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ToSIA—A tool for sustainability impact assessment of forest-wood-chains

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ABSTRACT

Within the forest sector, the sustainability concept has evolved from a narrow focus on sustainable wood production to a much broader evaluation of environmental, social, and economic sustainability for whole value chains. A new software tool – ToSIA – has been developed for assessing sustainability impacts of Forest-Wood-Chains (FWCs). In the approach, FWCs are defined as chains of production processes (e.g. harvesting–transport–industrial processing), which are linked with products (e.g. a timber frame house). Sustainability is determined by analysing environmental, economic, and social sustainability indicators for all the production processes along the FWC. The tool calculates sustainability values as products of the relative indicator values (i.e. indicator value expressed per unit of material flow) multiplied with the material flow entering the process. Calculated sustainability values are then aggregated for the segments of the FWC or for the complete chain. The sustainability impact assessment requires carefully specified system boundaries. ToSIA uses a data-oriented approach that is very flexible in the focus of the analysis and the selection of indicators of sustainability. An example of alternative Norway spruce management systems in Southern Germany and their effects on six sustainability indicators is presented. The less intensive management system with natural regeneration and motor–manual harvesting shows higher carbon storage and slightly less energy use. It creates more employment and higher labour costs, but the average rate of accidents is also higher. ToSIA offers a transparent and consistent methodological framework to assess sustainability impacts in the forest-based sector as affected, e.g. by changes in policies, market conditions, or technology. The paper discusses strengths and limitations of the approach and provides an outlook on further development perspectives of the methodology.

1. Introduction

Sustainability has been recognized as a target of good management in forestry for centuries. The concept of sustainable yield of forest resources was named already in 1713 by Hans Carl von Carlowitz in his *Sylvicultura oeconomica*. After the Brundtland report established sustainable development in a wider context (WCED, 1987), the concept as applied to forestry was also broadened and multi-dimensional aspects of sustainability were considered as a basis for sustainable forest management (e.g. Kessler et al., 1992).

The development of consistent criteria and indicators for sustainable forest management has been an important process in the 1990s (Nussbaum et al., 1996; Hall, 2001). Based on these criteria and indicators, State of Forests reports provide a useful source of information, monitoring the progress towards sustainable forest management (MCPFE, 2007; Howell et al., 2008). Another driver in the development of sustainable forest management was the introduction of forest certification, which led to noticeable changes in forest management in Europe (Rametsteiner and Simula, 2003). Important aspects of ecological sustainability, such as the conservation of forest biodiversity, are not yet sufficiently supported by certification standards (Wintle and Lindenmayer, 2008). However, as documented, e.g. by the latest State of Europe's Forest report, many sustainability indicators show positive trends (MCPFE, 2007).

The European Union (EU) Strategy for Sustainable Development adopted by the European Council in Gothenburg in June 2001 expressed the need “to judge how policies contribute to sustainable development”. In later communications it was postulated that full effects of policy proposals should be carefully assessed, including estimates of its economic, environmental and social impacts inside and outside the EU (European Commission, 2005). In response to these needs, ex ante sustainability impact assessment (SIA) methods have been developed in Europe (Helming et al., 2008; Tscherning et al., 2008). In general, the impact assessment methods aim to support decision-making by ensuring that potential policy options are environmentally and socio-economically sound.

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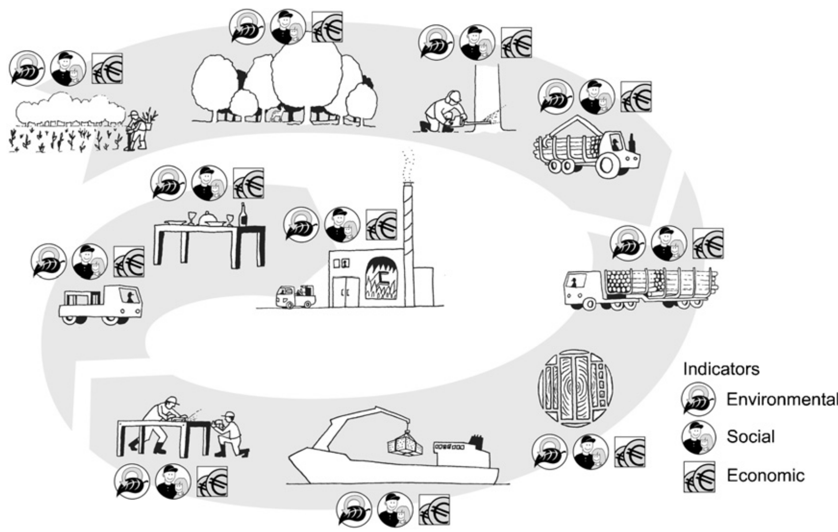

Fig. 1. ToSIA analyses sustainability impacts of forest-wood-chains (FWCs) using economic, social and environmental indicators, which are linked to the processes of the FWC from forest regeneration to the end-of-life of wood products.

With the ambition to develop a knowledge-based bio-economy, the sustainable development paradigm has been extended across whole economic sectors. The whole forest-based sector including the production chains using wood resources should perform in a sustainable way (CEC, 2008). Consequently, entire forest value chains need to be included in the sustainability impact assessment.

Despite intensive research efforts and many debates at all scales from local to global, scientifically agreed criteria are still lacking to assess if a given situation is sustainable or not, because it is difficult to define sustainability thresholds in a quantitative way (Bertrand et al., 2008). It has been proposed that focusing on unsustainable practices is more practical (Smith and McDonald, 1998) and with conceptually clear assessment frameworks it is possible to assess progress towards sustainability (Haberl et al., 2004). SIA compares the effects of alternative policies or management decisions on a given situation. To analyse changes in different criteria and indicators and to evaluate the alternatives, decision support methods like multi-criteria analysis can be used (Mendoza and Prabhu, 2003).

Ness et al. (2007) provided a categorisation of sustainability assessment tools into (i) indicators and indices, (ii) product related assessments, and (iii) integrated assessments, where each of these categories contained additional sub-categories. Reflecting on this categorisation it can be concluded that the various requirements from above call for an integrated impact assessment tool covering forest resource management and the complete forest-wood-chain with respect to the environmental, social and economic sustainability dimensions. Such a tool would need to build on existing frameworks of criteria and indicators (e.g., MCPFE, 2007). It could also utilise experience from product related assessments such as life-cycle assessment, which have assessed the environmental impacts, e.g. of forest operations (Berg and Lindholm, 2005; Sonne, 2006) or forest industries (Jawjit et al., 2006; Dias et al., 2007). The tool also needs to integrate the social and economic sustainability dimension in a balanced way.

The objective of this paper is to present such an integrated impact assessment tool for the forest-wood-chain: the tool for sustainability impact assessment (ToSIA). ToSIA is targeted at different users including policy makers, industry, other stakeholders, consultants and researchers. The tool has been developed in the European Commission (FP6) funded project EFORWOOD (Sustainability Impact Assessment of the Forestry-Wood-Chain). We present the conceptual approach and how it can be applied in different contexts. Its application is illustrated with an example of two forest management alternatives for a forest-wood-chain in Central Europe.

2. Materials and methods

2.1. ToSIA approach

ToSIA is a software tool that analyses sustainability impacts in the forest-based sector. The forest-based sector is described as Forest-Wood-Chains (FWCs) of value-adding production processes by which forest resources are converted into products and services. The chains may extend from forest resource management to the end-of-life of a wood product. ToSIA addresses three sustainability dimensions: environmental, economic and social. The sustainability impacts are described with indicators that are linked to production processes (Fig. 1). Using the material flow through the processes of the FWC, the sustainability impacts are linked to specified forest sector activities. ToSIA is designed to assess sustainability impacts of changes in the FWC due to deliberate actions (e.g. in policies or business activities) or due to external forces (e.g. climate change, global markets). This approach was first proposed by Päivinen and Lindner (2008). In the following we describe its implementation in the ToSIA software following the workflow shown in Fig. 2. We will present the approach with examples of a FWC that is starting from the forest and ending with the end-of-life of wood products. The tool can also be applied with the opposite perspective of consumed products which are traced back to the origin of the wood resource. But for simplicity, we only mention special data requirements for this type of application without further details.

2.2. Modelling forest-wood-chains

The goal and scope definition is the first important step in planning a SIA for the FWC. The goal of a SIA study affects the identification of FWC alternatives. Furthermore, the spatial, temporal, and technical system boundary definitions need to be set to specify the location, structure, content, and degree of detail of the studied FWC.

Forest value chains are linking forest resources with the production and consumption of wood products, but because of transport and trade, not all of these processes are necessarily located in the

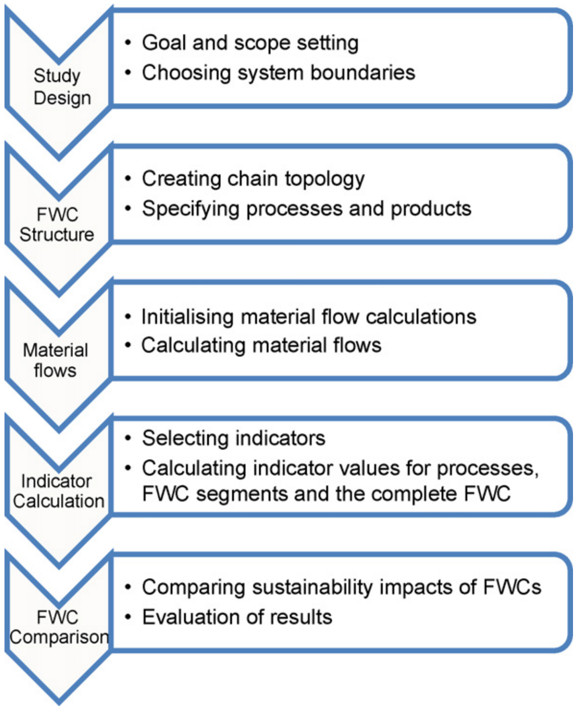

Fig. 2. ToSIA work flow indicating steps in conducting a sustainability impact assessment for the FWC.

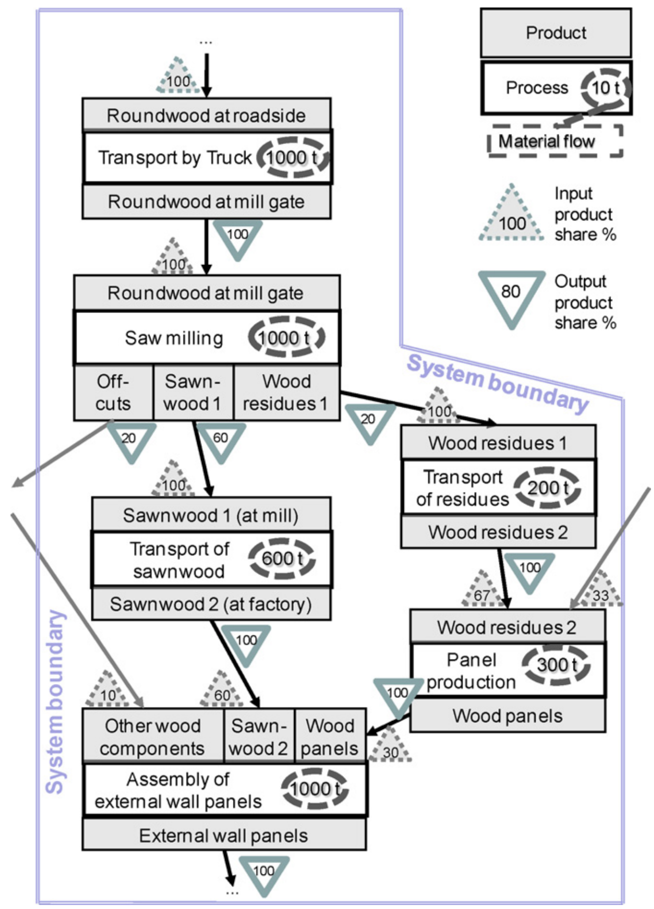

Fig. 3. Extract of the FWC topology showing selected processes and products and their connections. Product shares for input and output products enable the calculation of material flows along the FWC. The legend in the top right corner shows the elements of the topology. Grey arrows indicate where products leave or enter the system boundaries of the FWC. A process always changes the product, for example sawnwood 1 and sawnwood 2 are in different locations (i.e. at sawmill and timber frame factory, respectively). Output products are identical with input products of the subsequent process.

same geographical region. Simple FWCs like coppice forests producing only fuel wood for local consumption can be confined to the same geographical area. Many modern FWCs, however, include transport of raw or processed wood and its products. If the study case is restricted to a country, for example, there could be input of material from other countries (i.e. imports) as well as products leaving the country (i.e. exports). Moreover, the forest-based sector produces multiple products, many of which are mixtures of woody material and other materials. The definition of cut-off criteria for the analysis must be clear. Products may be excluded due to negligible amounts produced (e.g. wooden musical instruments) or because they are no longer considered a wood product (e.g. composite building materials). Imports and exports as well as other material flows entering and leaving the analysed FWC are handled as input and output products on the system boundary of the study case. ToSIA will calculate and display totals for material flows in both directions across the system boundaries.

The structure of the analysed FWC is specified in the chain *topology*. This defines all the processes and products and their connections in the studied chain. The basic components building up different FWCs are processes, products and product shares. A *process* is the most important element of a FWC. In a process material and energy is either transformed, changes characteristics or is moved to another location. Each process is related to a specified technology. Examples of FWC processes are stand regeneration, harvesting, transport, sawing, pulping, paper-making, printing, etc.

Products are the mass-based inputs and outputs of processes, such as spruce logs or finished wood furniture. The functional purpose of products is to link together processes to form chain structures. Processes can also receive input products from outside of the FWC system boundaries (e.g. imported wood material from another country used in furniture manufacturing).

To support the analysis and presentation of results, the processes of the FWC are grouped into four different segments of the FWC: forest resource management (FWC_{S1}), forest to industry interactions (FWC_{S2}), processing and manufacturing (FWC_{S3}), and industry to consumer interactions (FWC_{S4}).

As a convention in complete FWC analysis, the only process in the FWC that does not receive input products from a preceding process is the forest regeneration process at the beginning of the FWC. The end of the FWC usually consists of one or more waste management processes at the end-of-life of the wood products. In the case of material recycling, this last process of the FWC can be linked back into the processing and manufacturing segment of the FWC, thereby creating a loop in the chain topology.

2.3. Material flow calculations

A FWC is characterized by the composition of processes and the material flows through the processes. The amount of material that a process in a FWC handles is calculated based on the amounts received from processes that precede it. The consecutive calculation of material flows along the FWC is using the information of output product shares relative to the input flow of each process. Input product shares are also needed to enable material flow calculations in FWC that are consumption-defined. Both input and output product shares direct the flows through the FWC structure as defined with the chain topology (Fig. 3).

Material flows along the FWC may in reality show pulses and fluctuations. ToSIA does not consider these short-term effects, as it represents equilibrium flows along a FWC as they occur simultaneously in a reference period (usually one year, or averaged over a period of 5 years).

When ToSIA is calculating material flows through complex FWCs, data integrity checking is done by calculating material input/output balances for each process. If imbalances occur, it is necessary to adjust the product shares (to redirect material flows) or to create new input or output products (in multiple-country applications these are often import or export products).

Wood material flows in a FWC can be expressed in different measurement units (like volume in m^3, mass in tons, or economic value in €). Internally within the ToSIA system, however, material flows are captured in two measurement units: (i) organic carbon content within the wood (in tons) and; (ii) forest area (in hectares). The use of organic carbon content within the wood as reference flow has the advantage of being independent of factors such as moisture content and density which change a lot within the FWC. But due to natural variability of growth and mortality, carbon content is difficult to follow in stand development stages in FWC_{S1}. Therefore, ToSIA uses the forest area as internal reference unit for the resource management (in FWC_{S1}): each year a certain number of hectare of forest area is regenerated, growing in different development stages and finally harvested, to yield the wood that is then followed through the rest of the FWC. ToSIA is thus using two different internal information carriers: hectare of forest area in FWC_{S1} and tons of organic carbon in the harvested wood and wood products in FWC_{S2}–FWC_{S4}. The transformation takes place with the cutting of the trees. FWC_{S1} ends with marking the trees for cutting, whereas the technical operation of thinning or harvesting is part of FWC_{S2}. Transformation factors are used to convert hectare into tons of carbon in the processed wood including both stem wood and harvest residues.

To convert between different measurement units of the material flow, ToSIA applies conversion factors. Conversion factors are needed for individual products to convert the measurement unit of the product to the reporting unit of the process (see indicator calculation), to ToSIA's internal reference unit tons of carbon, and to €. Non-wood materials used in the value chain (e.g. nails, glue, filler) are attached to the wood material flow and are reflected through changes in conversion factors in FWC processes. The resource use of these materials is calculated separately from woody materials. However, otherwise they are not distinguished as separate material flows.

The initialisation of material flows can occur in different parts of the chain, e.g. by specifying the forest area, the harvesting amounts, or the amount of products consumed. Material flows in other parts of the chain are then derived from the FWC topology and the product shares. The forest area that is linked with the processes in FWC_{S1} is usually derived from forest inventory data. The tool does not consider explicit spatial locations of forest areas within the study region, but possible imbalances in the age–class distribution can be accounted for by using inventoried areas for the different development stages in FWC_{S1}.

2.4. *Sustainability indicator calculation*

2.4.1. *Indicator selection*

ToSIA can apply and calculate any indicator that can be linked to FWC processes via the flow amount. The indicators need to be clearly specified with a uniform measurement unit (e.g. €). The indicators are provided as relative indicator values per unit of input material flow into a process (Fig. 4). The indicator values can be reported per reporting units that differ from ToSIA's internal reference tons of carbon or hectare. For each process the same reporting unit should be used for all indicators.

In the EFORWOOD project, a sustainability indicator framework has been developed that is suitable for SIA of the FWC (Rametsteiner et al., 2008). From this indicator framework, environmental, social and economic sustainability indicators can be selected for the ToSIA applications. Data collection protocols have been prepared to enable consistent data collection along the whole FWC. The selection of indicators should always be balanced between the three dimensions of sustainability. Depending on the purpose of the SIA and the availability of data, different indicators may be chosen—also from other existing indicator sets. The indicator choice should allow to investigate the possible trade-offs between sustainability indicators as different dimensions of sustainability are often connected (e.g. environmentally damaging wood exploitation might be more cost efficient than low-impact logging practices).

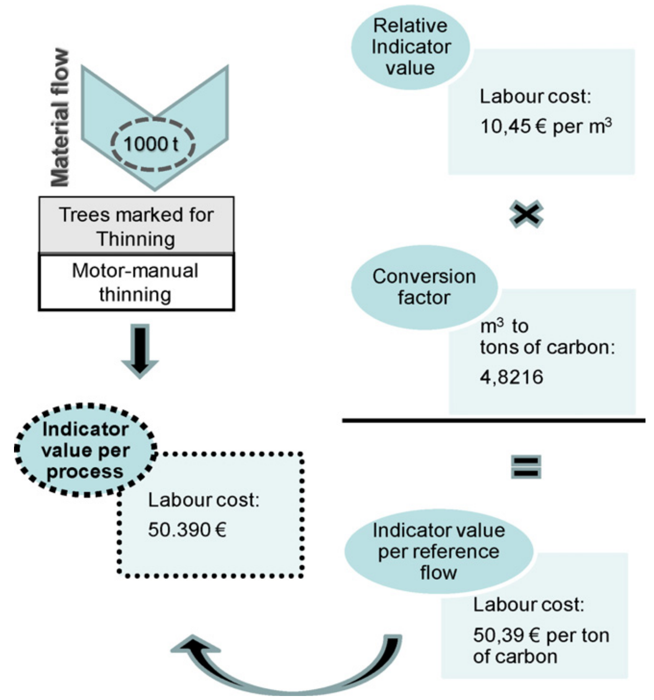

Fig. 4. Calculation example for the labour cost indicator in the thinning process. Indicator data are reported relative to the reporting unit of the process (m^3). ToSIA converts this with a conversion factor into the indicator value per reference flow (tons of carbon) and multiplies this with the material flow to calculate the indicator value per process.

ToSIA may also use qualitative indicators if certain sustainability criteria cannot be assessed otherwise. However, quantitative indicators are preferable, as they are easier to process and evaluate.

A small number of indicators such as *resource use* or *total production* can be calculated internally in ToSIA from the FWC information about material flows. But in most cases, relative indicator values need to be submitted to ToSIA from external sources, such as statistical data sources (e.g. from EUROSTAT), outputs of partial chain models (e.g. forest growth models, transport models or wood flow optimisation models), or expert judgements (in case no better data are available). Indicator values are reported together with metadata about the source and quality of the values and this information is accessible through the user interface to enable the user to judge the reliability of the sustainability assessment.

Many sustainability indicators (e.g. production costs, employment, energy use, GHG emissions) are relevant for the complete FWC, whereas some are only linked with a part of the FWC (e.g. biodiversity). ToSIA can use both whole-chain and chain-segment related indicators. To assess data completeness in the analysis it is important to specify in the data collection which indicators are not applicable to a process.

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2.4.2. Indicator calculation

Absolute sustainability indicator values for a process are calculated in ToSIA by multiplying the input material flow of the process with each of the process' relative indicator values (see Fig. 4). After calculating the indicator values for processes, the values can be aggregated to segments of the FWC, or the whole FWC. For most of the indicators, the aggregation can be done by summing up the indicator values of individual processes. However, some indicators may require a different way of aggregation. For example, indicators measured in % units are averaged (using material flow as weighting criteria).

While the majority of sustainability indicators can be linked with the production processes of the FWC, there are some indicators commonly included in impact assessments that are not meaningful at the process level. For example, total production describes the sector-specific performance of the complete FWC and can be calculated from ToSIA by adding products of the FWC in different categories. Another indicator calculated by ToSIA is *balance of increments and fellings*, where increments are collected per process in FWC_{S1}, while fellings are derived from the material flow in harvesting and thinning processes.

Sustainability impacts can also be assigned to the different products of the FWC. A procedure for this is presented in a companion paper (Palosuo et al., 2009, this issue).

2.5. System boundaries

A crucial concept of ToSIA is that all processes in different stages of the chain occur simultaneously and sustainability indicators are provided for one reference year. If we choose 2005 as starting point for the SIA, then all indicator values describe the situation in 2005 (e.g. average employment effect of a harvesting process in Germany, expressed in hours per m^3 round wood) and the material flow is quantified for the same year (i.e. the amount of m^3 harvested with this process in Germany). Dynamic forest growth processes are not considered in forest resource management, as the indicator values are collected per hectare of forest area in FWC_{S1} processes in 2005. However, to reduce the impact of stochastic effects of extreme events such as fire and storm damage, a moving average of 5 years can be used to calculate average harvest amounts.

The spatial system boundary of the indicators depends on the specification of the study case. In a region-defined SIA, all indicator values relate to the regional scope of the analysis, e.g. the country of Germany. ToSIA allows also for other types of SIA applications, where only one part of the FWC is geographically confined to a specific region. For example, EFORWOOD analyses a forest-defined Scandinavian production case, in which the forest resources are located in the region of Västerbotten, but the sustainability indicators for the rest of the FWC relate also to FWC processes in other parts of Europe where the wood is partly processed and a majority of wood products is consumed. Another example is the consumption-defined Iberian case study in EFORWOOD, in which the consumption of wood products takes place in Spain and Portugal, while a part of the forest resource management and wood processing is located outside of the target region.

The indicator definitions have also an effect on the system boundaries of the analysis. For example, when greenhouse gas (GHG) emissions are calculated in life-cycle analysis, it is required to include the supply chains (e.g. GHG emissions related to the production of harvesters are included in calculating GHG emissions of machine harvesting operations). However, as there is only limited experience available with the indicator data collection for the full range of sustainability indicators in different economic sectors, we currently exclude non-forest supply chains and focus on the SIA in the forest-based sector only.

2.6. Comparing and analysing chains

The purpose of ToSIA is to analyse and assess FWC-sustainability impacts of changes in the FWCs. Therefore, the SIA requires at least two indicator data sets of the same FWC study cases to compare. The simplest case is the comparison of two different FWC technologies under the same circumstances. This is illustrated in this paper with a comparison of two management alternatives in one FWC. Besides the technology change, policy changes and consumer changes are other typical examples of drivers that lead to changes in sustainability indicators of the FWC. While the comparison of technology alternatives may be meaningful under the current conditions for the same reference year, most other scenario analyses should include also a temporal dimension, as new policies need time to be implemented and market changes will evolve gradually.

As the development of the forest-based sector is very sensitive to changes in market conditions it is difficult to project sustainability indicator values very far into the future. However, scenario projections are available, e.g. from the IPCC (Nakicenovic and Swart, 2000; Inage Team, 2001), in which key socio-economic drivers have been specified. Based on these, it is possible to develop storylines for forest-based sector developments to be used as baseline reference futures (Arets et al., 2008). Against these reference futures, impacts of policy or market changes can be compared with ToSIA. Indicator values and material flows need to be estimated for both the FWC reference future and the FWC variant impacted by policy or market changes, using either external simulation models or expert judgements.

ToSIA will then compare the sustainability indicator values calculated for the different data sets. The results can be compared on a quantitative basis, for example by analysing the relative change of different indicator values for the whole FWC or its FWC segments. Development is ongoing to incorporate evaluation methods based on multi-criteria analysis (Mendoza and Prabhu, 2003; Wolfslehner et al., 2005) and cost–benefit analysis (Nas, 1996) into ToSIA. Moreover, policy impact analysis will be incorporated to compare changes in sustainability indicator values with policy targets.

2.7. Technical implementation

The ToSIA engine is implemented using the Open-MI framework (an open standard for linking models; http://www.openmi.org; Gregersen et al., 2007) and programmed in Java. ToSIA receives data about the FWC topologies, indicator values, etc. from a database in XML (eXtensible Markup Language) file format.

3. Example comparing technology options

The approach proposed in this paper is exemplified with a SIA comparing two FWCs from the Federal State of Baden-Württemberg in Germany with management alternatives of Norway spruce (*Picea abies* (L.) *karst*) which both produce timber for the use in house construction. The management alternatives differ in the resource management, harvesting and transport technology. The same production processes are used in the wood industry and the industry to consumer interaction. The forest management regimes investigated were natural regeneration (FM1) and planting (FM2). It is assumed that both management regimes produce the same quality of products. Table 1 shows the processes of these chains.

For demonstration of the approach six sustainability indicators were selected to characterize sustainability aspects of the forestry-wood-chain (Table 2): *Production costs* and *resource use* (economic

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Table 1
Processes of regional-defined spruce chains using two different forest management (FM) alternatives, natural regeneration (FM1) and planting (FM2) in Baden-Württemberg.

FWC segment	Natural regeneration (FM1) process name	Planting (FM2) process name
FWC_{S1}—Forest resources management	Regeneration with natural regeneration and weeding	Regeneration with planting and weeding
	Development of naturally regenerated spruce stand in young phase with 1 pre-commercial thinning	Development of planted spruce stand in young phase with 2 pre-commercial thinnings
	Development of natural regenerated spruce in medium phase	Development of planted spruce in medium phase
	Development of natural regenerated spruce in adult phase	Development of planted spruce in adult phase
FWC_{S2}—Forest to industry interaction	Pre-commercial thinning	Pre-commercial thinning
	Motor–manual 1.–2. thinning	Full-mechanised 1.–2. thinning: with medium harvester
	Motor-manual 3.–6. thinning	Full-mechanised 3.–6. thinning with large harvester
	Skidding with double-winch wheel skidders	Forwarding with medium forwarder
	Transport by truck for long timber	Transport by truck for short timber
	Final measuring and sorting at mill gate—long timber	Final measuring and sorting at mill gate—short timber
FWC_{S3}—Processing and manufacturing	Saw milling	
	Transport of wood residues	
	Panel production	
	Assembly of external wall panels	
FWC_{S4}—Industry to consumer interactions	Transport of external wall panels	
	House construction	
	Use of building	
	Demolition of building	
	Transport of demolished parts of building to recycling	

Table 2
Definition of indicators as used in the demonstration example.

Indicator	Specific indicator used	Definition	Unit
Production costs	Labour costs	Average labour costs	€
Resource use	Use of wood-based renewable material of virgin origin	Total amount of wood harvested (including felling residues)	kg
Employment	Number of persons employed	In full-time equivalents	-
Occupational safety and health	Non-fatal occupational accidents	Absolute numbers per 1000 employees	-
Energy use	Direct fuel use	Fuel used directly in the process	MJ
GHG emissions and carbon stock	Carbon stock in living woody biomass aboveground	Carbon stock in whole-tree biomass without stump and roots	CO_2 equiv.

indicators), *employment* and *occupational safety and health* (social indicators), *energy use* and *carbon stock* (environmental indicators). For each of the main indicators, only one specific sub-indicator was selected for the illustration case. The resource use indicator was derived from material flows entering FWC_{S2}, whereas all other indicators were aggregated along the FWC by summing up. The selected carbon stock indicator is only relevant in FWC_{S1} processes.

3.1. Results

Fig. 5 is presenting the indicator results aggregated to the FWC segments as well as for the total FWC. The two management alternatives are characterized by different indicator profiles along the FWC: regeneration by planting in FM2 results in higher labour costs and employment in FWC_{S1}, whereas the low mechanisation level used in FM1 causes less efficient harvest operations and increased demand for work force in FWC_{S2}. Totals for the whole FWC for labour cost and employment are larger in FM1. The mechanised harvesting system (harvester, forwarder) of FM2 increases the energy use, but the impact is hardly visible at total FWC level, because the energy use is strongly dominated by the industrial processing, which does not differ between the FWC alternatives. Motor-manual harvesting in FM1 causes more accidents, but the relative change (+7%) is smaller than the difference in employment (+15%). Resource use is identical in FM1 and FM2, because the same harvest volumes were chosen to compare the FWCs. Carbon stocks are larger in FM1, because the management is less intensive and considerable amount of tree biomass was left after the last thinnings to facilitate natural regeneration.

4. Discussion

The forest-based sector is providing significant amounts of income and employment to European citizens and as a sector based on the utilisation of a renewable resource it plays a central role in developing a more sustainable economy. Many socio-economic factors and policies affecting the sector are currently changing at rapid pace. Fluctuating energy prices, policies aiming at a strongly increased share of renewable energy use, and trade regulations all contribute to changes in the industry's competitiveness. At the same time, societal demands for goods and services from forests increase (Reid et al., 2005; Stenger et al., 2009). In this paper, we presented a new tool, ToSIA, to assess sustainability impacts in the forest-based sector. ToSIA provides a framework for transparently analysing how new policies, changes in market conditions, or new technologies will affect sustainability of entire FWCs.

The focus of ToSIA lies on sustainability impact analysis of changes to the FWC, rather than on assessing current sustainability. Walter and Stützel (2009) claimed that it is virtually impossible to substantiate scientifically that a system (or development path) is sustainable. Sustainability assessments in the agricultural sector focus often on unsustainable practices instead, which are evaluated using indicators, targets and thresholds (Smyth and Dumanski, 1995; Smith and McDonald, 1998; Walter and Stützel, 2009). However, while critical issues connected with intensive land use (e.g. soil loss, nutrient depletion, or pesticide leakage) can easily be addressed with targets and thresholds, there are many other sustainability aspects which lack clear scientific criteria to assess sustainability thresholds (Haberl et al., 2004). For example, dead

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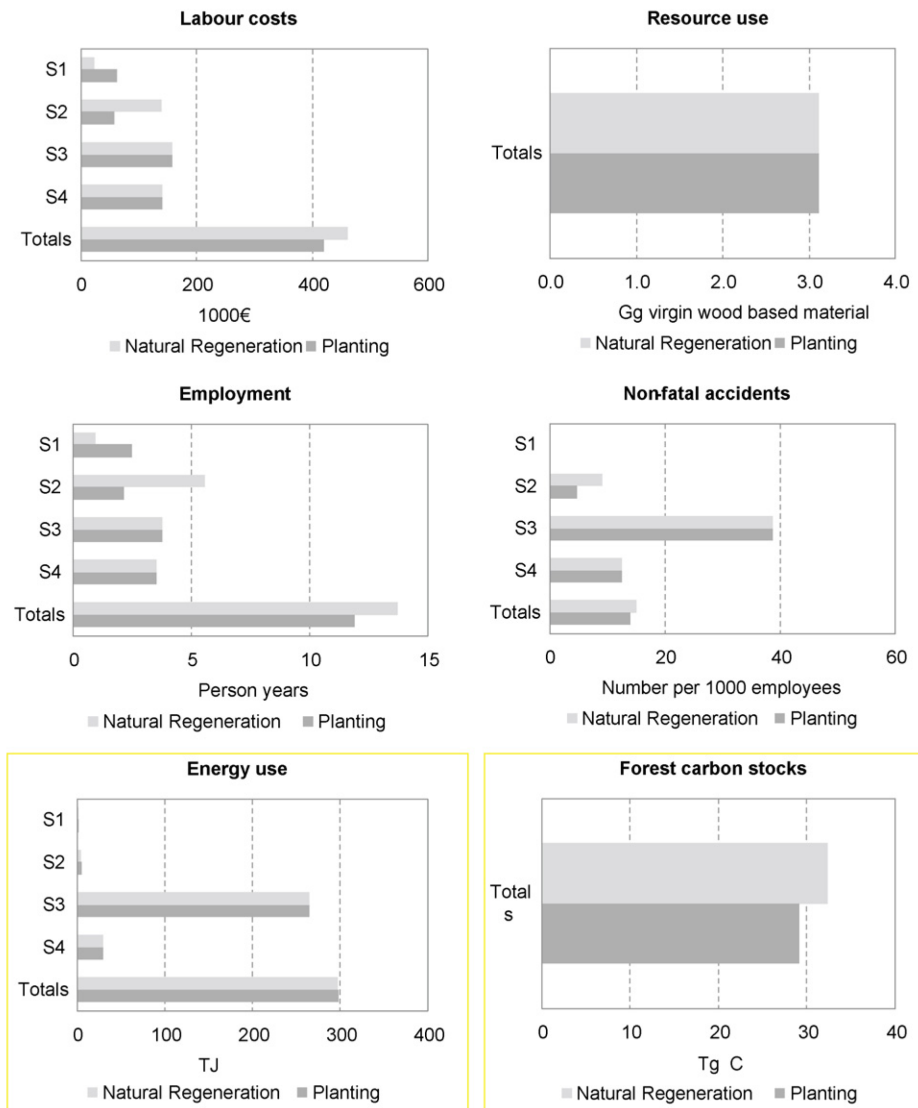

Fig. 5. Indicator results aggregated for FWC segments and the total FWC.

wood is a well-recognized indicator of forest biodiversity, but distinct thresholds are impossible to specify (Ranius and Fahrig, 2006). Our approach adopts a structured analysis of sustainability issues in the forest-based sector that can identify policy and technology options, which are fostering sustainable development (Weaver and Jordan, 2008).

Impact assessment in ToSIA is based on comparing the sustainability indicators of alternative FWC variants. Changes in policies, markets or technologies affect either the material flow amounts through the FWC, the chain structure, the indicator values given for the processes, or combinations of all of these. For example, to reach ambitious bio-energy targets, subsidies for early thinnings can make biomass extraction economically viable (Heikkilä et al., 2007), thereby affecting indicator values. Consequently, new biomass chipping supply chains are introduced – changing the FWC structure – and part of the small diameter wood is redirected from pulp to energy production (i.e. affecting material flows). Policy changes are implemented in ToSIA as alternative FWC scenarios, for which new FWC parameters and indicator values are collected to assess sustainability impacts. We are not aware of any other tool that would be applicable for such comprehensive assessments in the forest-based sector. Evaluation methods and a policy impact analysis interface will enhance the versatility of the tool applications by supporting the ranking and prioritisation of FWC alternatives. But already the comparison of different indicators as presented in this paper allows to analyse trade-offs between alternative scenario choices.

The results of the example document impacts of the technology alternatives on different sustainability dimensions and place them into the FWC perspective. FM1 provides more employment and income for the study region. It also has positive impacts for climate protection because of larger carbon storage and slightly smaller energy use. However, as a trade-off, the average accident rate at the whole-chain level is 7% larger. A ranking of the two FWC alternatives requires evaluation techniques that allow integrating across the different indicators. Multi-criteria and cost–benefit evaluation methods are currently under development and will soon be integrated into ToSIA.

As ToSIA uses a data driven approach, the reliability of the sustainability assessment depends both on the reliability of the single values as well as on the completeness of the data for the whole chain. It is crucial to document and provide as much information as possible about the uncertainties and assumptions attached to the data in the SIA. This is secured by collecting meta-data information and making this accessible in the user interface of the tool. The data driven approach enables to apply the best available

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knowledge in the assessment, combining statistical data with outputs of well-tested simulation models and expert assessments. A possible direction of further development would be to link dynamic models directly with ToSIA to calculate and update indicator values for new scenario runs. Up to now most models were specialised on either economic or environmental aspects and information covering the balanced set of sustainability indicators was not available. With growing SIA experience in the forest-based sector consolidated sets of sustainability indicators for the FWC will evolve and it can be expected that models will become available that generate multiple of these indicators (cf. Vötter, 2009).

ToSIA is aimed at different target users including the forest-based industry, national and international policy makers, consultants, and researchers. While some users will only apply the tool with existing data, e.g. from EFORWOOD, consultants and researchers are able to create new FWCs and use their own data. The case studies of the EFORWOOD project will provide a rich data source as reference for any future ToSIA applications (cf. http://www.eforwood.org). While relative indicator values are often specific for the local circumstances, the generic data compiled in EFORWOOD may be helpful as benchmarks. Existing products and processes can be reused in new FWC topologies, thereby significantly reducing the need to collect new conversion factors and product shares. The tool is very flexible and can be used at various spatial scales ranging from a local forest-wood-chain to continent level forest sector analyses. Moreover, ToSIA can also be applied at different levels of detail.

Conceptually, ToSIA treats simplified and detailed FWCs with many separate processes and products in the same way. But what is better—to apply ToSIA to very detailed or larger aggregated processes? Assessing very detailed FWCs requires large amounts of specific data, which may be time-consuming to collect for a large number of FWC scenarios. Using aggregated processes results in simpler FWC structures and less data points that need to be collected. Especially for applications at country level, it is beneficial to choose processes and products that match existing inventories (e.g. NACE product classification used in EUROSTAT). On the other hand, for applications in research aiming at developing improved FWC technology it can be meaningful to study detailed processes separately.

The selection of indicators is one crucial factor for the quality of the SIA. First of all, the indicators need to be relevant for the investigated scenario alternatives. Stakeholders may be involved in the selection process, to secure a broad acceptance of the assessment results (Fraser et al., 2006). The next important aspect is the availability and quality of data. Missing data for part of the FWC can obscure SIA and produce biased results. ToSIA warns about incomplete data affecting the material flow calculation in the user interface and also informs about the completeness of indicator values. It is important to complete the data set with expert judgements where other information sources are lacking. Incorrect product shares and conversion factors may strongly affect the material flow calculation and thus result in erroneous aggregated FWC indicator results. Information about uncertainty and sensitivity of the indicator values to various assumptions (e.g. on future technology efficiency) are crucial to evaluate the reliability of the results. Therefore, it may be advisable to focus on a smaller number of indicators, but to invest more resources to collect auxiliary data about the indicators values.

One limitation of the current ToSIA applications is that sustainability impacts outside of the chosen system boundaries are not considered. If the spatial system boundaries are set to the borders of Europe, wood production chains for example for pulp imported from Brazil are outside the system boundaries of the SIA. Hence, their sustainability impacts are not considered in European FWC assessments. The same is true for the impacts of non-forest supply chains. Thus, ToSIA is currently adopting an attributional rather than a consequential modelling approach (Ekvall and Weidema, 2004; Schmidt, 2008). Expanding system boundaries to implement consequential sustainability impact assessment can only be a target for long-term development of the method. Recent life-cycle assessment studies have investigated e.g. the land use and biodiversity impacts of bio-diesel production (Schmidt et al., 2009), but covering multiple sustainability indicators for the complete FWC would require a lot more information, which currently is not available. Restricting the system boundaries to the borders of Europe was a pragmatic solution adopted in EFORWOOD and should be seen as a starting point for further development. One option to expand system boundaries in future SIA would be to estimate "sustainability rucksacks" for all products that enter the FWC from outside system boundaries. Alternatively, the chain topology could be expanded by including aggregated processes (e.g. pulp production and transport from Brazil). Both approaches could work for supply chain effects too, once comparable sustainability assessments have been conducted for other sectors.

ToSIA offers a knowledge-based framework to assess SIA in the FWC. Very different aspects of forest resource management, processing and manufacturing and consumption of wood products are linked with each other in a logical and transparent way. This allows integrating and interpreting facts and offers versatile background for decision-making processes or for seeking compromises involving different stakeholders with conflicting views on the sustainability of the FWC.

Life-cycle analysis and carbon footprint are more and more accepted tools to quantify environmental impacts of products, especially related to the GHG emissions and the contribution to CO_2 mitigation. ToSIA provides a broader assessment framework for assessing the three-dimensional aspects of sustainability for the complete forest-based sector. Future applications of the tool will hopefully contribute to identify strategies that further improve the sustainability of the sector.

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