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Using stand-scale forest models for estimating indicators of sustainable forest management

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A B S T R A C T

Criteria and indicators (C & I) to evaluate the sustainability of forest management have been proposed by the Ministerial Conference on the Protection of Forests in Europe. Although primarily defined at the national scale, these C & I also have implications at scales ranging from forest stands to the forest management unit. In this paper, we review existing forest growth and ecosystem models from the point of view of applicability to prediction of indicators of sustainable management, focusing on stand scale models and management. To do this, we first present a conceptual framework for understanding the role of models in assessing forest management at the stand level in the context of sustainability criteria and indicators. We classify the criteria into those predictable using models operating at the stand scale, and those derivable either through scaling up or as solutions of a multi-objective management optimisation problem.

We conclude that to date, no comprehensive models exist that could be used to predict all the indicators simultaneously. The most promising approach seems to be a modular system where different models are combined and run simultaneously, with shared inputs and well defined mutual links. More modelling efforts are needed especially regarding the state of the soil, including carbon, nitrogen and water balances and physical effects. Models also need development in their ability to deal with heterogeneous stand structures and with non-woody forest products such as berries, mushrooms or cork. The outputs of the models need to be developed in a direction where they can be interpreted in terms of the recreational or biodiversity value of the forest.

Data requirements are most pronounced on the same issues as the gaps in model availability. It would be important to consider amending the national forest inventories and other similar standard data collection protocols with variables required for sustainability assessment. Importantly, combining different models in a modular system and with variable data sources requires advanced model parameterisation and evaluation methods and assessment of parameter and model uncertainty. The probabilistic, Bayesian approaches hold a lot of promise in this respect. Predictions using several different models or model systems, with systematic analysis of e.g. inter-model variability, could also be considered.

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1. Introduction

Since the end of the last century the concept of sustainability has become an important focus of forest management (FM). Sustainable forest management refers to the management of forests according to the principles of sustainable development, which integrates social, economic and environmental goals in a manner characterised by the Rio Declaration on Environment and Development and, more specifically, the Statement of Principles for the Sustainable Management of Forests.[1] Following the Rio declaration, sustainable development was subsequently applied to forest management in Europe by the Ministerial Conference on the Protection of Forests in Europe (MCPFE), who defined sustainable forest management (SFM)[2] and further a series of criteria and indicators (C & I) as tools to evaluate the sustainability of forest management (Appendix A). Around this time, analogous initiatives dealing with SFM and C & I began simultaneously in non-European countries (the Montreal Process, the Tarapoto process, etc.).

In the MCPFE approach, the *criteria* define and characterise the essential elements, as well as a set of conditions or processes, by which the sustainability of forest management may be assessed. The *indicators* are quantitative or qualitative variables that measure aspects of the criteria and are meant to be evaluated periodically to reveal the direction of change with respect to each criterion. While these definitions outline the type of issues that are relevant for sustainable management, subsequent developments have taken the concepts further. Lammerts van Bueren and Blom (1997) developed a hierarchical approach to the analysis and definition of forest management standards under the sustainability framework, separating underlying *principles* from the more detailed and case-specific *criteria* (principles, criteria and indicators, PCI). These guidelines have since been used for defining sustainable management for different conditions and scales, including country-level principles (Prabhu et al., 1999) and more detailed, operational certification schemes at the stand and forest management unit (FMU) level (PECF Council, 2010).

The PCI approach is meant for *ex post* assessment and is very practical in the sense that the indicators directly combine the physical *state* of the system and the *methods of management* of the system. This is somewhat different from the *ex ante* approach to management planning by means of *forest growth modelling*, where the state of the system is conceptually separated from the management methods. The model provides a prediction of how the state of the system will develop in time, given any set of management actions. If criteria are set for the desired/acceptable development of the state of the system, the model may then be used for assessing which management methods comply with the set objectives. Obviously, this restricts the use of models in sustainability assessment to questions where it is relevant to compare the implications of different management methods on the state of the system. If the methods themselves are judged unsustainable, models become redundant. For example, one might use a model to analyse whether continuous-cover forestry differs from even-aged forestry in terms of wood production, carbon sequestration, nutrient and water retention, etc., but this will be of no use if the up-front objective has already been defined as the avoidance of clearcuts.

Because the PCI approach combines the state of the system and the management methods, the scale of the analysis is critical, as management methods cannot be defined irrespective of scale (although similar definitions of SFM may exist at different spatial scales (Lammerts van Bueren and Blom, 1997)). While stand scale management alternatives cover basic silvicultural decisions, country scale methods include forest policies put to effect through legislation, subsidies and other policy instruments. As noted above, sustainable management has therefore been defined separately for different scales. From the point of view of modelling the state of the system, however, the scale is of less significance, as the physical state can – at least in principle – be scaled up and down between stand, FMU and country. What is more critical is the ability of the model to describe the processes relevant for the criteria of sustainability.

In forest management planning, stand-scale forest growth models are conventional tools that might be applied to individual stands and FMUs or to larger forest areas including country-level (Weiskittel et al., 2011). Until now, such models have mainly been developed for predicting wood production under different management regimes and in different sites. The requirements of sustainable forest management have set an increasing demand for models to expand their predictions to a variety of ecosystem services and to evaluate trade-offs between them. In order to do this, the models must include variables that allow us to assess the quality of the ecosystem services. Sustainability C & I offer a comprehensive definition and operational quantification for such variables. While the general set-up of forest growth models as a tool for management planning is still valid in the context of sustainable forest management (Monserud, 2003), it requires some important developments in both the outputs of the models, including variables relevant for sustainability assessment, and in the methods of evaluating the management operations, accounting not only for the economic returns of wood production, but for the multitude of criteria defining sustainability.

The latter problem has already received much attention in the scientific literature. Multicriteria optimisation methods have been

[1] http://www.un.org/esa/dsd/agenda21/, http://www.un.org/documents/ga/conf151/aconf15126-3annex3.htm.
[2] http://www.foresteurope.org/eng/Commitments/Ministerial_Conferences/.

proposed and developed as tools in SFM to account for the various, possibly competing goals defining sustainability (Monserud et al., 2003; Díaz-Balteiro and Romero, 2008; Kangas et al., 2008). Stakeholder involvement and participatory methods have become focal for defining and balancing the different objectives (Prabhu et al., 1999; Pukkala, 2002; Kangas et al., 2008; Nordström et al., 2010). However, these methodological developments have largely operated on the assumption that the relationship between management and indicators of sustainability is well understood, and less attention has been paid to the actual derivation of the indicators from the state of the stand. Brang et al. (2001) pointed out that the choice of indicators is often driven by data availability rather than theory, that the connection between indicators and the state of the stand is not explicit, and that important causal links between the indicators have not been appreciated.

Several studies have reviewed different forest and ecosystem models from the point of view of their usefulness for assessing SFM. Peng (2000) compared three models based on different approaches (empirical, succession and process models) for predicting future forest stocks under different management options, combined with the potential effects of climate change and fire disturbances. Monserud (2003) reviewed the expected utility of different classes of forest growth models for assessing the sustainability of alternative forest management regimes. Pretzsch et al. (2008) discussed the role of models in the societal process of decision-making about natural resources, providing a broad review of the significance of different types of model in the assessment and design of SFM. The general conclusion from these studies is that a wide suite of models would be required in order to analyse not only growth and yield but also the different aspects of ecosystem functioning and societal value that play a role in the sustainability criteria and indicators. However, an explicit derivation of indicators from dynamic growth models in the SFM context is rare (but see Huth et al., 2005; Azevedo et al., 2005).

Although they analyse the type of information required for sustainability assessment, most of the above-mentioned studies remain fairly abstract and conceptual on the question, "*How* do models provide information to assess SFM?" Assuming that sustainability indicators are an adequate tool to evaluate SFM, this translates into, "How do models provide information to estimate indicators?" Further important questions for the application of such models are, "What data are needed?", and "How can we evaluate this aspect of growth models?"

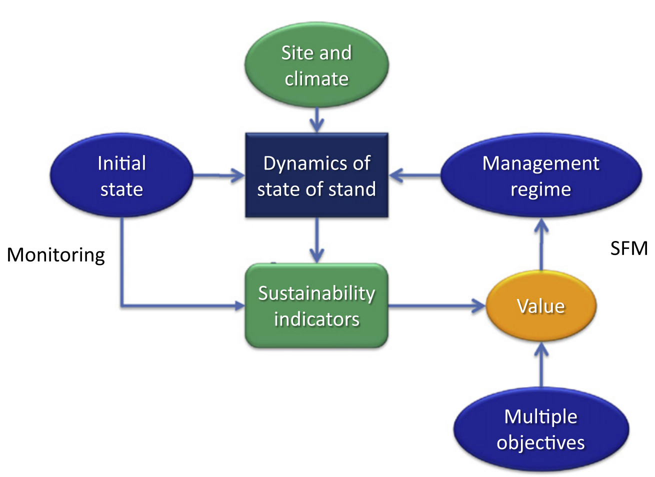

Fig. 1. Schematic presentation of the role of stand-level growth and ecosystem models in determining sustainability criteria and indicators. Monitoring the state of the stand provides both measurements of the indicators and an initial state for the stand-level model.

In this review, we first present a conceptual framework for understanding the role of models in assessing forest management at the stand level in the context of sustainability criteria and indicators. We have chosen the MCPFE indicators as a basis because they are well-known national level C & I. They are regarded here as a reference standard to illustrate the potential of models to simulate sustainability indicators. We focus on criteria describing the physical state of the system and directly relevant for models operating at the stand scale. The remaining criteria can be seen as derivable either through scaling up the stand-scale results, or as solutions of a multi-objective management optimisation problem, where the alternative management actions need to be defined separately for each scale and forest type. We will then review models that can be used to predict the different indicators, and thereby try to extract the key model-related components and variables required to assess SFM goals. We will consider current data sources for such models and how they might be augmented to improve the efficacy of modelling in an SFM context. In this light, we assess different data collecting protocols, such as national forest inventories (NFI) and permanent sample plots (PSPs), and review possible problems related to the evaluation of models using such data sources.

2. Conceptual framework

Stand-scale ecosystem and forest-growth models typically predict the temporal development of the growing stock and other state variables from (1) the initial state, (2) driving environmental and site variables, and (3) management actions applied. The time resolution of such models is typically daily, monthly or yearly, and the predictions extend over several decades. Model outputs include the state variables and any other variables derivable from these. In management planning, the outputs are used for determining the value of the products or services, such that the type of management yielding the maximum value can be chosen (Fig. 1).

The MCPFE defined six sustainability criteria covering ecological, economic and social aspects of forests, and related to each of these a number of indicators that can be used to measure the state of forests for sustainability assessment (MCPFE, 2002) (Appendix A). The indicators can be divided into four categories relative to the stand-scale modelling framework:

(1) *Indicators that are directly derivable from model outputs* (state variables). For example, the volume of the growing stock, the size of the carbon storage, shrub layer structure, tree species composition and volume of standing and lying deadwood are clearly in this category, provided that models exist for such predictions.
(2) *Indicators that are derivable through scaling up stand scale results.* Generally, those variables that are derivable at the stand level can also be calculated for larger areas, provided that sufficient input data are available (e.g. landscape pattern). It should be noted that it is at this larger scale that the overall assessment of sustainability usually takes place, but the stand scale results are required for the up-scaling.
(3) *Indicators that refer to sustainable management practices.* For example, one of the indicators directly demands that "forest management planning enhances sustainable management and use of forests". In the modelling framework, sustainable management practices are not necessarily understood *a priori*, but the models are to be used so as to assess the implications of different management options on multiple aspects of sustainability. Importantly, this requires that the models are responsive to the required management options.
(4) *Indicators that refer to current land-use and other national/regional statistics.* Some of the C & I aim at quantifying, e.g., the proportion of forest land under environmental

Table 1
Stand-scale indicators of Category 1 (see Section 2) and "minimal" model types needed for their estimation. GYM = growth and yield model, PBM = process-based growth model, BGC = model of biogeochemical cycles, SOM = soil organic matter. This list of indicators is based on the indicators proposed by the Ministerial Conference on the Protection of Forests in Europe (MCPFE, 2002) (Appendix A), supplemented with other stand-scale indicators relevant for each criterion.

Criterion	Indicator	Model types
C1: Maintenance and appropriate enhancement of forest resources and their contribution to global carbon cycles	Growing stock	GYM
	Total volume	GYM
	Age structure and/or diameter distribution	GYM
	Carbon stocks	PBM
	GHG emissions	PBM
C2: Maintenance of forest ecosystem health and vitality	Soil condition	BGC
	Fire hazard	Models with explicit stand structure
	Wind hazard	Models with explicit stand structure
	Pest and disease hazard	Models with explicit stand structure
	Broadleaved tree mixture is maintained	Models with explicit stand structure
	Felling and skidding damage	BGC, models of soil physics
	Water use (of forest ecosystem)	BGC
	Forest resources/growing stock	GYM
	Forest biodiversity (delayed DCP)	Biodiversity models
C3: Maintenance and encouragement of productive functions of forests (wood and non-wood)	Wood products	Wood quality models
	Non-wood products	Non-wood products models
	Productivity of the principal forest production	GYM
	Value and quantity of marketed roundwood	GYM, wood quality
	Other productions	Non-wood products models
C4: Maintenance, conservation and appropriate enhancement of biological diversity in forest ecosystems	Understorey shrub diversity	Models with explicit stand structure
	Tree species composition/ structural diversity	Models with explicit stand structure
	Long-lived and cavernous trees	Models with explicit stand structure
	Volume of standing and lying deadwood	Models with explicit stand structure, models of SOM
C5: Maintenance and appropriate enhancement of protective functions in forest management (notably soil and water)	Evidence of erosion	BGC, models of soil physics
	Water quality	BGC, models of soil physics
C6: Maintenance of other socioeconomic functions and conditions	Recreational services	Non-woody products, models with explicit stand structure

protection, the extent of relevant natural or semi-natural plant communities, or the proportion of forests under management planning. These are clearly not stand-level modelling issues.

In this review, we will focus on indicators that are directly derivable from model outputs (Category 1), assessing the requirements from stand-level growth and ecosystem models for providing information about the relevant MCPFE indicators. Secondly, we will discuss the data needs and availability for deriving and evaluating models providing information about these indicators as well as for the scaled-up Category 2 indicators. These will be essential for deriving the Category 3 indicators which, in addition, require that the models are realistically responsive to the management actions proposed. Category 4 indicators are not considered relevant for this review.

3. How do existing models estimate sustainability indicators at stand scale?

Over the years, a number of forest growth and ecosystem simulation models have been developed to predict forest growth and yield, forest succession and vegetation dynamics, net primary productivity, carbon storage, nutrient cycling, water and energy balance with the atmosphere, etc. (e.g., Fontes et al., 2010). Although there is not any "super-model" based on an holistic approach that would allow for the estimation of the many indicators for the six MCPFE criteria discussed here (Appendix A), a lot of scientific research and modelling work has been conducted that can be applied to estimating the indicators. In this section, we briefly review available stand-scale modelling approaches applicable to estimating the Category 1 indicators for the SFM sustainability criteria (Table 1). The objective here is to identify the type of models required for the different indicators, and their current state of applicability. For a more comprehensive review of modelling approaches, see e.g. Palahi et al. (2010).

3.1. Criterion 1: maintenance of forest resources and their contribution to the carbon cycle

This criterion is mostly concerned with issues conventionally predicted using growth and yield models (GYMs), including total volume, growing stock and age and diameter distribution. On the other hand, it also includes the requirement for predicting *Green House Gas (GHG) emissions* in relation to carbon accounting and other climate change issues. In many countries GYMs have already been combined with biomass expansion factors or equations that predict the total carbon content of the tree stock from variables measured or predicted with GYMs (Lehtonen et al., 2004; Eriksson et al., 2007; Calama et al., 2008), some of them also considering the turnover of leaves and fine roots (Hynynen et al., 2005; Rötzer et al., 2010). In addition, process-based models (PBMs) usually include tree carbon contents as basic state variables, also providing methods for estimating GHG emissions (Mäkelä et al., 2000). However, estimates of the carbon pools and fluxes also require those of the ground vegetation and soil. During the last decade some efforts have been made to link GYMs and PBMs to dynamic soil models for carbon accounting (Komarov et al., 2003; Hynynen et al., 2005;

Richards et al., 2005). Nevertheless, combining the dynamics of soil carbon and its interactions with the growing stock requires more information about the soil carbon balance under different environmental conditions and management options (Nave et al., 2010; Metcalfe et al., 2011). A lot of progress has been made on this issue in recent years (see below) (e.g. Jandl et al., 2007; Inatomi et al., 2010; Grote et al., 2011).

3.2. Criterion 2: maintenance of ecosystem health and vitality

This is a very broad criterion including several challenging issues from the modelling perspective. Firstly, it requires information about the *soil condition* defined in terms of carbon, water and nutrient contents and the physical condition of the soil. Soil carbon and nitrogen models driven by soil moisture, temperature and litter input have been developed to predict long-term changes in soil material balances especially in the context of climate change (Jansson and Halldin, 1979; Komarov et al., 2003; Liski et al., 2005), and have applications in whole-ecosystem studies of material fluxes and stocks (Karhu et al., 2011; Mäkipää et al., 2011; Wu et al., 2011). The Biome-BGC and Forest-BGC model families include both soil and above-ground material pools and fluxes, with a wide variety of applications to climate change impacts and diagnostics of ecosystem health (e.g. Running and Gower, 1991; Thornton et al., 2002; Pietsch and Hasenauer, 2005). A more management oriented approach to soil condition has related the physical condition of the soil to the amount and type of vegetation, the type of fellings, etc. (Selkimäki et al., 2012).

Also under Criterion 2, the *risks from environmental hazards* is an important and a very complex issue that so far has been rather little studied in the context of forest management, although the predicted increase of risk under climate change of various hazards has recently stimulated a lot of research in this area (see Hanewinkel et al., 2010; Seidl et al., 2011). The most important hazards are drought, fire, pests and diseases and wind, the risk levels largely depending on the region. The risks could be estimated through some structure characteristics if different forest components are considered (Hanewinkel et al., 2010). For example, fire risk has been related to stand basal area and diameter distribution in Mediterranean pine forests (González et al., 2006), the risk of bark beetle attack has been related to the age and structure of spruce forests in Austria (Seidl et al., 2007), and the risk of wind damage has been related to stand structure and tree slenderness in boreal forests (Peltola et al., 1999). Although risks posed by different hazards need to be derived from stand-scale variables, the occurrence of hazards is really a larger-scale phenomenon for modelling purposes. There are models that use a landscape level to analyse the relationship between forest structure at this scale and risks such as fire, insect damages and wind (Peltola et al., 2010), including applications of gap models in combination with regional assessments of fire risks (see references in Pretzsch et al. (2008)). Seidl et al. (2011) however, conclude that models supporting decision-making in forest management require a stronger integration of multiple disturbances.

Criterion 2 is based on the assumption that maintaining forest health requires stands to be more *heterogeneous* than currently, especially regarding their species composition. This calls for more variety of models for different species and models with more variable stand structures, particularly emphasising the need to understand species and tree-to-tree interactions better. Individual-tree models may be more suitable for the simulation of complex forests and the effects of novel management interventions on them (Rennolls et al., 2007) (see Criterion 4). Note however that heterogeneity can also be achieved at the forest management unit or landscape level.

3.3. Criterion 3: maintenance of the productive functions of forests

This criterion covers both wood production and the production and value of non-woody products. Models relevant for Criterion 1 generally provide measures of stem wood productivity as well, while *non-woody production* has received less attention. The significance and type of non-woody production is largely dependent on the forest region considered. In the Mediterranean areas non-wood products are frequently more important than wood products, e.g., cork, pine nuts, mushrooms, etc., and many growth models already include these non-wood products (see references in Calama et al. (2010)). On the other hand, the value of berries and game, for example, has not generally been considered in forest management in the Nordic countries, although those forest goods have been studied and are considered to have important recreational value for the general public (Bell et al., 2007).

For the economic returns from conventional wood production, *wood quality* indicators are crucial but have often been considered in rather simple terms such as division into timber and pulp assortments generally based on log diameter (Nieuwenhuis, 2002). However, when wood production and other economic functions of the forest need to be balanced, it becomes more important also to understand the development of wood quality in more detail (e.g. Hyytiäinen et al., 2004). For modelling purposes, stand structure (density, species mixture, size distribution and spatial structure) is an important determinant of wood quality development (Mäkelä et al., 2010).

3.4. Criterion 4: maintenance and enhancement of biological diversity

Biodiversity is related to the abundance of species and ecosystem types at different spatial scales (e.g. Whittaker, 1972), and hence variables related to biodiversity also need to be included in stand-scale models. Models including species mixtures and the ground layer vegetation are desirable for this purpose. For example, bird diversity is associated with forest structure at different spatial scales (Mitchell et al., 2001) and can be predicted from forest composition and structure variables (Azevedo et al., 2005; Gil-Tena et al., 2007). Also here, individual-tree models may be more suitable than mean-tree or diameter-class models (Rennolls et al., 2007; Pretzsch, 2009). They could also potentially deal with the structural diversity of continuous-cover forests that have been associated with biological diversity and forest health (Humphrey, 2005). For instance, the SILVA spatially-explicit tree growth model provides a good estimation of forest structural diversity (Pretzsch, 2009). However, as biodiversity is difficult to model from first principles in a forest growth context, modellers have utilised research on biodiversity indicators that can be derived from more easily measurable or modelled stand variables. One commonly used indicator is the volume of coarse woody debris in a forest (McComn and Lindenmayer, 1999). In order to model the amount of coarse woody debris, growth models need components for the mortality of trees, the shedding of large branches and the rates of decay of these in the forest floor (Mellen and Ager, 2002; Ranius et al., 2003; Herrero et al., 2010; Grote et al., 2011).

3.5. Criterion 5: maintenance of the protective functions of forests

This criterion again requires information about soil properties, such as its chemical and physical composition (see Criterion 2). The rest of the indicators listed under this criterion are related to management practices rather than the state of the forest, and therefore fall into Categories 3 and 4 (see Section 2).

3.6. Criterion 6: maintenance of the social function of forests

These are indicators that involve an economic assessment of the value of forests, largely on the basis of the variables and indicators described above. Two additional aspects, the recreational and the cultural value of forests are also included here and depend on various uses of the forest. For example, in the Nordic countries, the recreational value is related to availability of berries, mushrooms and game, as well as accessibility for hiking and skiing (Ahtikoski et al., 2011). The recreational value also depends on the agreeability of the scenery in the forest, relating to stand scale variables such as stand structure and species composition (Korpela et al., 2008). Linking GYMs or PBMs with visualisation tools offer a way to produce information of recreation value and beauty (Pretzsch et al., 2008). The cultural value relates for example to particular individuals of certain species (such as large, old trees that have traditionally been used for gatherings) or famous forests such as the French "Forêt de Troncais" installed by Colbert. Few growth models include indicators of the recreational or cultural value of the stand.

4. Key components of models predicting sustainability indicators at stand scale

As we have already noted, no forest growth or ecosystem model to date has been developed that covers all the sustainability issues described above in a realistically integrated way. In order to generate realistic estimates of the impacts of different management options to the multifunctional sustainability of forests, new models or model systems therefore need to be developed that cover all the processes and variables relevant for sustainability. This task poses many challenges related to the construction of such complex models: For example, how to portray the interaction between the different phenomena of interest (Ulrich, 1999 in Pretzsch et al., 2008; Pietsch and Hasenauer, 2005), whether to use an empirical, process-oriented or hybrid approach (Kimmins et al., 1999; Mäkelä et al., 2000; Pretzsch et al., 2008), and whether to combine existing models and their mutual links in a modular system, rather than building a comprehensive "model of everything" (Robinson and Ek, 2000; Mäkelä, 2003). However, whatever the method of model building, all such models will share the requirement of predicting the same indicators and therefore, will have to provide the variables needed for this prediction. To a large extent, this is what determines the data requirements of such models as well. Therefore, this section focuses on the choice of variables included in the model in order to be able to derive the required indicators.

On the basis of the considerations of sustainability criteria and how they relate to indicators derivable from stand-scale forest growth and ecosystem models, we identify the following as the most important model components:

- *Basic forestry variables* (e.g. volume, mean and dominant height, basal area, diameter distribution). These are usually provided by all conventional growth and yield models, however, many ecosystem models calculate whole stand material fluxes only.
- *Tree carbon fluxes and stocks* (e.g. ecosystem respiration, carbon sequestration, carbon content of biomass). Nowadays only PBMs comprehensively provide this kind of information, although tree carbon stocks can also be derived from GYMs through biomass expansion factors or biomass growth and/or prediction models. Most PBMs work at the stand scale and they have to be combined with other approaches to give information at tree level required for many indicators.
- *Descriptions of shrub and coarse woody debris components.* These components are directly or indirectly related to some C & I, such as biodiversity, carbon stocks, fire hazard, erosion, and wildlife. Therefore, incorporating separate modules to estimate shrub layer dynamics and the development of coarse woody debris provides information to increase the number of estimated indicators.
- *Soil nitrogen, water and physical condition.* This relates to both forest health (C2) and forest protective function (C5). Here a big challenge seems to be the large time constants of soil processes, which means that the current state of the soil integrates ecosystem history for decades and centuries (Merganicova et al., 2007). Models can potentially simulate this integration and have significant value in its future prediction; however, a lot of uncertainty is still incorporated in both measurements and process understanding.
- *Information on stand heterogeneity (species, age, structure, etc.).* An adequate stand structure estimation is explicitly required for three criteria (Table 1) and would also benefit other aspects, e.g., modelling competition and mortality (C1), wood quality (C3) and shrub layer dynamics (C5). However, most GYMs and PBMs have been developed for homogeneous stands (Landsberg, 2003). Gap models include a description of individual tree distributions but they present some structural problems (invariant height–diameter relation, simple mortality function) that frequently lead to unrealistic estimates of stand structure (Lindner et al., 1997; Monserud, 2003). Spatially explicit growth models offer a means for detailed stand structure estimation (Weiskittel et al., 2011).
- *Information on non-woody production and wood quality.* In order to provide estimates of the value of wood and non-wood products, growth models should estimate the quantity and quality of the products. Most models simulate the quantity and the size of wood products, but fewer models include predictions of some wood quality indicators (Mäkelä et al., 2010). Non-wood products also contribute to the value of the stand, either directly through product marketing or indirectly through e.g. the recreational value of the forest, but so far little attention has been paid to combining non-wood products as part of the value chain (Calama et al., 2010).

The above characteristics relate to the physical description of stand dynamics. When these variables have been predicted by the forest growth and ecosystem models included in the dynamic model system, more indicators covering all criteria can be evaluated (Table 2).

In addition to the above list of model components, it is important, whatever the model structure or underlying modelling approach, that the models intended for estimating sustainability indicators be realistically responsive to both management alternatives and climate. They also need to be reliable over a sufficiently long time horizon. These issues have implications for data requirements and model evaluation and are therefore analysed in more detail below.

- *Sensitivity to management alternatives.* Most forest growth models allow for simulating different management alternatives and as a consequence, are management sensitive to some degree. However, in order to be useful for evaluating the sustainability of forest management they should be management sensitive not only with respect to wood production but with respect to all the indicators included in the model (Table 2). In many cases, plenty of information is available about management effects at particular sites, but these effects cannot easily be generalised for inclusion in models. For instance, there are few and sometimes contrasting observations about the effect of thinning on soil carbon (Tonon et al., 2011). As an example, the FORCAST model provides outputs relevant for several sustainability indicators under forest management (Kimmins et al., 1999, 2010),

Table 2
Significance of different model components for estimating indicators for sustainability criteria C1–C6 (see Table 1).

Model component	C1	C2	C3	C4	C5	C6
Basic forestry variables	x		x			x
Carbon dynamics of trees	x					x
Carbon dynamics of field layer and soil	x			x		x
Coarse woody debris	x	x		x		
Shrub layer	x	x		x	x	
Soil (and tree) N		x				x
Soil and tree hydrology		x			x	x
Soil physical condition		x			x	x
Structure: mixed species		x		x		x
Structure: size distribution and spatial arrangement		x	x	x		x
Structure: regeneration and mortality		x		x		x
Non-woody production			x			x
Stem and/or wood properties (quality)			x			x

but its general application is limited because of the considerable amount of input data needed and the difficulty to test it rigorously (Landsberg, 2003).

- *Sensitivity to climate.* Because of climate change, it is becoming increasingly important that ecosystem models and forest growth models are able to simulate the effects of climate on the development of forest ecosystems (Aber et al., 2001; Medlyn et al., 2011). At the same time, it is important that the impacts of management are also included, as they may surpass or counteract any climate effects (Eastaugh et al., 2011). Most GYM use the site index as the main environmental driving variable and are therefore not directly applicable to changing conditions (Monserud, 2003; Soares and Tomé, 2007). Some recent site index models have been developed to include environmental impacts on model parameters (Bravo-Oviedo et al., 2008, 2010; Albert and Schmidt, 2010; Pretzsch, 2009; Nunes et al., 2011), but to what extent such models actually describe impacts of a changing environment and not only that of spatial environmental variation remains unclear. PBMs aim to simulate the growth pattern of stands in terms of the physiological processes that determine growth, making them useful, at least in principle, for long-term predictions, especially under changing management and climate conditions (Soares and Tomé, 2007). However, many questions and much uncertainty remain about the assumptions underlying the climate change predictions of PBMs as well (Medlyn et al., 2011).
- *Long term time horizon.* In order to evaluate the sustainability of a management alternative it is necessary to estimate indicators at medium and long term. When simulating over one or more rotations or uneven-aged stands, natural population dynamics cannot be ignored. Both regeneration and mortality have an impact on the development of forest structure and species composition. Furthermore, regeneration is a key process for forest adaptation to climate change (Lindner et al., 2008), and mortality has implications on biodiversity and carbon balance. A long-term population dynamics approach has most clearly been taken by the gap model family with applications in several forest biomes and types (Kellomäki et al., 1992; Prentice et al., 1993; Bugmann and Fischlin, 1996; Lexer and Honninger, 2001). While these models have been shown to nicely illustrate the qualitative dynamics of forest succession, their validation has been judged very difficult (Bugmann, 2001; Monserud, 2003). On the other hand, many empirical and process models do not include a module to simulate natural regeneration at all, and sometimes regeneration models have been developed independently of growth models (Weiskittel et al., 2011).

5. Data needs and sources for models that predict sustainability indicators

As seen above, sustainability criteria address an extremely wide range of issues, affected by both management actions and environmental changes. This poses a challenge for growth and ecosystem modelling, as no current model includes all the components required (see list in Table 2). Whether a new comprehensive model is aimed at, or a selection of existing models is to be combined in a decision-support system (DSS), new data will be needed for (1) model development, (2) testing and calibration, and (3) model applications. For model development, testing and calibration, the data should include the components of Table 2 in combination with relevant independent variables that are largely model-specific. For applications, input data are required to provide appropriate initial values, site-specific parameters and model driving variables for the situations of interest.

When considering data availability, the model's domain of scale is of primary importance. As regards the growth and ecosystem models themselves, our focus is on the stand scale where most of the impacts of forest management on tree growth and stand dynamics take place. This is therefore the level at which the models must be developed, and the primary level of their evaluation (but note that models intended for predictions at the stand scale often require model-specific data defined at sub-stand scales, including, e.g., tree-level data for individual-based empirical models and data on specific physiological and structural components for PBMs). As regards model application, on the other hand, our stated purpose is that of regional or national estimation of sustainability, requiring that the models be run for many different points in space covering the whole area of interest. To be applicable to such scaling-up exercises, the models need to be evaluated over a wide range of conditions, and the related input data requirements are extensive, likely utilising multiple sources (Fig. 2).

5.1. Data for model development and evaluation at stand level

Acquiring forest ecosystem data for model development and testing is not straight-forward, due to the complex nature of the system and the long time spans involved. Efforts have therefore been made to set up national and international measurements and monitoring networks since the early 20th century to facilitate and unify data collection for variable purposes. Although the current objective of predicting and assessing sustainable management in a comprehensive manner has likely brought up completely new measurement needs, it would be very helpful if the existing data sets could be utilised at least partly for this purpose. Here, we

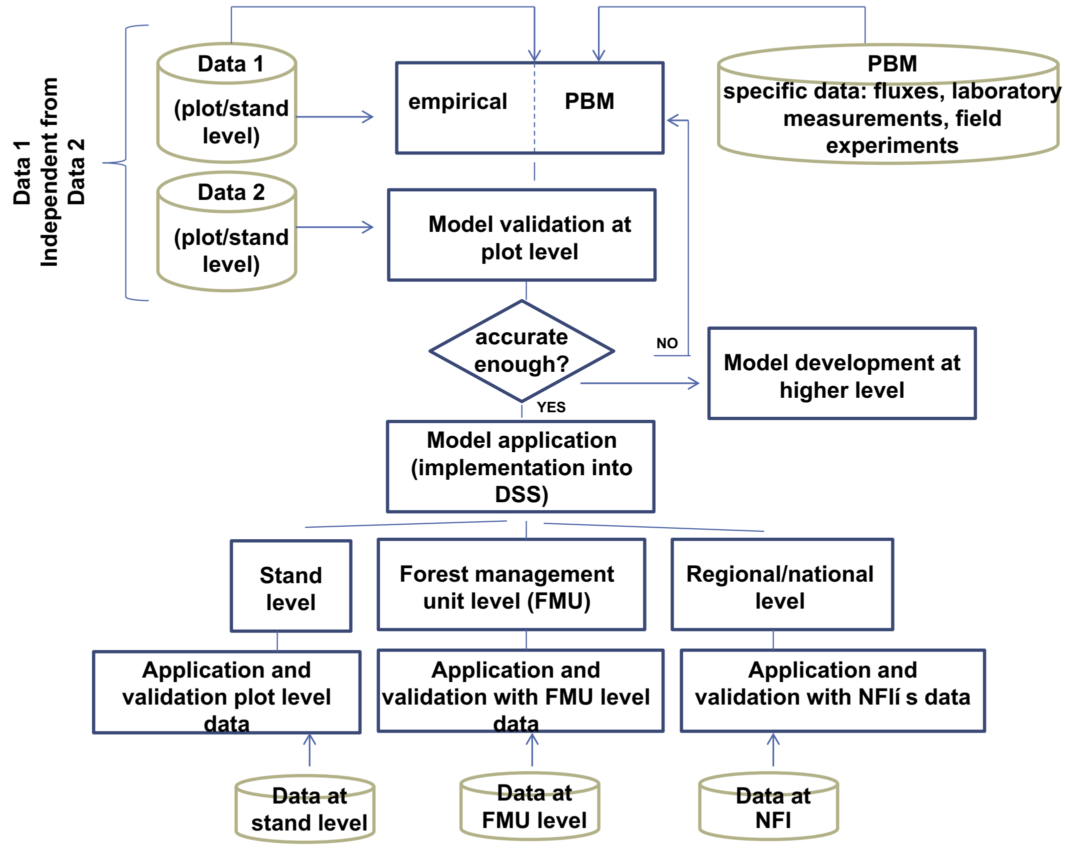

Fig. 2. The role of different data sources during a growth model's life span; DSS – Decision Support System, FMU – forest management unit, NFI – National Forest Inventory, PBM – process-based model.

review the available sources of forest ecosystem data, so as to assess the extent to which they can provide information for developing and testing models for the sustainability indicators.

Designed experiments provide a valuable source of information for original model development and testing. The most relevant designed experiment types for forest ecosystem studies are provided by permanent experimental plots of forest management, long-term ecological research sites, and free air CO_2 enrichment (FACE) experiments.

In forestry, *permanent experimental plots* have been established to study the growth and yield responses of different silvicultural systems, or responses to different management practices, such as regeneration method, response to spacing, timing, intensity and type of precommercial and commercial thinnings, fertilisation and pruning (Eriksson and Karlsson, 1997; Mäkinen and Isomäki, 2004a, 2004b; Kukkola and Saramäki, 1983; Varmola and Salminen, 2004; Mäkinen et al., 2005; Río et al., 2008; Pretzsch et al., 2010). While most of these mainly focus on wood production (C3), some more recent experiments have been set up to explore other productive functions (Almeida et al., 2010; Paulo and Tomé, 2010; Calama et al., 2011) or various alternative harvest methods (e.g. Jakobsson and Elfving, 2004) that may have relevance to biodiversity indicators (C4).

Recently, several studies have developed methods for extending the applicability of the growth and yield experiments to a wider scope of forestry issues. This would often require some supplementary measurements not included in the original measurement plan. For example, growth and yield experiments can provide strong empirical evidence of the long-term impacts of forest management on carbon sequestration (C1), assuming that reliable biomass models exist for tree species of interest (e.g. Eriksson, 2006). Permanent experiments can also be applied for assessing management impacts on biodiversity (C4), such as mortality, structural stand properties (age, size or tree species structure) (Montes et al., 2004), or the amount and type of deadwood which is known to be an important measure of forest biodiversity (McComn and Lindenmayer, 1999). Especially, permanent experiments with untreated control plots are of special value for modelling mortality and deadwood dynamics (e.g. Hynynen, 1993; Río et al., 2001; Mäkinen et al., 2006).

Permanent experiments can also be used for studying the relationships between management and forest health and vitality (C2, Table 2), although trials very seldom have been established for these purposes. For example, spacing and thinning trials have been used to study the effects of varying thinning regimes on the occurrence of snow damages in Scots pine (*Pinus sylvestris* L.) (Valinger et al., 1994), or on the development of root rot (Piri, 1998; Mäkinen et al., 2007). Long term fertilisation experiments provide information on the impacts of intensive fertilisation on vitality of trees and other vegetation (Mälkönen, 1990; Linder, 1998). Moreover, permanent experiments allow detecting changes in climate-growth response (Martín-Benito et al., 2010a) or the effects of thinning on this response (Misson et al., 2003; Martín-Benito et al., 2010b), information that can be used to test growth models behaviour under different climates.

In ecosystem studies, designed experiments have been carried out in *long-term ecological research sites* which have been established in various parts of the world since the 1980s, including e.g. the famous sites of Hubbard Brook in USA and Solling in Germany. They aim at a comprehensive understanding of forest ecosystems in terms of the physiological processes that regulate the material fluxes of carbon, nutrients and water between the physical environment and living organisms, and have provided the basic information necessary for developing and parameterising PBMs (Rastetter et al., 2003). Some well-known examples include the Harvard forest in USA which has been a site for comprehensive ecosystem studies since 1988 (Foster et al., 2003), and Flakaliden in Sweden, where a nutrition and irrigation experiment has been carried out in a barren *Picea abies* forest since 1986 (Linder, 1998). More recently, designed ecological experiments have been established in the form of *FACE experiments* (free air CO_2 enrichment), with the objective of analysing the impacts of climate change and increasing CO_2 concentrations on forest ecosystems (e.g. Rogers et al., 2006; Leakey et al., 2009). These studies especially provide information for modelling the carbon and nutrient dynamics and hydrology of trees, ground vegetation and soil.

Monitoring networks were primarily established for following the state of the system of interest (e.g. de Vries et al., 2003), but they may also provide information that is valuable for model development and testing. The most important monitoring networks for forest ecosystem model development under the sustainability paradigm include National Forest Inventory (NFI) and its Permanent Inventory Plots, forest health monitoring networks, and Eddy Covariance measurement sites.

National Forest Inventory data (NFI data) form a representative and objective sample from the current state of the forest resource in the inventoried forest area. Although ideal for empirical monitoring, these data are not particularly useful for stand-level model development as such, because the measurements are not repeated, plot size is too small (Stage and Wykoff, 1998; Hynynen and Ojansuu, 2003), and additional input data are required. However, NFI data can be suitable for validating some important structural aspects (C2, C4), such as size-distribution models (diameter and/or height distributions), d/h ratio or tapering, crown dimensions, etc. NFI can also provide data for modelling the probability of occurrence of biotic and abiotic forest damages (e.g. Hellgren and Stenlid, 1995; Jalkanen and Mattila, 2000; Mattila and Nuutinen, 2007) or stand properties important for biodiversity (e.g. FFRI, 2011).

In some cases the NFI plots have been made permanent and therefore object of periodic re-measurements. In some countries (e.g. Spain) this is standard practise, while others have established a special network of *Permanent Inventory Plots* (PIPs). Data from these plots have been used for growth and yield modelling purposes as such (e.g. Söderberg, 1986; Hynynen et al., 2002; Hordo et al., 2006; Pettersson and Melin, 2010). Providing detailed and representative data, these measurements are useful for model development and calibration, and may be combined with indicators other than forest productive function in the same way as above.

Forest health monitoring sites/networks began to develop in various parts of the world since the 1980s as a response to concerns about air pollution, and they now provide well-established data collection networks especially in Europe and North-America. In USA, the forest health monitoring (FHM) program is a collaborative network of nationwide monitoring plots that generates data on sustainability concerns (e.g. Conkling et al., 2002; Edgar and Burk, 2006; Tkacz et al., 2008). In Europe, the main monitoring network is overseen by the International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests (ICP Forests), operating under the UNECE Convention on Long-Range Transboundary Air Pollution. ICP Forests monitors the forest condition in its 41 member countries, including USA and Canada (http://www.icp-forests.org/). The network continues to generate data for scientific research, covering such topics as forest condition, ozone, defoliation, deposition, biodiversity and carbon budgets at two levels of intensity (Fischer and Lorenz, 2011): Annual crown condition surveys (and less regularly also surveys of other variables such as soil or ground vegetation) are carried out on about 7500 permanent so-called Level I plots which often coincide with NFI plots. Much more intensive monitoring is carried out on about 500 Level II plots which represent typical forest ecosystems of Europe. These data are made available for use on request. Several country-specific research papers using these monitoring data have been published (Wulff et al., 2012; Bille-Hansen and Hansen, 2001), as well as investigations with a network-scale focus (e.g. Solberg et al., 2009; Wamelink et al., 2009; Dijkstra et al., 2009; Simpson et al., 2006). Peer-reviewed ICP publications are inventoried at http://icp-forests.net/page/scientific-publications. Working in cooperation with ICP Forests, the FutMon project (http://www.futmon.org) has been developed with the aim of making the European Monitoring System more effective, partly via harmonisation and improvement of monitoring and data collection methods. Some additional monitoring of crown condition, deposition and meteorological and vegetative parameters takes place under FutMon in connection with national forest inventories. The project aims to provide for a comprehensive analysis of the network-generated data (for example, with respect to carbon allocation in trees) and formation of predictions of response to clean air policies. The FutMon project generates periodic synthesis reports (e.g. Fischer and Lorenz, 2011).

Since the 1990s, ca. 50 *eddy covariance measurement sites* have been established in European forests for the purpose of monitoring carbon, water and other greenhouse gas fluxes under several research networks (EUROFLUX, CARBOEUROPE, GHG-Europe) (e.g. Aubinet et al., 2000; Granier et al., 2008; Schulze et al., 2010), as part of a world-wide network (e.g. Baldocchi et al., 2001). In many sites, other related ecosystem measurements are also being carried out, such as growth, soil state and properties, stocks and fluxes of nitrogen, elements of the hydrological cycle, and processes of ground vegetation (Högberg et al., 2001; Porte et al., 2002; Andersson et al., 2004; Schulze et al., 2009). These sites currently provide invaluable information for developing and testing PBMs of growth and ecosystem processes (Berninger et al., 2004; Medlyn et al., 2005; Schmid et al., 2006; Mäkelä et al., 2008). However, this network is different from the NFI networks in that the sites were chosen subjectively and do not provide a representative sample of forests in an area.

In summary, the existing data sources and networks provide much information relevant for the sustainability indicators (Table 3). However, none of the data sources is comprehensive, and therefore problems of consistency are likely to arise when data from various sources has to be combined for model development and testing. A lack of suitable data from the existing sources appears to be the greatest regarding details of stand and tree structure, relevant especially for criteria C2 and C4.

5.2. Model applications: input data and scaling issues

The type of input data required is largely model- and application-specific, but in all cases, data are needed about the initial state of the stand (or stands) to be simulated, and about site-specific model parameters and environmental driving variables. The latter must be specified for the entire period of interest. If all of these can be measured or estimated for all the stands in question, the application of the model is more or less straight-forward. This may be the case for single stands or small areas, such as forest management units, where the required measurements can be taken, and where e.g. weather inputs can be generated from adjacent meteorological records.

Problems of scaling arise when the models need to be applied across a large area where there is insufficient information about model inputs at the stand scale. In such cases, input data are generally available on a coarse spatial grid either as grid-average (e.g. soil maps and climate projections) or point samples (e.g. NFI data, forest

Table 3
Applicability of available data sources for developing and evaluating sustainability indicators as classified above in Table 2. ERS = ecosystem research sites, FACE = face experiments, PSP = permanent sample plots, PIP = Permanent Inventory Plots/inventory growth plots, NFI = National Forest Inventory, FHM = forest health monitoring sites, ECS = Eddy Covariance Sites.

Model component	ERS	FACE	PSP	PIP	NFI	FHM	ECS
Basic forestry variables			x	x	x		
Carbon dynamics of trees	x	x	x	x	x	x	x
Carbon dynamics of field layer and soil	x	x					x
Coarse woody debris	x		x		x	x	
Shrub layer	x		x		x	x	
Soil (and tree) N	x	x	(x)			x	(x)
Soil and tree hydrology	x					x	x
Soil physical condition	x		(x)			x	(x)
Structure: mixed species			x	x	x	x	
Structure: size distribution and spatial arrangement			(x)	x	x		
Structure: regeneration and mortality			x	x	x		
Non-woody production			x			x	
Stem and/or wood properties			(x)				

health monitoring plots). Several approaches have been proposed to carry out the required up-scaling. If the averaged or sampled data are used for the whole grid element, the models may need re-calibration using input and output data, both at the desired larger scale (Van Oijen et al., 2009). For non-linear models, there may be a need to modify model structure first (Ewert et al., 2011).

The large-scale input data are generally available from variable sources and result from long-term environmental monitoring. Data for model initialisation and also for analyses applying the models is most readily obtainable from *national forest inventories*. These typically provide information on stocking characteristics, such as species, basal area and volume, with new additions including, e.g., the amount and quality of deadwood (e.g. Eid et al., 2002; Backeus et al., 2005; Mäkelä et al., 2011; Tomppo et al., 2011). An increasing source of information is provided by *remote sensing*, available from different satellite programmes such as Landsat TM, SPOT and MODIS. These data particularly provide information on leaf area, important for PBM simulations (Patenaude et al., 2008), but the ability to offer other stocking components is developing rapidly (Tomppo et al., 2008). A fast expanding source of data is provided by *lidar scanning* which also bears promise for more detailed structural information, such as tree height, crown size, crown shape (Patenaude et al., 2008) and definition of vertical layers (Ferraz et al., 2012).

A global *map of soil properties*, including e.g. texture, soil depth and water holding capacity, is maintained by FAO (FAO, IIASA, ISRIC, ISSCAS and JRC, 2009). Similar data sets are also available regionally (e.g. for Europe ESBN and EC, 2004). *Global topographical data* are available from remote sensing. Among the most detailed digital elevation models (>100 m resolution at the equator) that are freely available are the SRTM90 (Reuter et al., 2007; Jarvis et al., 2008) and the ASTER-GDEM (Tachikawa et al., 2011).

Historical *climate data* are now available for most countries on a spatial grid of the order of 1×1–100×100 km^2, on the basis of a network of meteorological stations and standard methods of interpolation (e.g. New et al., 1999, 2000; Hijmans et al., 2005; Mitchell and Jones, 2005). These data usually include monthly climatologies or monthly time series of, at least, temperature and precipitation and other variables allowing for the calculation of global radiation and air humidity. Even more climatic variables such as wind speed are available through reanalysis data (e.g. Uppala et al., 2005). Several climate models provide projections of a wealth of climate variables into the *future* according to different climate scenarios. Globally data from General Circulation Models are available (e.g. Mitchell et al., 2004) while in some regions also downscaled data from Regional Climate Models (e.g. for Europe from van der Linden and Mitchell, 2009) are available. The climate models have in the past been driven by the atmospheric CO_2 as specified in the IPCC's SRES scenarios (Nakicenovic et al., 2000) which are currently being superseded by a new set of future pathways, namely the representative concentration pathways (RCPs, Van Vuuren et al., 2011). Historical and future *nitrogen deposition data or projections* are also available globally (Galloway et al., 2004; Dentener, 2006) although in much less variety than the climate change scenarios.

In regional model applications, inventory data have been applied both non-spatially and spatially. In non-spatial analyses, sample plots of NFI grid can be used as such representing a given forest area (e.g. Nuutinen et al., 2000; Backeus et al., 2005; Barreiro and Tomé, 2011, 2012). This kind of approach is suitable for large-scale applications, which do not require high spatial resolution of the results.

In smaller-scale local analyses (at the levels of municipality, forest estate or village) whole-coverage spatial data are required. They can be obtained by means of multi-source inventory methods, such as multi-source national forest inventories (MS-NFI). A multi-source inventory method combines field measurement data with remote sensing data and other digital data (e.g. land-use maps and elevation models). Using satellite images, the characteristics can be estimated for areas located between the NFI sample plots network. The non-parametric *k* nearest neighbour estimation method has been commonly applied in the image analysis (e.g. Reese et al., 2002; Tomppo et al., 2008). MS-NFI techniques have already been applied to estimate traditional forestry variables in Finland, China and New Zealand (Tomppo et al., 1999, 2001; Tuominen et al., 2010; Mäkelä et al., 2011) but also to assess biodiversity-related issues such as landscape quality for the three-toed woodpecker (*Picoides tridactylus*) in a region in southern Finland (Pakkala et al., 2002).

By means of the MS-NFI, forest information can be obtained for smaller areas than with the field measurements only, and the results can be calculated and presented for any given area, in the form of statistics or thematic maps.

5.3. Implications of uneven data availability for modelling

The above sections show that in addition to an assembly of models depicting different aspects of sustainability, the available data come from different sources, and both the models and data are provided at a multitude of scales. This makes the problems of model parameterisation, evaluation and application far more complex than has been the case for, e.g., traditional growth and yield models where the problem of parameter estimation is well-defined and solvable using standard statistical methods, provided that an adequate data set is available for fitting the models. Traditionally models are evaluated with a data set independent from the one used for model development (Vanclay and Skovsgaard, 1997; Yang et al., 2004; Burkhart and Tomé, 2012) but it is difficult to define the independence of the two data sets. In recent years, modellers have therefore increasingly turned to new methods accounting for large uncertainties and multiple simultaneous data sources.

The methods come with a variety of different names, including 'data assimilation', 'model-data fusion', 'inverse modelling' and 'Bayesian calibration' (Van Oijen et al., 2005; Wang et al., 2009). They have in common that uncertainties about data and models are expressed in the form of probability distributions. For the data, the distributions represent uncertainty about measurement error, both random and systematic. For the models, the distributions represent uncertainty about how plausible the individual models are, and uncertainty about what their parameter-values should be. The role of the data is to improve the model distributions, i.e. reduce the degree of uncertainty that they represent. Two types of distribution are distinguished to that end: prior and posterior distributions, representing uncertainty before and after a dataset has been processed. Posterior distributions are derived by multiplying the priors with the so-called likelihood function which embodies the information from the dataset. This multiplication is an application of Bayes' Theorem, so the methods are often referred to as being 'Bayesian'. Terminology is not consistent, however, and in some disciplines the term 'cost-function' is used rather than likelihood. The strengths of the Bayesian approach are threefold: (1) it is rigorously based on probability theory, (2) it not only helps in model parameterisation and model selection but at the same time quantifies uncertainties in model inputs and outputs, and (3) the likelihood function can easily accommodate information from very different types of measurements. The last point is probably most relevant for model application to SFM, where so many different sources of information need to be combined.

Bayesian model calibration was introduced in forest modelling by Green et al. (1999) and has since been applied to parameterisation of different forest models (e.g. Van Oijen et al., 2005; Van Oijen and Thomson, 2010; Svensson et al., 2008). A good technical introduction to different implementations of the Bayesian approach is given by Wang et al. (2009). The use of the approach for comparison of different forest models is still quite rare but examples are appearing (Van Oijen et al., 2012; submitted for publication; Fu et al., 2012).

6. Conclusions

This paper has reviewed stand-scale forest and ecosystems models with respect to their ability to provide information about the criteria and indicators of sustainable forest management proposed by the Ministerial Conference on the Protection of Forests in Europe. While many of the criteria concern national or continental scale issues and are not predictable with stand-scale models (Category 4, Appendix A), a set of criteria could be identified that concern the physical state of forest stands and the impact of stand-scale management actions on that (Category 1). Furthermore, the stand-scale predictions can be scaled up to regions and countries, provided that sufficient input information is available (Category 2). An important role of models in the assessment of sustainability could be to help reassess the management actions that lead to sustainability in terms of the stand-scale criteria, e.g., by means of multiobjective optimisation (Category 3). The following conclusions mainly concern the immediate stand-scale criteria and indicators of Category 1 which was the focus of this review.

It is clear that to date, no comprehensive models exist that could be used to predict all the indicators simultaneously. It may not be desirable to aim at producing such a comprehensive model either. A better approach could perhaps be to aim for a modular system where different models are combined and run simultaneously, with shared inputs and well defined links with each other. Such efforts are already in progress (e.g. Azevedo et al., 2005).

The prediction of many of the indicators would require understanding of processes not included in forest DSS to date. The most crucial issues are related to the state of the soil, including carbon, nitrogen and water balances but also physical alterations of the soil. Secondly, models need development in their ability to deal with heterogeneous stand structures. Thirdly, more model development appears to be due regarding non-woody forest products such as berries, mushrooms or cork. The outputs of the models need to be developed in a direction where they can be interpreted in terms of the recreational or biodiversity value of the forest as well.

Data requirements are most pronounced on the same issues as the gaps in model availability. In order to improve the applicability of models for sustainability assessment at a large geographical scale, unified data acquisition methods are needed. It would be important to consider amending the national forest inventories and other similar standard data collection protocols with variables required for sustainability assessment. In particular, information about the state of the soil and about variable elements of stand structure would be crucial.

Combining different models in a modular system and with variable data sources requires advanced model parameterisation and evaluation methods and assessment of parameter and model uncertainty. The probabilistic, Bayesian approaches hold a lot of promise in this respect. Predictions using several different models or model systems, with systematic analysis of e.g. inter-model variability, could also be considered.

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Appendix A

Criteria and indicators defined by Ministerial Conference on the Protection of Forests in Europe (MCPFE, 2002) classified according to the stand-level modelling framework (see Section 2): Type 1: Indicators directly derivable from model outputs; type 2: Indicators derivable through scaling up stand scale results; type 3: Indicators that refer to sustainable management practices; type 4: Indicators that refer to current land-use and other national/regional statistics.

Criteria	Indicators	Type
C1: Maintenance and appropriate enhancement of forest resources and their contribution to global carbon cycles	1.1. Forest area (total and in subclasses)	4
	1.2. Growing stock	1
	1.3. Age structure and/or diameter distribution	1
	1.4. Carbon stock	1
C2: Maintenance of forest ecosystem health and vitality	2.1. Deposition of air pollutants	4
	2.2. Soil condition	1

Appendix A (*continued*)

Criteria	Indicators	Type
	2.3. Defoliation	1
	2.4. Forest damage	1
C3: Maintenance and encouragement of productive functions of forests (wood and non-wood)	3.1. Increment and fellings (balance)	3
	3.2. Roundwood	1
	3.3. Non-wood products	1
	3.4. Services	2
	3.5. Forests under management plans	4
C4: Maintenance, conservation and appropriate enhancement of biological diversity in forest ecosystems	4.1. Tree species composition	1
	4.2. Regeneration	1, 3
	4.3. Naturalness	4
	4.4. Introduced tree species	4
	4.5. Deadwood	1
	4.6. Genetic resources	4
	4.7. Landscape pattern	2
	4.8. Threatened forest species	4
	4.9. Protected forests	4
C5: Maintenance and appropriate enhancement of protective functions in forest management (notably soil and water)	5.1. Protective forests – soil, water and other ecosystems (area)	3, 4
	5.2. Protective forests – infrastructure and managed natural resources (area)	3, 4
C6: Maintenance of other socioeconomic functions and conditions	6.1. Forest holdings	4
	6.2. Contribution of forest sector to GDP	3, 4
	6.3. Net revenue	3, 4
	6.4. Expenditures for services	3, 4
	6.5. Forest sector workforce	3, 4
	6.6. Occupational safety and health	3, 4
	6.7. Wood consumption	4
	6.8. Trade in wood	4
	6.9. Energy from wood resources	2, 4
	6.10. Accessibility for recreation	4
	6.11. Cultural and spiritual values	4

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