHARCOAL"
Units: M3 / Year

charcoal wood pr exo fao = CHARCOAL production exo · FAO TCF CHARCOAL
Units: M3 / Year

charcoal wood pr exo gfn2011 = CHARCOAL production exo · GFN2011 TCF CHARCOAL
Units: M3 / Year

charcoal wood pr exo gfn2012 = CHARCOAL production exo · GFN2012 TCF CHARCOAL
Units: M3 / Year

classified forest = IF THEN ELSE(Time<2011, CLASSIFIED forest past,CLASSIFIED forest future)
Units: Ha

"deforestation due to over-thinning" = MIN(MAX(0, (Forest Land - classified forest · SWITCH FOREST AREA PROTECTION) / DEFORESTATION ADJUSTMENT TIME),"intended deforestation due to over-thinning")
Units: Ha / Year

deforestation for mining = SWITCH DEFORESTATION FOR MINING · MIN(MAX(0, (Forest Land - classified forest · SWITCH FOREST AREA PROTECTION) / DEFORESTATION ADJUSTMENT TIME),intended deforestation for mining)
Units: Ha / Year

deforestation through forest fires = SWITCH FOREST FIRES · MIN(MAX(0, Forest Land / DEFORESTATION ADJUSTMENT TIME), normal area deforested by forest fires)
Units: Ha / Year

direct deforestation for fire wood = MIN(MAX(0, (Forest Land - classified forest · SWITCH FOREST AREA PROTECTION) / DEFORESTATION ADJUSTMENT TIME),intended direct deforestation for fire wood)
Units: Ha / Year

direct deforestation for industrial wood = MIN(MAX(0, (Forest Land - classified forest · SWITCH FOREST AREA PROTECTION) / DEFORESTATION ADJUSTMENT TIME),intended direct deforestation for industrial wood)
Units: Ha / Year

FAO TCF CHARCOAL = 0.006
Units: M3 / Kg
Source: (FAO Statistics Division, a)

"firewood demand (air - dry kg)" = total population · share of population using wood · FIREWOOD CONSUMPTION PER PERSON
Units: Kg / Year

firewood h exo gfn2011 = firewood prod minus charcoal exo fao · GFN2011 TCF WOOD FUEL
Units: M3 / Year

firewood h exo gfn2012 = firewood prod minus charcoal exo fao · GFN2012 TCF WOOD FUEL
Units: M3 / Year

firewood h exo tcf1 = firewood prod minus charcoal exo fao
Units: M3 / Year

firewood prod minus charcoal exo fao = "WOOD fuel(nc) harvest exo" - charcoal wood pr exo fao
Units: M3 / Year

forest conversion to cropland = SWITCH DEFORESTATION FOR CROPLAND · MIN(MAX(0, (Forest Land - classified forest · SWITCH FOREST AREA PROTECTION) / DEFORESTATION ADJUSTMENT TIME),intended conversion forest to cropland)
Units: Ha / Year [0,10000,5000]

Forest Land= INTEG (reforestation - "deforestation due to over-thinning" - deforestation for mining - deforestation through forest fires - direct deforestation for fire wood - direct deforestation for industrial wood - forest conversion to cropland - residual charcoal induced deforestation,INITIAL FOREST LAND)
Units: Ha

FOREST land exogenous
Units: Ha
Source: (FAO Statistics Division, a)

FOREST TIMBER IN 2004 = 3.23507e + 008
Units: M3
Source: (FAO Forestry Department, 2010 excluding other wooded land)
Comment: Needed for calibration purposes

GFN2011 TCF CHARCOAL = 0.001
Units: M3 / Kg
Source: (Global Footprint Network, 2011)

GFN2011 TCF WOOD FUEL = 0.543478
Units: Dmnl
Source: (Global Footprint Network, 2011)

GFN2012 TCF CHARCOAL = 0.00596
Units: M3 / Kg
Source: (D. Moore, personal communication, 2012 pers. comm) taken from (United Nations Economic Comission for Europe & FAO, 2010)

GFN2012 TCF WOOD FUEL = 0.913993
Units: Dmnl
Source: (D. Moore, personal communication, 2012 pers. comm) taken from (United Nations Economic Comission for Europe & FAO, 2010)
Comment: unclear why this is necessary at all if FAO firewood data is already reported in solid-m^3

green firewood harvest = MIN (MAX(0,(Timber Volume - SWITCH PROTECTION TIMBER · classified forest · MINIMUM TIMBER VOLUME PER HA IN CLASSIFIED FOREST) / DEFORESTATION ADJUSTMENT TIME),"intended green firewood harvest (solid - m3)")
Units: M3 / Year

harvest exo gfn2010org = woodfuel h exo gfn2010org + industrial wood harvest exo
Units: M3 / Year

harvest exo gfn2011 = woodfuel h exo gfn2011 + industrial wood harvest exo
Units: M3 / Year

harvest exo gfn2012 = woodfuel h exo gfn2012 + industrial wood harvest exo
Units: M3 / Year

```
harvest exo plain fao = "WOOD fuel(nc) harvest exo" + industrial wood
       harvest exo
       Units: M3 / Year

harvest exo tcfw1 tcfc10 = woodfuel h exo tcf1 10m3 char exo +
       industrial wood harvest exo
       Units: M3 / Year

industrial timber harvest = MIN (MAX(0,(Timber Volume - SWITCH
       PROTECTION TIMBER · classified forest · MINIMUM TIMBER VOLUME
       PER HA IN CLASSIFIED FOREST) / DEFORESTATION ADJUSTMENT
       TIME),"residual industrial wood demand (m3)")
       Units: M3 / Year

industrial wood harvest exo = "SAWLOGS + VENEER log (nc) harvest exo"
       + "OTHER indust roundwd(nc) harvest exo"
       Units: M3 / Year

"intended green firewood extraction (green kg)" = "firewood demand
       (air - dry kg)" · PROPORTION OF FIREWOOD DEMAND SATISFIED WITH
       GREEN WOOD EXOGENOUS · (1 - MOISTURE CONTENT OF AIR DRY
       FUELWOOD) / (1 - MOISTURE CONTENT OF GREEN WOOD)
       Units: Kg / Year

MOISTURE CONTENT OF AIR DRY FUELWOOD = 0.13
       Units: Dmnl

Data: 13% in the wet and 15% in the dry. May actually be

slightly lower in Africa? but not below 10%.

http: / / www.fao.org / docrep / q1085e / q1085e0c.htm

MOISTURE CONTENT OF GREEN WOOD = 0.5
       Units: Dmnl
       Source: (FAO, 1983)

net deforestation = forest conversion to cropland + direct
       deforestation for fire wood + direct deforestation for
       industrial wood + residual charcoal induced deforestation +
       "deforestation due to over-thinning" + deforestation for
       mining + deforestation through forest fires - reforestation
       Units: Ha / Year

net natural reproduction and growth = Forest Land · "nat. annual
       timber increment"
       Units: M3 / Year

net timber inflow = net natural reproduction and growth - timber
       removal
       Units: M3 / Year

"OTHER indust roundwd(nc) harvest exo"
       Units: M3 / Year
       Source: (FAO Statistics Division, a)

proportion of firewood demand satisfied with green wood = "intended
       green firewood extraction (green kg)" / ((1 - MOISTURE CONTENT
       OF AIR DRY FUELWOOD) / (1 - MOISTURE CONTENT OF GREEN WOOD)) /
       "firewood demand (air - dry kg)"
       Units: Dmnl [0,1,0.1]
       Comment: this should better be dynamic. The green wood should
       be residual if harvest of dead wood cannot satisfy the
       firewood demand.

proportion of forest land classified = classified forest / FOREST
       land exogenous
       Units: 1
```

```
proportion of land protected = PROTECTED area / total land area
       Units: 1

PROTECTED area
       Units: Ha
       Source: (IUCN & UNEP-WCMC, 2011)

reforestation = SWITCH REFORESTATION · (SWITCH EXOGENOUS
       REFORESTATION · REFORESTATION exogenous + (1 - SWITCH
       EXOGENOUS REFORESTATION) · average reforestation)
       Units: Ha / Year

residual charcoal induced deforestation = MIN(MAX(0, (Forest Land -
       classified forest · SWITCH FOREST AREA PROTECTION) /
       DEFORESTATION ADJUSTMENT TIME),intended charcoal induced
       deforestation not due to agricultural conversion)
       Units: Ha / Year

residual timber harvest for charcoal = MIN (MAX(0,(Timber Volume -
       SWITCH PROTECTION TIMBER · classified forest · MINIMUM TIMBER
       VOLUME PER HA IN CLASSIFIED FOREST) / DEFORESTATION ADJUSTMENT
       TIME),"residual charcoal wood demand (m3)")
       Units: M3 / Year

"SAWLOGS + VENEER log (nc) harvest exo"
       Units: M3 / Year
       Source: (FAO Statistics Division, a)

timber cleared through conversion to cropland = forest conversion to
       cropland · timber volume per ha
       Units: M3 / Year

timber cleared through conversion to mines = deforestation for mining
       · timber volume per ha
       Units: M3 / Year

timber extraction per ha = timber removal / Forest Land
       Units: M3 / (Ha · Year)

timber removal = residual timber harvest for charcoal + green
       firewood harvest + industrial timber harvest + timber cleared
       through conversion to cropland + timber cleared through
       conversion to mines + timber removed by forest fire
       Units: M3 / Year

timber removed by forest fire = SWITCH FOREST FIRES · MIN (Timber
       Volume / DEFORESTATION ADJUSTMENT TIME,(deforestation through
       forest fires · timber volume per ha + normal area thinned by
       forest fires · timber volume per ha · "PROPORTION OF REDUCTION
       OF TIMBER PER HA THROUGH NON - DEFORESTING FOREST FIRES"))
       Units: M3 / Year
       Comment: Conceptual mistake: should not be normal area but
       normal proportion of area affected. Discovered to late to fix

total land area = TOTAL COUNTRY AREA - TOTAL INLAND WATER AREA
       Units: Ha

total timber harvest = green timber harvest + SWITCH DEAD FIREWOOD
       HARVEST AS PART OF EF · "dead firewood harvest (solid - m3)"
       Units: M3 / Year

"WOOD fuel(nc) harvest exo"
       Units: M3 / Year
       Source: (FAO Statistics Division, a)

wood harvest for energy use = firewood harvest + charcoal timber
       harvest
       Units: M3 / Year
```

```
woodfuel h exo gfn2010org = "WOOD fuel(nc) harvest exo" · GFN2011 TCF
       WOOD FUEL
       Units: M3 / Year

woodfuel h exo gfn2011 = firewood h exo gfn2011 + charcoal wood pr
       exo gfn2011
       Units: M3 / Year

woodfuel h exo gfn2012 = firewood h exo gfn2012 + charcoal wood pr
       exo gfn2012
       Units: M3 / Year

woodfuel h exo tcf1 10m3 char exo = firewood h exo tcf1 + charcoal
       wood pr exo 10m3eff
       Units: M3 / Year
```

10.3.7 Equations of the changed Animal husbandry and forestry sector

```
charcoal timber harvest = residual timber harvest for charcoal +
       "charcoal timber harvested from conversion to agriculture
       (m3)" + "charcoal timber harvested from conversion to mines
       (m3)"
       units: M3 / Year

"charcoal timber harvested from conversion to agriculture (m3)" =
       timber cleared through conversion to cropland · (1 - FRACTION
       OF TIMBER WASTED IN CONVERSIONS)
       units: M3 / Year

"charcoal timber harvested from conversion to mines (m3)" = timber
       cleared through conversion to mines · (1 - FRACTION OF TIMBER
       WASTED IN CONVERSIONS)
       units: M3 / Year

"commercial timber harvest (m3)" = "formal firewood harvest (m3)" +
       industrial timber harvest + residual timber harvest for
       charcoal + "charcoal timber harvested from conversion to
       agriculture (m3)" + "charcoal timber harvested from conversion
       to mines (m3)"
       units: M3 / Year

"dead firewood harvest (solid - m3)" = "intended dead firewood
       extraction (kg)" / "WEIGHT OF AIR - DRY FIREWOOD PER SOLID -
       M3"
       units: M3 / Year

EXPONENTIAL FORESTRY PRODUCTION GROWTH RATE = 0.0189
       units: 1 / Year
       Source: exponential regression

forestry production = SWITCH FORESTRY PRODUCTION EXOGENOUS · IF THEN
       ELSE(Time<2009,FORESTRY production exogenous past,forestry
       production exogenous future extrapolation) + (1 - SWITCH
       FORESTRY PRODUCTION EXOGENOUS) · "commercial timber harvest
       (m3)" · VALUE added per m3 harvested wood exogenous
       units: Cfa99 / Year

forestry production exogenous future extrapolation = 1e - 006 ·
       EXP(EXPONENTIAL FORESTRY PRODUCTION GROWTH RATE · Time)
       units: Cfa99 / Year
       Comment: this is an exponential extrapolation of past data of
       forestry production

FORESTRY production exogenous past
       units: Cfa99 / Year

"formal firewood harvest (m3)" = green firewood harvest + "dead
       firewood harvest (solid - m3)" · (1 - SHARE OF INFORMAL AND
```

```
        PRIVATE FIREWOOD HARVEST)
        units: M3 / Year

green firewood harvest = MIN (MAX(0,(Timber Volume - SWITCH
        PROTECTION TIMBER · classified forest · MINIMUM TIMBER VOLUME
        PER HA IN CLASSIFIED FOREST) / DEFORESTATION ADJUSTMENT
        TIME),"intended green firewood harvest (solid - m3)")
        units: M3 / Year

industrial timber harvest = MIN (MAX(0,(Timber Volume - SWITCH
        PROTECTION TIMBER · classified forest · MINIMUM TIMBER VOLUME
        PER HA IN CLASSIFIED FOREST) / DEFORESTATION ADJUSTMENT
        TIME),"residual industrial wood demand (m3)")
        units: M3 / Year

residual timber harvest for charcoal = MIN (MAX(0,(Timber Volume -
        SWITCH PROTECTION TIMBER · classified forest · MINIMUM TIMBER
        VOLUME PER HA IN CLASSIFIED FOREST) / DEFORESTATION ADJUSTMENT
        TIME),"residual charcoal wood demand (m3)")
        units: M3 / Year

SHARE OF INFORMAL AND PRIVATE FIREWOOD HARVEST = 0.97
        units: Dmnl [0.8,1,0.01]

SWITCH FORESTRY PRODUCTION EXOGENOUS = 1
        units: Dmnl

value added per m3 harvested wood = IF THEN ELSE(Time<2009,FORESTRY
        production exogenous past / "commercial timber harvest
        (m3)",forestry production exogenous future extrapolation /
        "commercial timber harvest (m3)")
        units: Cfa99 / M3

VALUE added per m3 harvested wood exogenous
        units: Cfa99 / M3
```