Computers and Electronics in Agriculture 222 (2024) 109091

Contents lists available at ScienceDirect

Computers and Electronics in Agriculture

journal homepage: www.elsevier.com/locate/compag

Original papers

A generic simulation model for relating forest CO_2 intake and CO_2 emissions by forest operations – The R-package *care4cmodel*

Peter Biber[a,*], Stefano Grigolato[b,c], Julia Schmucker[d], Hans Pretzsch[a], Enno Uhl[a,e]

[a] Chair of Forest Growth and Yield Science, Technical University of Munich, Hans-Carl-von-Carlowitz-Platz 2, 85354 Freising, Germany
[b] Department of Land, Environment, Agriculture and Forestry, University of Padova, Viale Dell'Universita', 16 Legnaro, Italy
[c] Department of Forest and Wood Science, Stellenbosch University, Stellenbosch, Matieland 7602, South Africa
[d] Southern Swedish Forest Research Centre, Swedish University of Agricultural Sciences, Sundsvägen 3, 234 56 Alnarp, Sweden
[e] Department of Biodiversity and Conservation, Bavarian Institute of Forestry, Hans-Carl-von-Carlowitz-Platz 1, 85354 Freising, Germany

ARTICLE INFO

Keywords:
Generic forest simulation model
Carbon sequestration
CO_2 emissions
Forest operations
Forest dynamics
System dynamics

ABSTRACT

Carbon stocks and flows in forest ecosystems play an important role in the context of climate change mitigation. Different aspects of the forest carbon balance, however, are often treated independently, leading to a fragmented, disciplinary knowledge. With the R-package *care4cmodel* we want to support a consolidated view of forest growth and forest operations with respect to carbon flows. The software is, in essence, a pragmatic simulation tool that allows juxtaposing the CO_2 uptake due to wood increment and the CO_2 emissions due to forest operations for given silvicultural concepts in an arbitrary area, over time. At the core, the approach is a dynamic forest area model where forest development stages are represented in a cyclical sequence, which can be broken by disturbances. The model scales up growth and yield information given per forest development stage and unit area to the dynamically simulated development stage areas. This allows to quantify the total forest area's CO_2 uptake, and to estimate the CO_2 emissions caused by forest operations. The forest operations in our implementation include the maintenance of the forest road network, felling trees, debranching and bucking the stems, and extracting the timber to a landing at a forest road. The transport from there to the industry is beyond the system boundary. For the CO_2 uptake of the forest system, the current model version focuses on the wood increment only. We use a practical example to demonstrate the basic features of the model and its plausible behaviour. Beyond the current focus of the model, we see a broad field of applications as a generic meta model, especially in the context of ecosystem service provision.

1. Introduction

The study at hand wants to provide the first version of a tool that allows to put two aspects of the forest carbon balance in context that have been mostly treated independently so far: CO_2 uptake due to forest growth and CO_2 emissions due to forest operations. On the one hand, the importance of forests as carbon stocks and possible CO_2 sinks for climate change mitigation is beyond doubt (Anderson-Teixeira et al., 2021). There is also no doubt that both, stock and sink, can be strongly influenced by the silvicultural treatment (Mäkelä et al., 2023; Bravo et al., 2017; Jandl et al., 2007). On the other hand, there is the realm of forest operations and machinery, where intensive research is done about fuel consumption and efficiency (Haavikko et al., 2022; Schweier et al., 2019). From recent studies (Kärhä et al., 2023; Bacescu et al., 2022) it can be simply derived that the CO_2 emissions caused by harvesting one cubic meter of wood are usually by two or three orders of magnitude smaller than the amount of CO_2 which went into the biological production of the same cubic meter. Despite that, the emissions should not be seen isolated from the ongoing forest dynamics and silvicultural measures, as forest operations, regarding their type, intensity and timing, strongly depend on silvicultural conceptions and forest dynamics. When projecting CO_2 emissions from operations and CO_2 sequestration by forest growth from cubic meters in stands to a larger area (e.g. a forest enterprise), the shares of different stages of forest development are crucial as these stages may strongly differ in terms of CO_2 sequestration, and silvicultural measures that require operations with specific CO_2 emissions. Silvicultural guidelines for practitioners usually represent a time sequence of stand-level information about

---

* Corresponding author.
E-mail address: p.biber@tum.de (P. Biber).

https://doi.org/10.1016/j.compag.2024.109091
Received 22 December 2023; Received in revised form 21 May 2024; Accepted 22 May 2024

growth and yield over a whole rotation, often combined with recommended forest operations and related topics, but they tell us nothing about what it means in the area to have different developmental stages in parallel, or to start a new silvicultural approach from scratch. Especially the latter will, for a long time be visible in a strongly unbalanced distribution of the different stages of forest development (Biber et al., 2021; Schwaiger et al., 2019). Compared to a forest system that is balanced in this regard, we have to surmise considerable differences in terms of CO_2 sequestration and emissions in the area.

Throughout this study, we will often use the term "silvicultural concept", meaning an idea of how a certain type of forest stand should be or is managed from its establishment to the final harvest. Typically, such a concept perceives the life of a forest stand as a sequence of several development phases. Each such phase is defined by its typical stand properties and silvicultural actions. Often, such concepts are written down in silvicultural textbooks or silvicultural guidelines. Forest yield tables can be seen as a special, highly detailed type of how a silvicultural concept can be described. When such a concept comes with sufficient quantitative information, as we will detail below, it can be used with the tool we are going to introduce with this study.

Evidently, forests are not only shaped by planned management but also by natural disturbances whose probabilities typically depend on the stage of a stand's development (i.e. the stand structural traits connected to the phase of development, cf. Hanewinkel et al. (2011). This fact deserves additional attention as a trigger of unplanned forest operations, e.g. extensive salvage harvest after a storm event. The continual occurrence of disturbances does typically prevent the theoretically ideal normal forest equilibrium even under otherwise optimum conditions (Knoke et al., 2021; Hanewinkel, 2002).

A holistic view of a system that comprises the components i) managed forest dynamics, ii) disturbances, iii) CO_2 uptake, iv) CO_2 emissions from operations, and their development in time calls for integration in a simulation model. The general development in forest modelling during the last decades showed a trend towards models that build up even large-area forest dynamics from the dynamics of the single trees, whose establishment, growth, harvest, and possible death is individually simulated (Shifley et al., 2017). While the insights that can be generated by such models are momentous, potential users in science and practice often lack the advanced skills and the highly detailed information required to initialize and drive such models. Especially when only aggregated information is available or detailed information is too costly in relation to the question to be answered, there seems to be a broad range of cases where more aggregated model approaches can be useful.

Typical applications of that kind, which are much related to the idea of this study, would be assessments of silvicultural concepts where the dynamics and loss risk of a forest stand under a given management are known or assumed to be known, and the consequences of installing such a concept on a large area should be assessed. As mentioned above, silvicultural concepts are usually defined in practice as a sequence of stand development phases where basic growth and yield information is given for each phase as well as the time a stand typically spends in a given phase. This kind of definition is highly valuable, because it integrates information coming from scientific research plots, forest inventories, and often scenario simulations with models that operate on higher levels of resolution, e.g. single tree based stand simulation models (Pretzsch et al., 2021).

The idea of simulating forest dynamics as a chain of stages that stands undergo in sequence as they develop is actually not new. Formally often defined as Markov Chains or matrix models first approaches were implemented since the late 1960s, and the concept has ever since been used in the context of forest management despite the leading role of higher resolution forest models (Strigul et al., 2012; Kouba, 2002; Buongiorno and Michie, 1980; Usher, 1969).

As we shall demonstrate below, the conceptual framework of System Dynamics (Sterman, 2000) offers itself for the aggregated modeling approach we propose with the study at hand. This includes the definition of the model as a set of differential equations. While there is powerful commercial software available that allows even graphical System Dynamics modelling, like VENSIM, iTHINK, and Powersim, such software would require very specialized skills to construct a model that is flexible enough for our purpose (e.g. allows the user to choose the number of state variables at runtime). The free programming language R, in contrast, has become a widespread standard in professional data analysis and visualization providing a high flexibility and an excellent accessibility at the same time. With the R package *deSolve* (Soetaert et al., 2010), there is a collection of precise and fast algorithms for numerically integrating differential equations available. This allowed us to implement our model as an R package that is worldwide available to the large community of R users in forest science and forestry, and requires no more than basic R-skills for operation.

With the study at hand, we introduce the R-package *care4cmodel* whose core is a generic forest phase–area simulation model. Generic, in our context, means that the model is applicable for any silvicultural concept anywhere as long as users can provide sufficient quantitative information. Keeping this required input small enough to make it actually usable in practice was an important design requirement. Therefore, with a small set of required inputs, our model allows dynamic simulations for arbitrary forest management concepts in the area under user-defined initial phase-area distributions and risk scenarios. Two evaluation modules, one for forest growth and yield information, and one for estimates of CO_2 emissions by forest operations complement this core. A set of standard visualization routines is provided in addition. The main target audience of the R-package are forest scientists, practitioners, and students worldwide. As the core of the model is generic, extensions to other forest applications beyond the one introduced here (i.e. beyond the focus on CO_2 related information) are possible and planned. To our best knowledge, the study at hand is the first one that combines forest growth and yield with forest operations in a dynamic context and on a highly generic level, especially with regard to selected relevant aspects related to CO_2.

It is important to state that the aim of *care4cmodel* is not to provide a full forest carbon balance. Obtaining the extensive input information required to do so would overburden and therefore exclude most potential users. Therefore, the CO_2 related functionality we provide with the package concentrates on a few key aspects only. The output of *care4cmodel*, however, can be easily taken as the basis for any subsequent more detailed evaluation by anyone who commands the information that is additionally required. The technical environment provided by R seems ideal for such an approach.

The R package *care4cmodel* is free software and publicly available under the GPL-3 licence on CRAN since 16-11-2023 (https://CRAN.R-project.org/package=care4cmodel). It comes with a vignette that provides step-by-step instructions of how to use the software (https://cran.r-project.org/web/packages/care4cmodel/vignettes/getting-started-with-care4cmodel.html). While the aim of the study is not an actual assessment of a silvicultural concept, we demonstrate the main features of the model and its plausibility by example of a silvicultural concept for Scots pine stand management.

2. Implementation

2.1. Overview

The current model version has the following basic system properties and boundaries: It assumes that a larger forest area (typically several hundred up to thousands of hectares) is managed under a given silvicultural concept of interest. As this silvicultural concept comprises several typical phases of stand development, the development of their area shares is simulated over a user defined time span. The user provides the initial area shares. For standard use, forest growth and risk conditions are considered constant throughout a simulation. Based on the simulated area shares, the model provides a broad set of standard forest growth and yield variables at different levels of detail. Most of the growth and yield variables are related to wood volume, and can thus be transformed into stored carbon. The current version, however, focuses on the CO_2 uptake by wood increment which is the core variable of sustainable forest production that can, at the same time, be most directly influenced by silvicultural decisions. CO_2 uptake or release from other biological processes in the forest, like soil processes or deadwood decay is currently not considered. Concerning the release of CO_2 due to forest operations, it takes into account the harvest of timber and the regular maintenance of the most important infrastructure, i.e. the forest road network (which is assumed existing from the beginning). The harvest, in our concept, comprises the felling of the trees, cutting the stems into logs and transporting these to nearest appropriate landing at a forest road. The truck transport from the forest to the industry is beyond the system boundaries.

Within this outline, we want to provide a first compact version of a tool that allows to explore and compare silvicultural approaches with regard to the most important aspects of CO_2 uptake and release on forest estate level, that can directly be influenced by forest management.

The fundamental idea of the model is that the development of forest stands under a given silvicultural concept can be reasonably divided into a number of phases which have each typical properties in terms of i) growth and yield variables, ii) risk of disturbances, iii) silvicultural actions, iv) amount and size of harvested wood, and v) the type of forest operations. Each of these phases covers a specific time span, and the phases follow upon each other in a sequence. This is the way silvicultural concepts are typically defined for and communicated to practitioners. To be compatible with this kind of concept definition was an important design requirement of the software (Section 2.4, Table 1). Note that the information contained in such a concept definition provides the basis for estimating CO_2 uptake and emissions.

Accordingly, the conceptual backbone of the model is a set of state variables each of which represents the area covered by a certain stand development phase. Together, these areas sum up to the total area assumed to be managed under the silvicultural concept of interest, e.g. in a landscape or a forest estate, typically comprising several hundred or thousands of hectares. In the current model version, the overall area has to remain constant throughout a simulation run. This concept is visualized in Fig. 1 using System Dynamics notation (Sterman, 2000). Rectangles (“stocks”) represent state variables, i.e. development phase areas. Double-outlined pipe-like arrows (“flows”) represent the flows of areas into and out of stocks, and the single-lined arrows indicate causal dependencies. The visualization shows that the areas cyclically flow through the phases; the final phase is followed by the initial phase again. Areas flowing from the final phase to the initial phase (flow “Transition 5” in Fig. 1), indicate a final harvest on these areas, which is followed by the establishment of a new initial stand. The transitions from one phase to the next depend on the amount of area that is currently in that phase, and on the dwell time, i.e. the average time one unit area is spending in the developmental phase, according to the user’s concept definition, including the variance of the dwell time (Section 2.2). Note that in the package *care4cmodel* the number of phases is completely up to the user and defined at runtime. Fig. 1 is insofar incomplete, as it – for the sake of clarity – shows only regular area flows, but not such that are caused by disturbance events. In the actual model, random disturbances (Section 2.3) can cause area losses that flow back to the initial phase from each development phase. Given an initial distribution of the total forest area over the development phases, the dwell times and the phase-wise risk of area losses per unit time (i.e. one year), this core model performs dynamic simulations of how the areas covered by the phases develop over time. As the required concept definition includes essential growth and yield information per unit area for each phase (e.g. standing volume, wood increment per year, harvested wood volume per year), this can easily be scaled up to the whole area after the actual simulation (Section 2.5.1). This growth and yield information in turn comprises the information required to estimate the CO_2 emissions caused by the forest operations (Section 2.5.2). Evidently, the growth and yield information offers itself for straightforward estimates of the carbon storage and momentary uptake in the wood (Section 2.5.3).

2.2. Simulating area dynamics

According to the classic theory of sustainable forestry, the “normal forest model” (Hundeshagen, 1848; see also Speidel, 1972; Heyer, 1883), our model concept as shown in Fig. 1, would have to represent each stock, i.e. the area covered by a certain phase, as a construction that works like a conveyor belt with constant speed. This means, if a portion of area enters a stock (coming from the previous stock) at a point of time, exactly the same area would leave the stock (and enter the subsequent one) exactly after the duration of the respective stand development phase (i.e. the dwell time). Initial phase-area distributions would be simply cycling through the phases but be preserved in principle forever. This is, however, not entirely realistic, as there is always a blur due to environmental and biological circumstances (e.g. variation in site conditions, stand density, genetics). There is, in addition, the influence of the forest managers who try to counteract unbalanced area distributions by taking appropriate stands earlier or later to the next treatment phase. A well-tried way to take into account such buffering and variation is to describe the change of the area A in one stock that has the dwell time D with the following differential equation (Bossel, 2007)

$$\frac{dA}{dt} = u - A\cdot\frac{1}{D} \tag{1}$$

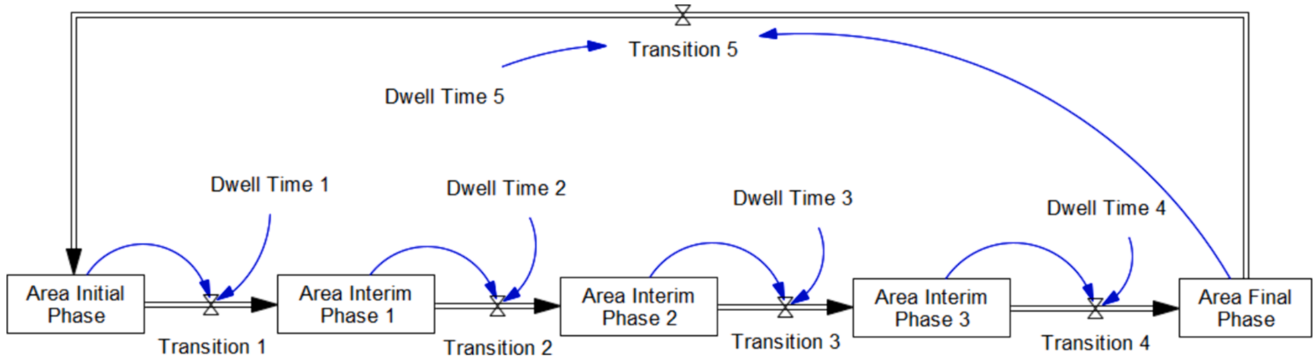

Fig. 1. System Dynamics notation of the core model, representing a cyclic arrangement of forest areas flowing through a chain of subsequent stand development phases. Users can freely define the number of phases and their dwell times at runtime. Note that area flows due to disturbance events are not included into this figure for the sake of clarity. The rectangles (“stocks”) represent state variables, i.e. development phase areas. Double-outlined pipe-like arrows (“flows”) represent the flows of areas into and out of stocks, and the single-lined arrows indicate causal dependencies. Figure designed with the software VENSIM PLE. 9.0.0.

where t is time, u the inflowing area from the previous stock, and $A \cdot 1/D$ the area flowing out into the subsequent stock. This represents a first order exponential delay, and it implies that a momentary inflow at a time 0 causes an outflow that is exponentially distributed over time with the mean $\mu = D$ and the variance $\sigma^2 = D^2$. This is, however, only realistic when the assumption of "perfect mixing" is valid for the stock. This assumption means that all items in the stock have the same probability of leaving, independent of when they entered (Sterman, 2000). While this is regularly the case (in good approximation) with stocks that have typically short dwell times, as in the tree growth model by Nguyen et al. (2012), it does not hold for our stock definitions where forest areas can spend up to a few decades in one stand development phase. E.g. in a forest management concept with a rotation period of 120 years and six stand development phases, one phase would in average take 20 years (note, that our model does not require each stock to have the same dwell time). In order to come up for this problem, the model internally represents each stock as a chain of n subsequent sub-stocks with a dwell time of $D_{sub} = D/n$ each, their outflow definitions resulting in 1st order exponential delays as in Equation (1). The number of sub-stocks, n, should be chosen great enough so that the assumption of perfect mixing, as mentioned above, approximately holds for the sub-stocks. The overall stock then behaves as an n^{th} order exponential delay, which implies that the outflow response to a momentary inflow at a time 0 follows an Erlang distribution with the probability density function

$$p(t) = \frac{\left(\frac{n}{D}\right)^n}{(n-1)!} \cdot t^{n-1} \cdot e^{-\frac{n}{D} \cdot t} \tag{2}$$

with the mean $\mu = D$ and the variance $\sigma^2 = D^2/n$ (Sterman, 2000). This means, model users can conveniently choose n for each stock by the variance in dwell time they consider realistic and desire to allow for the outflow response to an inflow. The density function of the Erlang distribution is unimodal and its symmetry increases with n. For $n = 1$, it becomes an exponential distribution.

Consequently, our model implementation extends from the aggregated view as shown in Fig. 1 to a circular chain of sub-stocks, each single one acting as a 1st order exponential delay (Fig. 2). All n sub-stocks that belong to one stand development phase together form an n^{th} order exponential delay with the properties shown above.

Our implementation uses the R function *ode()* from the *deSolve* package (Soetaert et al., 2010) with the *lsoda* algorithm as default for the simulation of the area dynamics, i.e. numerical integration of the differential equation system that forms the core model. Experienced users can select from the whole range of alternative algorithms available for *ode()*.

2.3. Simulating disturbance events

While also regular silvicultural actions can be considered as disturbances from an ecological point of view, we are using the term "disturbance" from a forest management perspective, i.e. exclusively for unplanned natural events such as windthrow, snowbreak, or insect infestations. Obviously, users who want to include such disturbance events in simulations have to provide information about their probabilities. State forest or large private forest estates usually have good information about their typical damage rates from permanent inventories. Regularly, however, such information will be considerably imprecise in practice. Still, professional forest managers have at least a rough realistic idea of the risk they have to deal with. In any case, it will often be more useful to consider even such imprecise information instead of just ignoring it. In order to support the users in this regard, we have implemented the concept of cumulative survival probabilities (see e.g. Staupendahl and Möhring, 2011), which is very intuitive. Following that idea, the software expects as an input for each phase the probability that a stand will survive from the time of its establishment to the end of that phase. Note, that these survival probabilities comprise all kinds of disturbances that could happen in one stand development phase in one number. Considering that, the input can be seen as a series S of time-probability pairs of values. For a silvicultural concept with n phases this would be

$$S = (t_0 = 0, p_0 = 1), (t_1, p_1), (t_2, p_2), \cdots, (t_{n-1}, p_{n-1}), (t_n, p_n) \tag{3}$$

Where t_0 is the time of stand establishment with the corresponding survival probability p_0 which must be obviously 1. The times $t_1, t_2, \cdots, t_n$ are the times between the ends of the phases $1, 2, \cdots, n$ and t_0, and $p_1, p_2, \cdots, p_n$ are the probabilities that a stand survives from t_0 to $t_1, t_2, \cdots, t_n$, respectively. This implies for any stand development phase i that $p_{i-1} \geq p_i$. This intuitive definition of survival probabilities provided by the user, however, requires to be internally transformed into mean annual area loss probabilities. These are obtained by assuming an exponential decay with a constant decay rate, $r \leq 0$, in each phase. For an arbitrary phase i, this can be written as

$$p_i = p_{i-1} \cdot e^{r_i \cdot (t_i - t_{i-1})} \tag{4}$$

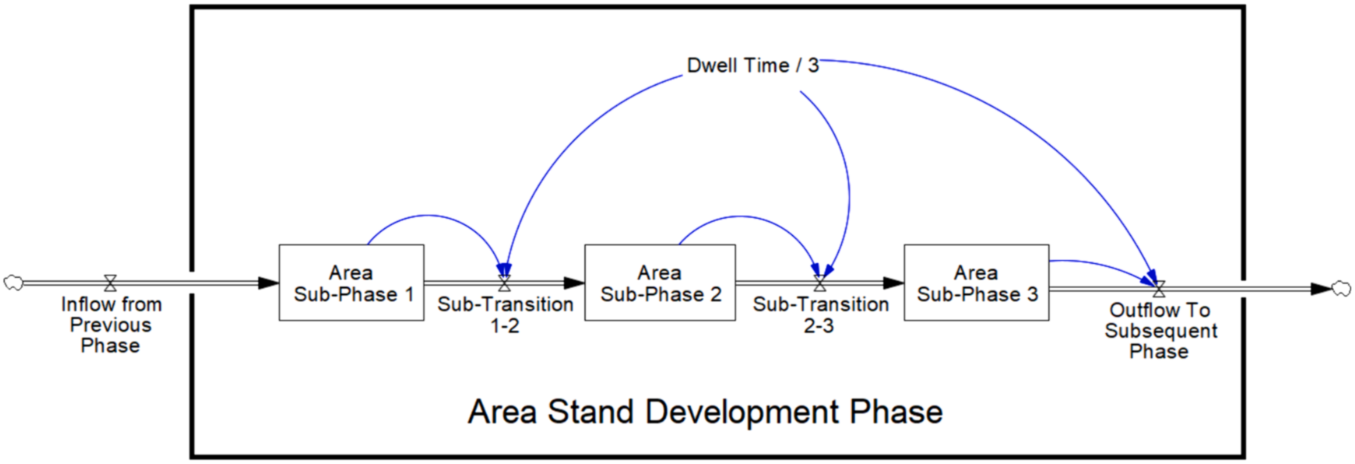

Fig. 2. Subdivision of a stock representing the area covered by a stand development phase as in Fig. 1. In this example, the stock (outer rectangle) consists of $n = 3$ sub-stocks whose areas sum up to the current area of the whole stand development phase. Each sub-stock behaves as a 1st order exponential delay each having a dwell time of $1/n$ of the whole phase's dwell time. In our implementation, users can freely choose n for each phase at runtime. The rectangles ("stocks") represent state variables, i.e. areas of sub phases inside one development phase. Double-outlined pipe-like arrows ("flows") represent the flows of areas into and out of stocks, and the single-lined arrows indicate causal dependencies. Figure designed with the software VENSIM PLE. 9.0.0.

which allows to calculate the phase specific mean decay rate

$$r_i = \frac{\ln\left(\frac{p_{i-1}}{p_i}\right)}{t_i - t_{i-1}} \tag{5}$$

The mean annual area loss probability in phase i then results as 1 minus the mean annual survival probability:

$$\text{p\_loss}_i = 1 - e^{r_i} \tag{6}$$

In a given stand development phase, *p_loss* could be interpreted as the mean damage effect of an event that causes premature area loss. The simplest way to apply these phase-wise loss probabilities were to move a relative area share of *p_loss* from each phase's area to the initial phase in each simulation year. We attempted, however, to implement a more realistic distribution of the damage effect strengths. While it is under debate how exactly the extent of random forest damages is distributed (Gardiner et al., 2008), there seems to be agreement that at a given average, small damages are frequent while heavy damages are comparably rare (Hanewinkel et al., 2014; Thom et al., 2013); exponential distributions are often taken as a model for that (Thom et al., 2013). In order to achieve at least a qualitatively plausible representation, we draw an exponentially distributed random number $k_j \sim \text{Exp}(\lambda = 1)$ for each simulation year j (λ being the distribution's single parameter). We take this number as the year's individual disturbance event strength, the expectation being 1. For $k_j = 1$, i.e. a normal year, we assume that disturbance events with a strength that causes exactly p_loss will take place in that year. For e.g. $k_j = 2$, we assume events happening that have the same effect as if two normal year disturbances happened in sequence; this applies analogously to any values of $k_j > 1$. For $k_j < 1$, we obtain accordingly weaker events and damages. Thus for each stand development phase i in each year j, the relative area loss to be applied in each year results as:

$$\text{p\_loss\_actual}_{i,j} = 1 - \left(1 - \text{p\_loss}_i\right)^{k_j} \tag{7}$$

In this concept, each year has one random disturbance event strength k_j, but this can mean different things for the whole forest area, as the stand development phases have their individual p_loss_i. Even a year with heavy events can have relatively low damages in the area, if stable stand development phases (i.e. their p_loss_i is small) that are less affected by the events dominate. Vice versa, if very susceptible phases are prevalent, even average damage years can cause heavy losses in the area.

In order to allow for easy risk scenario modifications when using the software, we implemented the option to adjust Equation (7) with a general risk level parameter, m. The idea is to consider Equation (7) as the user-defined standard risk level of the silvicultural concept of interest, which we allow to be altered with m. The parameter m is interpreted in exactly the same way as the parameter k_j in Equation (7); e.g. $m = 3$ is an overall risk level triple to the standard, i.e. three times the standard strength events happening in sequence. This leads to an extension of Equation (7):

$$\text{p\_loss\_actual}_{i,j} = 1 - \left[\left(1 - \text{p\_loss}_i\right)^{k_j}\right]^m \tag{8}$$

The annual hazard-induced area loss per phase results straightforwardly from multiplying $\text{p\_loss\_actual}_{i,j}$ with the actual area covered by phase i in the year j, technically more precise, when simulation time has an integer year value. This results in damage events being accounted for once per year. As the areas of each phase are split into sub-stocks (see above), the hazard-caused outflows are actually calculated and applied on sub-stock level, whereby we apply to each sub-stock the $\text{p\_loss\_actual}_{i,j}$ of the phase it belongs to. Simulating damage events means instantaneous changes of the areas covered by the stand development (sub-) phases. Although technically not trivial, this is nicely supported by the R package *deSolve* (Soetaert et al., 2010) we use in our implementation.

2.4. *Concept definition*

In order to access the simulation features as described above, and for allowing post-hoc evaluations of forest growth and yield and carbon flows, users have to provide information as exemplified in Table 1. The example represents a modern silvicultural concept for the management of Scots pine (*Pinus sylvestris* L.) stands on sites with a good water and nutrient supply in Central Europe. In essence, it prescribes thinnings from above which are followed by extended periods of final harvest (Río Gaztelurrutia et al., 2017; Franz, 1983). In this example, the numbers were obtained by aggregation from high-resolution simulation runs with the single tree based forest growth simulator SILVA (Pretzsch et al., 2002) combined with yield table evaluations. We defined the concept as a sequence of six different stand development phases, where the software requires for each the overall duration in years (i.e. the dwell time D according to Equations (1), (2)), and the number of subphases (i.e. n in the sense of Equation (2). In this example, we chose n for each phase in order to achieve an average subphase dwell time ($D_{sub} = D/n$) of about five years. Given initial areas for each of the stand development (sub-) phases, this information is sufficient for simulating the forest area dynamics as described in Section 2.2. In order to take into account disturbance events (Section 2.3), the cumulative survival probabilities have to be provided. Accordingly, the values given in Table 1 correspond to the variables $p_1, p_2, \cdots, p_n$ in Equation (3). In our example the values were estimated after Staupendahl and Möhring (2011) using the parameterization of a Weibull probability function for Scots pine by Staupendahl (2011).

All other variables to be provided in the concept definition are not required for the dynamic simulation itself, but for the post-hoc calculations that generate information about growth and yield dynamics and CO_2 uptake and emissions on the area. All these values are to be understood as averages that are valid as long as an area is attributed to the corresponding phase. They represent the development of a stand covering one hectare given the quantitative assumptions of the concept definition, and assuming the stand survives from its establishment to the end of the last phase. In detail, these variables are: i) the standing wood volume (m^3/ha); ii) the removal volume (m^3/ha/a), which is the annual average volume removed according to plan; iii) the mortality volume (m^3/ha/a) which is the annual average volume of trees dying normally due to competition-based mortality as foreseen in the concept, not due to disturbance events; iv) the standing stem number (1/ha), i.e. the average number of living trees; v) the removal stem number (1/ha/a), which is the number of regularly harvested trees, these make up the removal volume; vi) the average diameter at breast height (1.30 m), dbh, of the standing trees (cm), vii) the average dbh (cm) of the regularly harvested trees, corresponding to the removal volume and stem number; viii) the periodic annual volume increment (m^3/ha/a). Note, that the volume increment is not required to be given by the user, as it results from the other variables as follows (using the column names of Table 1, with the index i indicating an arbitrary stand development phase):

$$\text{volume inc}_i = \frac{(\text{volume standing}_{i+1} - \text{volume standing}_i)}{\text{duration}_i} + \text{volume removal}_i + \text{volume mortality}_i \tag{9}$$

Also, note that the removal volume and stem number have to be given as annual averages while, in practice, stands are harvested intermittently. This fact is taken into account in the post hoc calculations where required (Section 2.5).

There is no general rule or recipe, whatsoever, how to come to a useful concept definition in the above-mentioned sense. The sources can be very different, e.g. published silvicultural guidelines, yield tables, research or observation plots, forest inventories, simulations with high-resolution models or combinations thereof. Even hypothetical concepts

Table 1
Example for a concept definition compatible with *care4cmodel*. Technically, such concepts are represented as an S3 object (class c4c_concept) in the software (Section 2.6).

Phase #	Phase name	Duration	Number of sub-phases	Volume standing	Volume remove	Volume mor-tality	Stem number standing	Stem number remove	dbh standing	dbh remove	Survival prob. cum.	Volume inc.
Units		a	n	m^3/ha	m^3/ha/a	m^3/ha/a	1/ha	1/ha/a	cm	cm	p	m^3/ha/a
1	initial stand	15	3	0	0.0	0.0	7000	0.0	0.0	0.0	0.999	3.9
2	young growth	14	3	59	0.0	0.1	6237	0.0	5.8	0.0	0.996	10.7
3	immature timber	29	6	206	1.6	1.7	4168	17.6	10.3	12.9	0.979	9.1
4	mature timber	49	10	374	4.4	1.6	970	7.6	22.9	25.8	0.910	7.5
5	final harvest phase I	19	4	446	8.8	0.6	510	8.1	30.2	41.9	0.868	5.8
6	final harvest phase II	29	6	378	16.5	0.5	356	12.3	32.7	41.5	0.791	3.9

can be handled. The temporal resolution, i.e., the number of development phases to use depends on what fits best the user's question, and, pragmatically, the detail level of the information they have available. A good general guideline is to consider that one development phase should be distinguishable from others by typical stand structures and tree sizes, and by typical forest operations taking place during that phase. The variables describing a forest stand in the concept definition (standing volume, mean stem diameter, etc.) are understood as average values per phase. In practice, information about the precision of these values is hardly available, and when simulating a concept on a larger area, such variation would cancel out. Therefore, it is not included in the concept definition. However, with regard to variation, variation in time is an essential part of the model approach (see Section 2.2) as is the stochastic simulation of disturbance events (see Section 2.3).

2.5. Post-hoc calculations

Immediately after a simulation run according to sections 2.2 and 2.3, the available information only covers the development of phase areas and area flows over time. The detailed output of the simulation algorithm is reduced and aggregated to three $n \times m$ matrices, **A**, **B**, **C**. Each of the rows $i = 1, \cdots, n$ represents a point in time where the first row represents the initial situation, and the subsequent rows represent the situation $i - 1$ years later. Horizontally, the columns $j = 1, \cdots, m$ stand for the phases as defined in the underlying concept in ascending order. For the example concept shown in Table 1, the matrices would have 6 columns and 101 rows if the user chose a simulation time of 100 years. Matrix **A** contains the phase areas, so each entry $a_{i,j}$ is the area covered by phase j at the end of year i. Matrix **B** contains the annual area outflows from each phase due to damage events. Therefore, each entry $b_{i,j}$ is the area moving out of phase j to the beginning of phase 1 during year i. These outflows can also exist for the first development phase, as the model also allows stands to be thrown back to the start inside this phase. The matrix **C** contains the area inflows to the phases due to regular development; accordingly, each entry $c_{i,j}$ is the area that is moving into phase j during year i. The matrices **A** and **B** are the basis for all subsequent calculations in the current software version. Matrix **C** is currently not required for standard use. However, its calculation is no significant computational burden, and we expect it to become useful in future applications.

2.5.1. Growth and yield

By simply multiplying the phase-wise areas given in matrix **A** with the corresponding area-related volume variables from the concept definition, we obtain the i) standing volume, ii) regular removal volume, iii) mortality volume, and the iv) volume increment on the whole area of interest for each point in time of the simulation. In order to obtain the removal volume due to hazard events, the area flows given in matrix **B** must be multiplied with the corresponding standing volumes from the concept definition, as we consider the stands on these areas as lost. The software provides these volume-related variables for all stand development phases separately, and also in an aggregated format, where the volumes are summed up over all phases.

In addition, the growth and yield output comprises a table with detail information about the harvested wood that is required for estimating the CO2 emissions due to harvest operations. That means the total harvested volume is broken down to regular or disturbance-induced harvest, and the mean dbh of the harvested trees. In case of regular harvest, this is the phase-wise removal dbh, whereas in case of disturbance-induced harvest, this is the standing dbh. Both are taken from the concept definition (cf. Table 1). The table also provides the mean volume of the harvested trees, which result from dividing the phase-wise removal volume by the removal stem number from the concept definition. While this is the procedure for regular harvest, analogously the concept definition's standing volume has to be divided by the standing number of stems for damage-induced harvest. The mean distance (m) between the harvested trees is also estimated as follows for regular harvest

$$\text{dist} = \sqrt{\frac{10000}{N_{\text{removal}} \cdot \Delta t}} \tag{10}$$

where N_{removal} is the phase-wise removal stem number (1/ha/a) from the concept definition, Δt is the time interval (a) between two harvest operations (default 5 a), and the constant 10000 converts the resulting distance unit into m. For damage-induced harvest, the calculation is simply

$$\text{dist} = \sqrt{\frac{10000}{N_{\text{standing}}}} \tag{11}$$

with N_{standing} being the corresponding phase's standing tree number (1/ha) as it is considered lost on the affected area.

2.5.2. Fuel consumption and CO_2 emissions by forest operations

In order to estimate fuel consumption and the resulting CO_2 emissions we consider the harvest of timber and the regular maintenance of the forest road network. The harvesting method considered in *care4cmodel* is a full mechanized Cut-to-Length (CTL) system, which involves the utilization of a combination of two forestry machines: a harvester responsible for felling trees and processing them into logs, and a forwarder tasked with extracting the logs from the forest to the nearest appropriate landing located at a forest road side. This harvesting method is one of the most common world-wide for industrial roundwood harvesting (Lundbäck et al., 2021). The secondary transportation in terms of truck transport system and transport distance from the forest to the wood processing sites (e.g. sawmill, pulp and paper industry) is not considered in the current version of the model. Currently, two options for calculating the fuel consumption due to harvest machines are available. The first option, called “nordic” in the software, is taken from a publication by Kärhä et al. (2023). For the felling, debranching and bucking, we assume the usage of a harvester where the machine’s consumption in liters diesel fuel per m^3 harvested wood, cons, is estimated as follows:

$$\mathrm{cons}_{\mathrm{harvester}} = 0.494 + \frac{0.105}{\mathrm{tv}} + \frac{9.501}{\mathrm{hv}} + 0.149 \cdot \mathrm{th} \tag{12}$$

With tv being the average merchantable wood volume over bark per harvested tree, and hv being the harvested volume per ha. the parameter th is a flag which is 1 if the operation is a thinning, and 0 if it is a final harvest. For extracting the logs to the forest road, we assume a forwarder whose diesel fuel consumption per m^3 wood, cons, is estimated by:

$$\mathrm{cons}_{\mathrm{forwarder}} = 0.516 + 0.049 \cdot \frac{\mathrm{aed}}{100} + \frac{17.033}{\mathrm{hv}} - 0.106 \cdot \mathrm{msoil} \tag{13}$$

Here, aed is the average extraction distance in m, which results from the area’s forest road density, frd, (in m/ha, to be provided by the user) as

$$\mathrm{aed} = \frac{10000}{\mathrm{frd} \cdot 4} \text{(Heinimann, 2017; Matthews, 1939)} \tag{14}$$

The variable msoil is a flag which is 1 if the operation takes place on mineral soil and 0 if not (i.e. organic soil, typically peat).

The other option we call “standard” uses the following equation for the harvester’s fuel consumption per m3 harvested wood, estimated after Bacescu et al. (2022):

$$\mathrm{cons}_{\mathrm{harvester}} = \frac{1}{1.834 + 0.642 \cdot \ln(\mathrm{tv})} \tag{15}$$

This equation is valid for timber lots where the mean dbh of the harvested trees is at least 15 cm. In case of smaller lots, Eqn. (12) is used to fill the gap. The equation for estimating the forwarder’s fuel consumption per m^3 wood is based on data published by Grigolato and Cadei (2022):

$$\mathrm{cons}_{\mathrm{forwarder}} = 3.24 \cdot 10^{-4} \cdot \mathrm{aed} + 0.469 \tag{16}$$

The diesel fuel consumption for forest road maintenance in liters per ha and year is estimated, in accordance with (Enache and Stampfer, 2015) as a function of forest road density (m/ha), frd:

$$\mathrm{cons}_{\mathrm{maintenance}} = 0.25 \cdot \mathrm{frd} \tag{17}$$

Fuel consumption in liters diesel is converted into kilograms of emitted CO_2 with the common factor of 2.61 kg/l (Cosola et al., 2016).

All equations above are implemented as separate functions, but for applying them to the output of the growth and yield evaluations above, we implemented an overarching function which calls them in an organized way (see Section 2.6). Importantly, it takes into account that wood can be debarked and volume is lost in the process of felling and cutting logs, so the amounts of wood transported by the forwarder are somewhat smaller than what was felled by the harvester before. We assume the usual standard harvest loss factor of 10 %, and assume 12 % volume share for bark as default (Prodan, 1965), but allow for user-specific values.

2.5.3. CO2 equivalents of wood

For calculating the amount of CO_2 equivalents stored in a given wood volume, users have to provide the assumed raw wood density, r (kg/m^3), which is usually given for air-dry wood, i.e. for a water content, p, of 12 %. The calculation is defined as:

$$\mathrm{co}_2 = \frac{r}{2} \cdot \left(1 - \frac{p}{100}\right) \cdot 3.67 \tag{18}$$

This implies that half of the dry biomass would be the mass of C, which is expanded to the corresponding mass of CO_2, which means a factor of 3.67. As the default value for the raw wood density, we use 520 kg/m^3 which is typical for Scots pine and about in the middle of the range of the species specific wood densities, about 0.3 to 0.7 kg/m^3, in Europe (Knigge and Schulz, 1966).

2.6. Technical realisation

In this section we provide an overview of the technical implementation mainly with a focus on the user’s perspective. We can only cover the core functions and options here, for a full overview, we have to redirect readers to the R package’s documentation. Note, that the package comes with a vignette “Getting Started with care4cmodel” which is an illustrated step-by-step introduction to using it. Both, documentation and vignette are accessible at the package’s webpage on CRAN and locally, after installing the package on the user’s machine.

As a general implementation feature, we utilized the S3 style object oriented programming (OOP), which is R’s sparsest and at the same time most widely used OOP concept (Wickham, 2019). On the top level, where standard users interact with the software, we defined four tasks which are covered with one function each (Table 2). We called the first task “concept definition”; its purpose is to transform user-provided information about the silvicultural concept of interest (as in Table 1) into an R object that can be technically used for simulations. The function for this task is called `c4c_concept()`; its typical input is a data frame that results from importing tabular data, e.g. from a spreadsheet software, into R. If the transformation is successful, the output is an S3 object of class `c4c_concept`, which is the structure of how concept definitions are represented in the package. The function `c4c_concept()` also calls an extensive validation. It will terminate with an error and provide an informative error message in case incomplete or inconsistent information has been provided.

Given a valid `c4c_concept`, the second task, running a simulation, is available. The corresponding top-level function is called `simulate_single_concept()`. Besides requiring the user to provide the desired concept definition, it also requires the assumed initial areas of each stand development phase given in the concept. Information about the time span to be covered and the desired risk level must be provided in addition. Internally, the function performs the simulation of the area dynamics (Section 2.2) including risk events (Section 2.3), and calculates the resulting growth and yield information (Section 2.5.1). The output is an S3 object of class `c4c_base_result`, which is, in essence, an extensive list of matrices and data frames providing information about the temporal development of the phase areas, the area flows between the phases and their reason (regular or induced by disturbance events). It contains, in addition, extensive growth and yield information on different levels of aggregation, and metadata about the simulation and calculations.

This object forms the basis for the third task, the evaluation for fuel consumption and CO_2 emissions due to forest operations, stored CO_2 equivalents in the living and harvested trees, and CO_2 uptake due to wood increment. The function performing this task is called `fuel_and_co2_evaluation()`, and besides the `c4c_base_result` object, it requires inputs that quantify the assumed forest road density in the area of interest (m/ha), the wood density to be used in CO_2 related calculations, the wood volume loss fraction due to harvest, and the share of the bark related to the wood volume. In addition, the harvest method to be used must be chosen (“standard” or “nordic”, see Section 2.5.2). Note that these inputs have not been made part of the concept definition, in order to allow fuel and CO_2 focused evaluations with different assumptions using the same `c4c_base_result` object, i.e. based on the same simulation run. The output of the function is an object of class `c4c_co2_result`, which is a list of three data frames providing information about CO_2 emissions, carbon storage, and fuel consumption

Table 2
Top level tasks and implemented functions of *care4cmodel*.

Task	Function	Main input	Output
concept definition	c4c_concept()	data frame	object of class c4c_concept
run a simulation	simulate_single_concept()	object of class c4c_concept, inital phase areas, time and risk parameters	object of class c4c_base_result
fuel and CO_2 evaluation	fuel_and_co2_evaluation()	object of class c4c_base_result, forest road density, wood and harvest-related parameters, assumed machinery	object of class c4c_co2_result
result visualization	plot() (internally implemented as plot.c4c_base_result() and plot.c4c_co2_result() according to R's S3 conventions)	object of class c4c_base_result, or object of class c4c_co2_result	ggplot object either for direct display or post-hoc modification

on different levels of aggregation. The object also comprises metadata about the underlying simulation and calculations.

Finally, for the task of convenient and standardized result visualization, we have adapted the S3 generic function `plot()` for `c4c_base_result` and `c4c_co2_result` objects. Both methods generate an object of class `ggplot` (Wickham, 2016) that can either be directly displayed or post-hoc modified to the user's convenience. Both plot methods offer a choice of nine and seven thematically different diagrams for base and CO_2 related results, respectively.

The top-level functions described above guarantee the logical order of all calculations when the model is applied. Internally, they are using a larger number of sub-functions that perform the specific tasks described above. Some of these, e.g. estimating fuel consumption of forest machinery, converting wood volume or fuel mass into the equivalent CO_2 mass, etc., might be of interest to some users, independent from our model. A special function that might help users providing realistic stand survival probabilities in their concept definitions is called `survival_weibull()`. It implements a concept published by (Staupendahl, 2011) and comes with parameters for five main Central European tree species (see the package's documentation). As a service to such users, the R-package makes these functions separately available with full documentation and working examples as required by the CRAN standards. Interested readers find the full list of functions in the documentation that comes with the package.

3. Results — Model demonstration

In order to demonstrate an application case, we used one of the two exemplary silvicultural concepts that come with the package. This is the concept shown in Table 1 which, in a nutshell, represents a modern approach to manage Scots pine stands in Central Europe (see Section 2.4). We simulated this concept with three levels of risk, corresponding to the parameter m in Equation (8), namely 0 (no damage events), 1 (normal), and 5 (five times the normal risk level), as defined in Section 2.3. For the total forest area, we assumed 1000 ha, and we initialized the simulation with a very imbalanced distribution of the concept's six stand development phases; i.e. initially the whole area was attributed to the initial stand phase, which can be interpreted as an afforestation. We chose this initial situation in order to be able to demonstrate distinctive dynamics. For the same reason, we simulated over a period of 200 years, while typical model applications would use shorter time spans, where the assumption of constant growth and technological conditions (efficiency of forest machinery) is less questionable. In the CO_2 related evaluations we assumed a forest road density of 30 m/ha, a value which is typically found in professionally managed forests (Dvořák et al., 2017). For all other parameters, we used the model defaults. In this publication we must focus on selected results, only, but the full set of output graphs is available in the online supplement, where interested readers also find the R script we used for simulation and evaluation.

The area dynamics we obtained with our simulations (Fig. 3) expectedly show strong oscillations due to the unbalanced initial situation. These oscillations are, however, dampened and would in theory level off on the long run (Sterman, 2000). They are most pronounced for the simulation with no hazard events (risk level 0). For the normal risk level, the oscillations are only subtly weaker, but for risk level 5, we see that frequent disturbance events significantly dampen the long-wave oscillations, and make the system approach a different distribution of development phases, as less stands arrive in the later phases due to them being thrown back into the initial phase before. As a consequence, also the resulting standing stem volumes (Fig. 4) show long-wave dampened oscillations, which are least pronounced under high risk. Thus, while risk level 0 would on the long run lead into a classic normal forest equilibrium, regular damage events lead into deviating near-equilibria as argued e.g. by (Knoke et al., 2021) or (Hanewinkel, 2002).

Under high risk, the system also approaches the least level of total volume, which is due to the lower representation of the older development phases with their high volumes per unit area. Analogous results are obtained for the annual removal stem volume (Fig. 5), which includes regular as well as damage-induced harvest. Fig. 5 shows the effect of the different risk settings and their redistribution effect on the harvest taking place in the different phases and between regular and damage-induced removals. The stem volume increment (Fig. 6) peaks when the most productive development phases 2 and 3 have the highest shares. The higher representation of these phases due to disturbance events also explains why, in contrast to the standing volume, the overall level of increment is not impaired by frequent damages.

Considering the different types of annual CO_2 emissions (Fig. 7), the high share of emissions due to the regular maintenance of the forest road network is striking. In the diagrams it is visible as a constant "socket" of almost 20,000 kg CO_2/year. This value is almost never excelled by the sum of the variable emissions by cutting trees and moving the timber to the forest road. Unsurprisingly, these variable emissions roughly follow the amounts of harvested wood (Fig. 5). In total, the CO_2 emissions exceed 60,000 kg/year only under exceptional circumstances in this simulation.

The ratio between the total annual CO_2 emissions and the uptake of CO_2 equivalents by the annual stem volume increment (Fig. 8) covers a range of about 0.0025 and 0.01; i.e. the emissions are by two or three orders of magnitude smaller than the uptake by the growing stem wood. Even the pattern we observe for risk level 0, a distinct peak between simulation time 100 and 150 years, has complex reasons. While forest operations are most CO_2 efficient for large trees, the lower increment at times when large-tree harvest dominates the area, counteracts this efficiency. For risk levels 1 and even more 5, the damage-induced peaks seem interesting. As our current models for fuel consumption do not consider possibly more difficult conditions on damage areas, the reason is here in the tree dimensions. Our concept assumes a thinning-from above silviculture. Therefore, the average tree in regular removal is

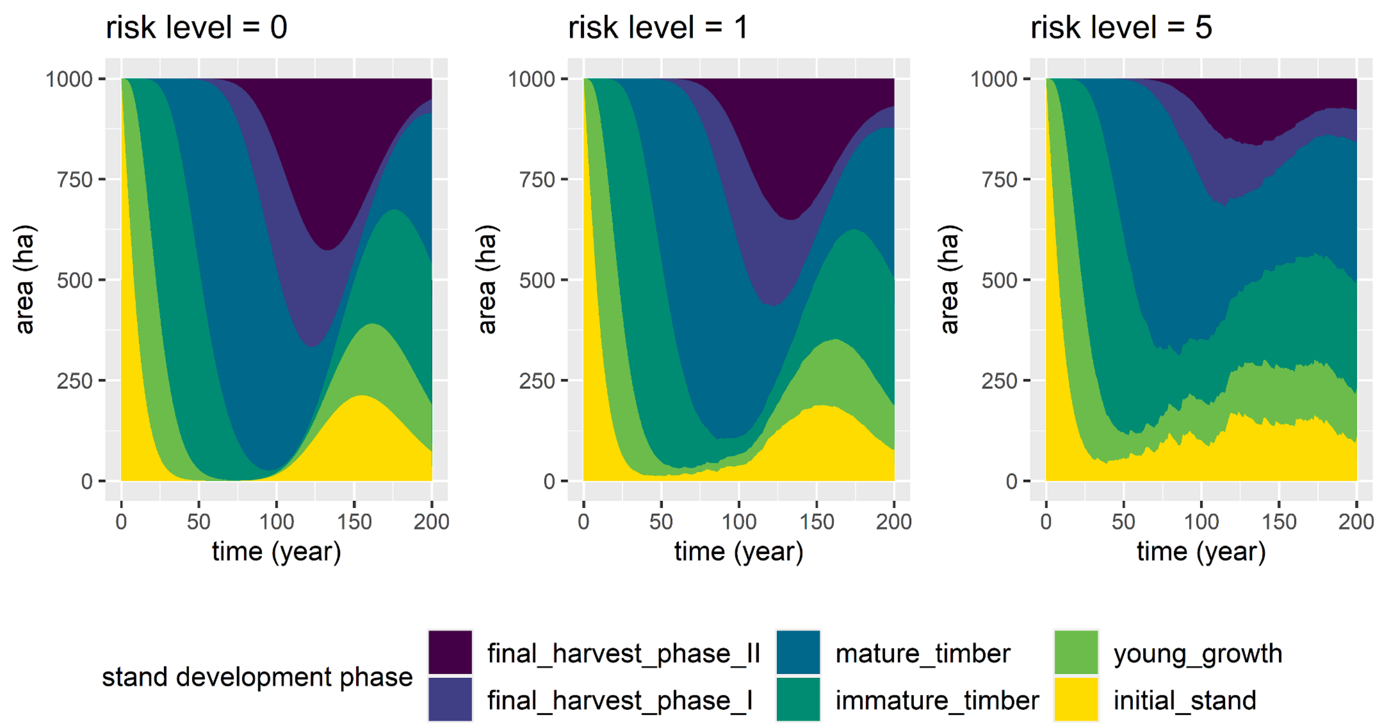

Fig. 3. Simulated development of the areas covered by the different stand development phases.

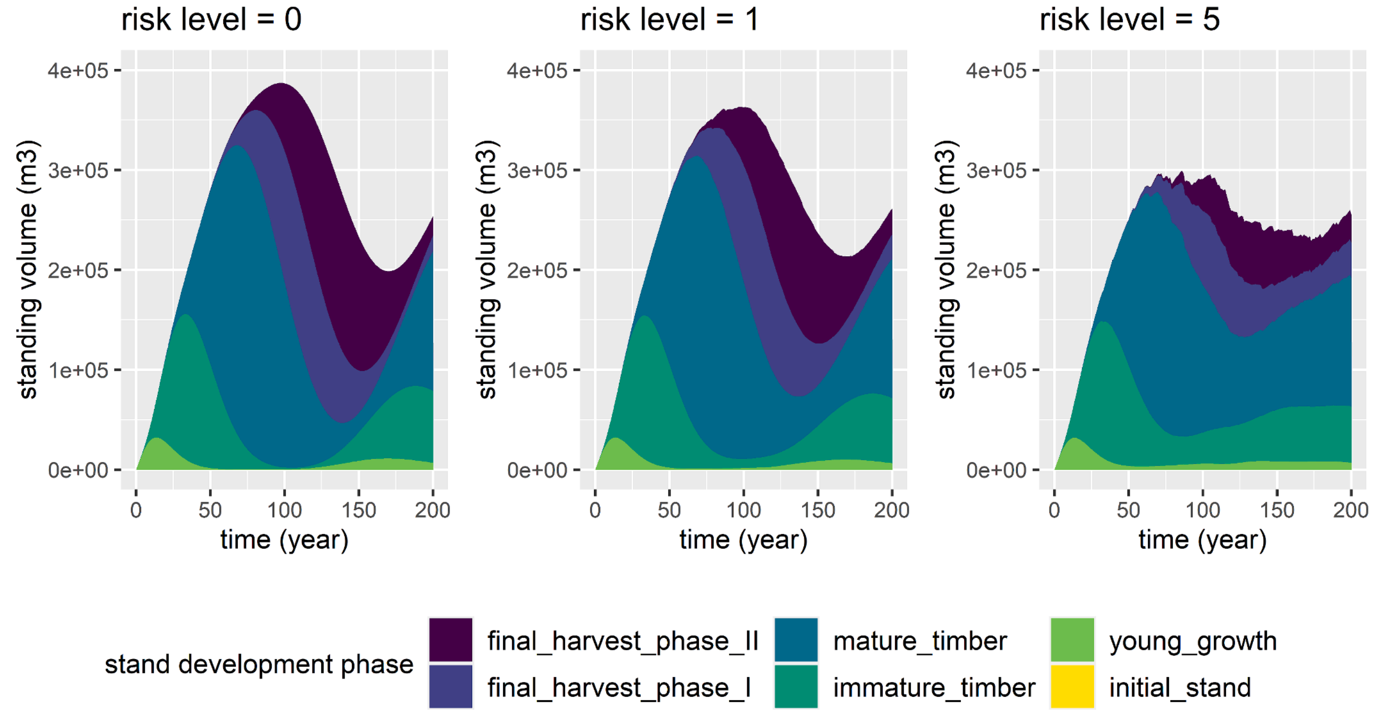

Fig. 4. Simulated development of the standing stem volumes by stand development phase.

larger than the average remaining tree (see concept definition in Table 1). When a damage event occurs, the whole stand is subject to harvest, covering smaller trees in average and thus being less CO_2 efficient.

When we plot the total annual CO_2 emissions against the annual stem wood increment in CO_2 equivalents for each point in time and connect the subsequent dots (Fig. 9) we obtain a type of diagram that is useful for identifying equilibrium states a dynamic system is attracted to. The loop-like shape obtained for risk level 0 indicates that the simulation starts with a low-emissions-low-uptake state. Subsequently emissions stay low, while the uptake increases to a maximum. At about that time, the emissions increase with at the same time declining increment. In essence, the system is moving in a narrow spiral closer and closer to an equilibrium point where emissions are comparably high and the increment is intermediate. With an extended simulation time of, say, 400 years (or shorter simulation time, but more balanced initial conditions),

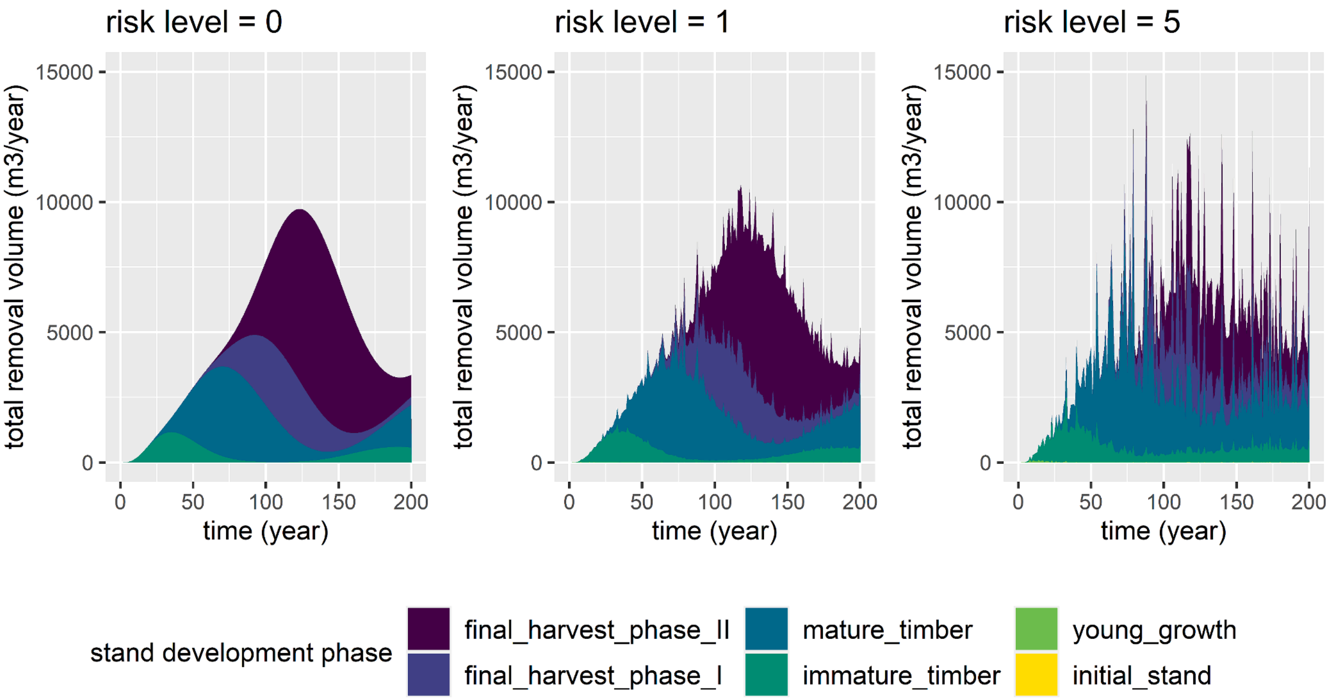

Fig. 5. Simulated development of the amounts of the removal stem volume per year. This includes regular harvest as well as harvest due to hazard events.

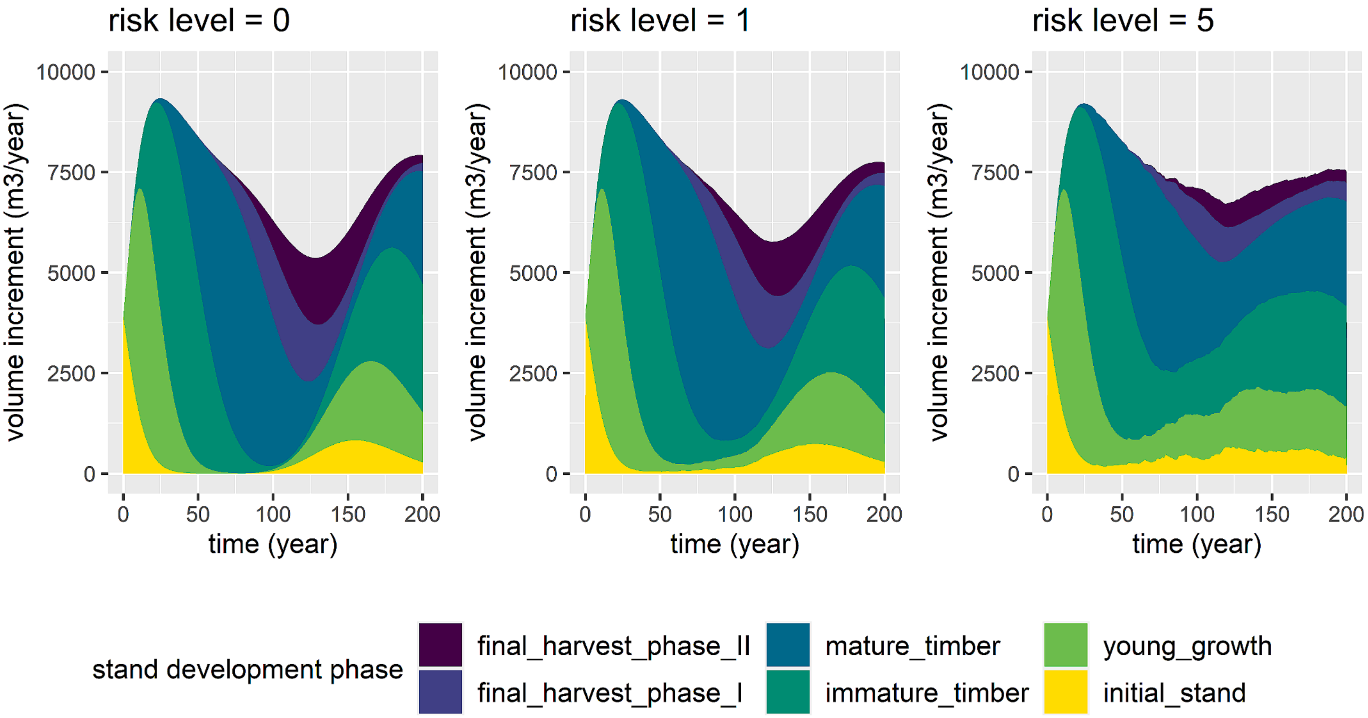

Fig. 6. Simulated stem volume increment per year and ha.

this theoretical equilibrium point could be precisely visualized. In practice, however, random events will always disturb such an equilibrium as is visible for risk level 1 and 5. But also under these conditions, the diagrams indicate kind of an equilibrium zone which the system is being attracted to. This zone seems to be slightly upward (i.e. higher emissions) and right (i.e. higher increment) of the diagram region where the system is attracted to without any disturbances. From the authors' point of view, this is an interesting example of how disturbances shift the equilibrium state of a managed forest system.

4. Discussion

4.1. Possibilities and limits of the new tool

With this study, we proposed a software representing a pragmatic generic simulation tool for assessing arbitrary silvicultural concepts for arbitrary forest types when implemented in the area. It can be seen as a meta-model, where users can plug in and make simulations for any silvicultural concept of interest, based on a small set of input

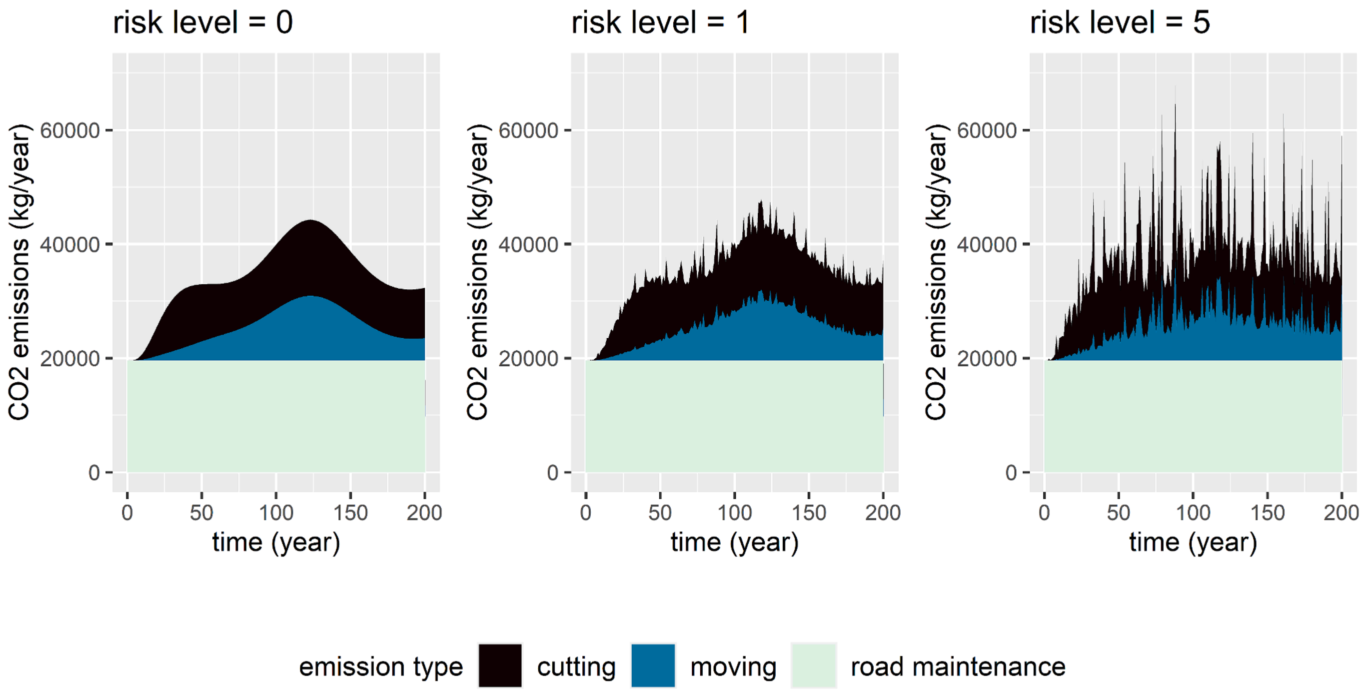

Fig. 7. Simulated CO_2 emissions from fossil fuel consumed in forest operations, by emission type. "Cutting": Emissions by harvesters, "moving": Emissions by forwarders, "road maintance": all required works to keep the forest road network intact.

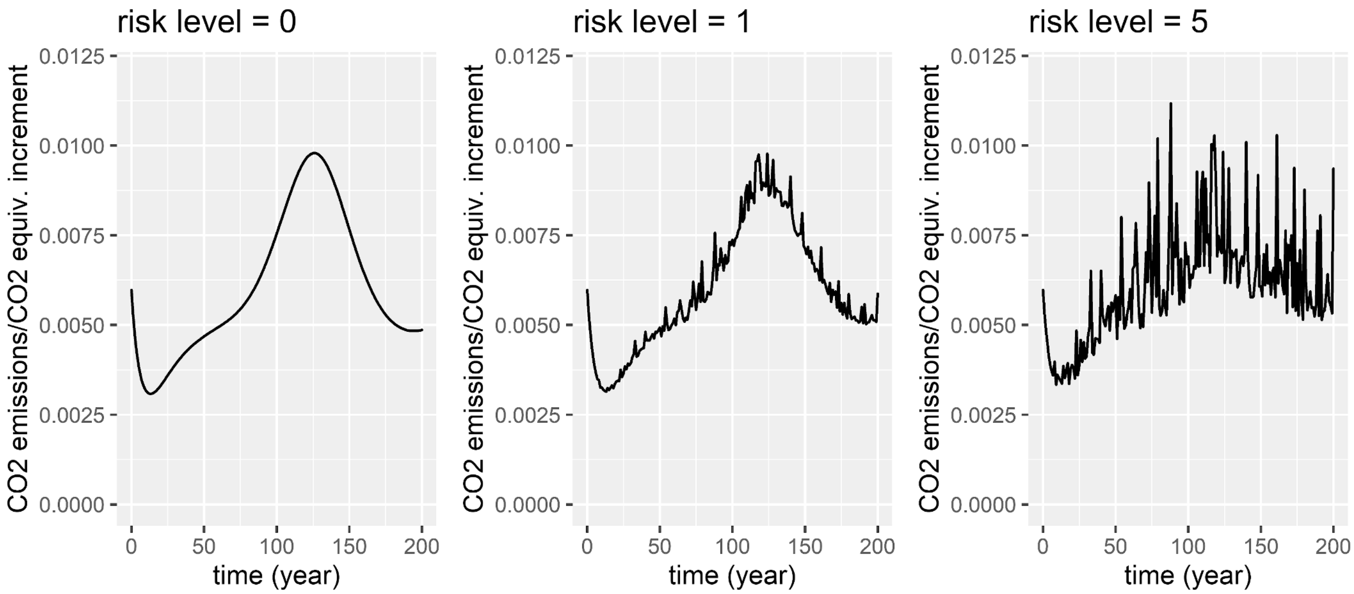

Fig. 8. Simulated development of the ratio of total annual CO_2 emissions and the total annual uptake of CO_2 due to the annual stem wood increment (converted from wood volume to the equivalent CO_2 mass).

information that is realistically available in practice. At the output side, this concept required us to focus on the most important essentials from a forest management perspective. Users, however, who command sufficient additional information, can easily use the output of our model for their own extended calculations. We will discuss this in more detail with a focus on carbon balances in Section 4.2. As the presented simulations show, the core of the model, i.e. the simulated area dynamics are plausible, also when comparing the output for different risk levels. This opens the door to use it as a meta-model for a broad field of applications beyond the one presented here. We will come back to this point at the end of this section, but before, we will discuss the current implementation.

The plausibility of the upscaled growth and yield information strongly depends on the plausibility of the silvicultural concept provided by the user. While the model itself is not able to judge if the user's numbers are realistic or not, the function that generates concept objects, `c4c_concept()`, performs a series of validity checks to prevent concept definitions which are basically inconsistent. A major limitation of the current core model is that it can deal with only one silvicultural concept per simulation, while often in practice, the transition from one concept to another is an important problem to be dealt with (Reventlow et al., 2021). Allowing for such transitions will be an important feature in future versions of the software. Another limitation is the constancy of forest growth conditions (provided indirectly as phase wise dwell times

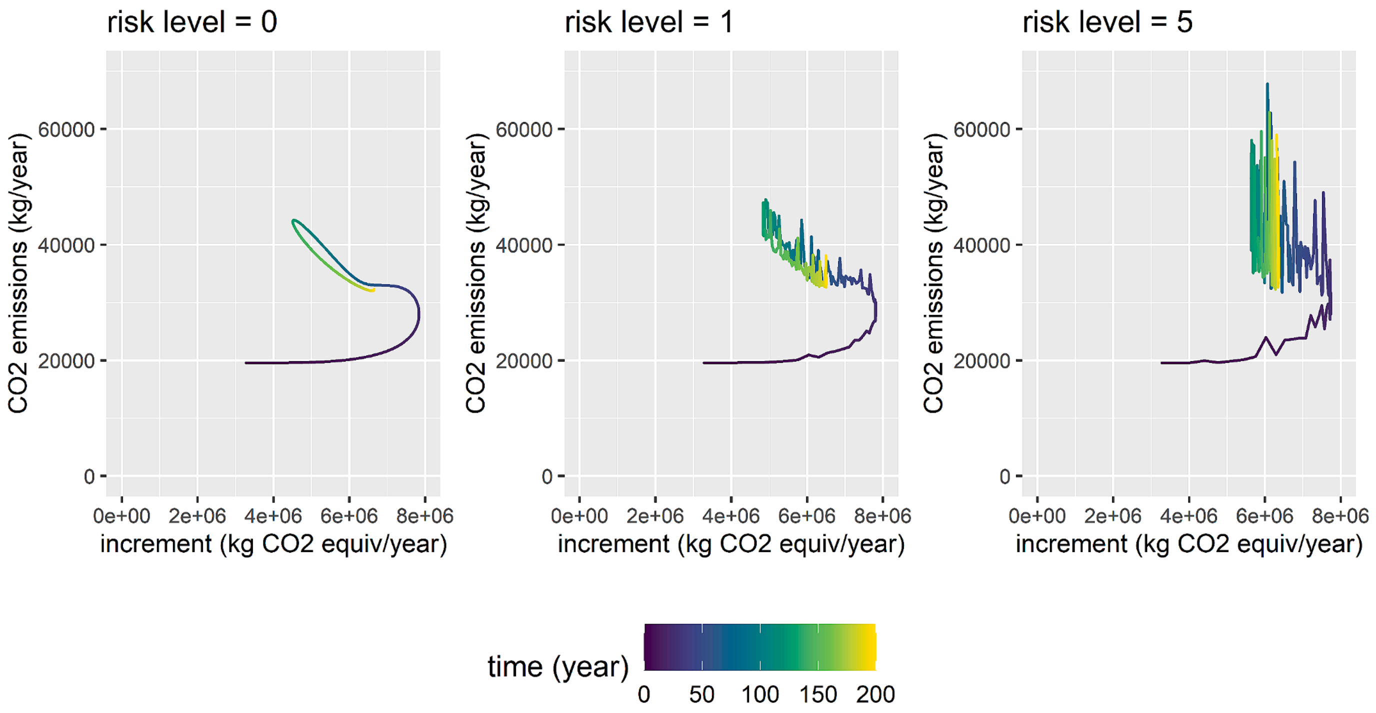

Fig. 9. Simulated total CO_2 emissions plotted against the stem wood increment in CO_2 equivalents. Note that none of the diagram axes represents time. Time is rather represented by the color of the plotted line; the darker the color of a line section, the earlier in the simulation it is.

in the concept definition) and risk levels which have been shown to be not realistic for longer time spans due to climate and other environmental changes (Pretzsch et al., 2023; Schmied et al., 2023; Lecina-Diaz et al., 2021; Pretzsch et al., 2014). While we plan to implement such options to be accessible in a standardized way, advanced users of R can overcome this limit with the current version already. It just takes to simulate with constant settings for reasonably short time spans and to feed the system status obtained in the end into a new simulation with an updated concept and risk level. This can be easily automatized in R, and the temporal resolution of the assumed trend development depends solely on the quality of information the user can provide.

The model does not explicitly take into account disturbances that are non-stand replacing in the sense of Thom et al. (2013), i.e. single trees killed by bark beetles, snow break, etc. Such disturbances have to be implicitly reflected in the numbers describing the silvicultural concept of interest. They would, dependent on what happens with the damaged trees, count either as regular harvest or as normal mortality.

4.2. *Pragmatic approach vs. full C-balancing*

Importantly, as pointed out in the introduction, the idea behind our model is not to provide a full forest carbon balance. The latter would mean users have to provide an amount of information that is virtually impossible to obtain for most of them. Soil carbon dynamics would be arguably the most important additional component required, but even if our software would include such a sub model, users would have to provide initial values for the most important soil carbon stocks and other relevant soil information in sufficient precision. Therefore, we limit ourselves to the CO_2 uptake by above ground wood increment and the CO_2 emissions due to the most important forest operations, but any users who have the information needed for more complete balancing can directly build up on our model's output.

Our focus on the two opposed CO_2 flows mentioned above seems logical, as the wood increment represents the biological production of the raw material wood, and the forest operations are the actions required to make that raw material available to society. Wood volume and volume increment in the forest (as required for our concept definition, see Table 1) is usually defined as merchantable wood that includes the bark and not only the stem, but also all branch material above a certain threshold diameter, usually 7 cm over bark. This comprises the bulk of the trees' above ground biomass. Users who want, despite that, an estimate that includes twigs, leaves, and roots could apply appropriate expansion factors (see e.g. (Pretzsch, 2009) directly to the output of our model, if available for their tree species and conditions of interest.

Deadwood is another forest carbon pool that is deliberately not included in our model. Here as well, users would need to provide estimates of the initial values of the deadwood stocks together with deadwood decay rates for their conditions. To obtain an idea of the relative importance of deadwood, we take Germany as an example, which represents very well at least Central European forest conditions, i.e. managed temperate forests. From the German national forest inventory we know that there is an annual average above ground wood increment of about 11 m^3/ha and an aboveground standing wood volume of 340 m^3/ha. The average deadwood stock is 20 m^3/ha (Schmitz et al., 2014). This means, the deadwood stock is less than 6 % of the standing aboveground wood, and the total accumulated deadwood amounts to less than just twice the annual wood increment. Therefore, covering the deadwood in addition would require users to put in a lot of effort for a comparably small benefit. However, as our approach allows including annual mortality volumes (see Table 1) there is already an interface to more detailed evaluations related to deadwood. Soil-bound carbon stocks are usually considerably greater than those bound to deadwood, but compared to the wood increment, their change rates are usually much slower, and information about soil carbon comes with a high degree of imprecision in general (Grüneberg et al., 2014). Here again, the benefit of burdening users with obtaining the extensive additional information requirements seems questionable. Keeping the model focused on the most relevant variables and therefore applicable in practice, but being open to extended evaluations is a more useful approach from our point of view.

4.3. Towards a consolidated view on the relationship between forest CO_2 uptake and CO_2 emissions by forest operations

While there is a vast body of literature that analyzes the efficiency and productivity of forest operations (Cosola et al., 2016), there are not many studies that provide functions that allow to estimate fuel consumption on a condensed level (Kärhä et al., 2023; Manner et al., 2016) that is feasible for implementing it in a software as ours. We see the current options we provide as a first pragmatic approach, and would be happy to be able to include a broader variety of harvesting systems in the future. With such extensions in mind, the model generates information that remains unused in its current version, but might become useful in the future, e.g. the mean distance between harvested trees (Equations (10), (11)). With regard to quantifying the carbon uptake and storage, the current model version is limited to stem wood and its increment. As mentioned above, this provides already useful information from the authors' point of view. However, the model is compatible with the more detailed approach developed by Biber et al. (2018) that has been successfully applied by Biber et al., (2020) and Schwaiger et al. (2019). Adapting that detailed tool (that was mainly designed by the first author of this study) to the output of *care4cmodel* is also part of the concept of future development.

While, clearly, many kinds of extensions like those mentioned above, seem desirable (including spatial features), they have to be considered with some caution. One strength of the software, as we perceive it, is that using it is not overly complex, which makes it appropriate for quick approximate analyses, scenario comparisons, etc. Any extension that might increase the degree of realism on the detail level bears the danger of making the model less generic, and will always make it more complex to work with for the user. This concerns both, the quality and amount of information users have to provide, and the amount of decisions they have to make before being able to run a simulation.

From that perspective, we do not see our model in competition with the current high-resolution mainstream in forest modelling (Shifley et al., 2017); we see significant synergies, in contrary, as the information required for driving aggregated models often offers itself to be generated by high-resolution models beforehand. Synergies can also be seen in the other direction: The computing speed of aggregated models can allow for exploring a broad spectrum of large-area scenarios, enabling a pre-selection of a few that can be taken up in high detail with high-resolution models.

4.4. Extensions beyond the current implementation

This brings us back to the point raised in the beginning of this discussion, the use of *care4cmodel* as a *meta*-model for many purposes beyond its current implementation. We see two reasons for the special suitability of the model and its implementation in that context. First, the generic definition of silvicultural concepts includes growth and yield information that has to be provided by the user, i.e. the model does not require an own growth and yield parameterization. Even yield tables can be directly defined as a silvicultural concept in their original temporal resolution. Also merely hypothetical concepts can be scrutinized (e.g. "what would we achieve in the area if we could install a silvicultural concept with properties as …?"). Second, with the approach of *care4cmodel*, any information like e.g. stand structure and diversity, or provision of certain ecosystem services, that can be reasonably attributed to stand development phases can be meaningfully upscaled to a whole estate area or a landscape. This opens a wide field for analyses, especially in the context of forest ecosystem services. Detailed information about area flows as provided in the matrix **C** (see Section 2.5) could turn out useful for future refined analyses.

In order to avoid the software complexity trap as mentioned above, such extended applications do not necessarily have to implemented in the package *care4cmodel* itself. The package is free open source software in order impose no constraints for other scientists, practitioners or developers to use it as convenient in their own studies or to embed it in their own free software.

5. Conclusions

With the R-package *care4cmodel* we were able to provide a generic model for assessing silvicultural concepts in the area with a focus on a pragmatic juxtaposition of CO_2 by forest growth with the CO_2 emissions due to forest operations. Enabling that, it creates an operational connection between the field of forest dynamics and forest operations.

By not overburdening users with extensive requirements for input information, the model is actually useable in practice. Consequently, the output can focus on the most essential information only. It is, however, easily available for extended evaluations by users who have the required information.

Beyond its present focus, the approach has a high potential to serve as a meta-model for a broad field of applications and extensions beyond its current focus. This includes especially the provision of a broad range of ecosystem services that can be linked to certain stand development phases, and their shares of an area.

The availability as a free open source software is intended to encourage and facilitate such developments.

Funding

This study is a part of the CARE4C project that has received funding from the European Union's HORIZON 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement # 778322.

CRediT authorship contribution statement

Peter Biber: Writing – original draft, Software, Methodology, Investigation, Conceptualization. **Stefano Grigolato:** Writing – review & editing, Methodology, Investigation. **Julia Schmucker:** Writing – review & editing, Investigation. **Hans Pretzsch:** Writing – review & editing, Conceptualization. **Enno Uhl:** Writing – review & editing, Project administration, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The software is open source and freely available here https://CRAN.R-project.org/package=care4cmodel.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.compag.2024.109091.

References

Anderson-Teixeira, K.J., Herrmann, V., Morgan, R.B., Bond-Lamberty, B., Cook-Patton, S. C., Ferson, A.E., Muller-Landau, H.C., Wang, M.M.H., 2021. Carbon cycling in mature and regrowth forests globally. Environ. Res. Lett. 16, 053009 https://doi.org/10.1088/1748-9326/abed01.

Bacescu, N.M., Cadei, A., Moskalik, T., Wiśniewski, M., Talbot, B., Grigolato, S., 2022. Efficiency assessment of fully mechanized harvesting system through the use of fleet management system. Sustainability 14, 16751. https://doi.org/10.3390/su142416751.

Biber, P., Nieuwenhuis, M., Black, K., Borga, M., Borges, J.G., Felton, A., Hoogstra-Klein, M., Lindbladh, M., Zoccatelli, D., 2018. Synthesis Report: Discrepancies between ES Needs and ES Outputs Under Current FMMs. ALTERFOR Deliverable 3.

Biber, P., Felton, A., Nieuwenhuis, M., Lindbladh, M., Black, K., Bahýl', J., Bingöl, Ö., Borges, J.G., Botequim, B., Brukas, V., Bugalho, M.N., Corradini, G., Eriksson, L.O., Forsell, N., Hengeveld, G.M., Hoogstra-Klein, M.A., Kadıoğulları, A.İ., Karahalil, U., Lodin, I., Lundholm, A., Makrickienė, E., Masiero, M., Mozgeris, G., Pivoriūnas, N., Poschenrieder, W., Pretzsch, H., Sedmák, R., Tuček, J., 2020. Forest biodiversity, carbon sequestration, and wood production: Modeling synergies and trade-offs for ten forest landscapes across Europe. Front. Ecol. Evol. 8, 291. https://doi.org/10.3389/fevo.2020.547696.

Biber, P., Schwaiger, F., Poschenrieder, W., Pretzsch, H., 2021. A fuzzy logic-based approach for evaluating forest ecosystem service provision and biodiversity applied to a case study landscape in Southern Germany. Eur. J. Forest Res. 140, 1559–1586. https://doi.org/10.1007/s10342-021-01418-4.

Bossel, H., 2007. Systems and Models: Complexity, Dynamics, Evolution, Sustainability. BoD – Books on Demand.

Bravo, F., del Río, M., Bravo-Oviedo, A., Ruiz-Peinado, R., del Peso, C., Montero, G., 2017. Forest Carbon Sequestration: The Impact of Forest Management, in: Bravo, F., LeMay, V., Jandl, R. (Eds.), Managing Forest Ecosystems: The Challenge of Climate Change, Managing Forest Ecosystems. Springer International Publishing, Cham, pp. 251–275. doi: 10.1007/978-3-319-28250-3_13.

Buongiorno, J., Michie, B.R., 1980. A matrix model of uneven-aged forest management. For. Sci. 26, 609–625. https://doi.org/10.1093/forestscience/26.4.609.

Cosola, G., Grigolato, S., Ackerman, P., Monterotti, S., Cavalli, R., 2016. Carbon footprint of forest operations under different management regimes. Croatian J. For. Eng. 37, 201–217.

Dvořák, J., Natov, P., Lieskovský, M., 2017. Modelling of forwarding distance to maximize the utilization of medium and high-power harvester technology. J. For. Sci. 63 (2017), 45–52. https://doi.org/10.17221/114/2016-JFS.

Enache, A., Stampfer, K., 2015. Machine utilization rates, energy requirements and greenhouse gas emissions of forest road construction and maintenance in Romanian mountain forests. JGE 4, 325–350. https://doi.org/10.13052/jge1904-4720.445.

Franz, F., 1983. Zur Behandlung und Wuchsleistung der Kiefer. Forstw Cbl 102, 18–36. https://doi.org/10.1007/BF02741834.

Gardiner, B., Byrne, K., Hale, S., Kamimura, K., Mitchell, S.J., Peltola, H., Ruel, J.-C., 2008. A review of mechanistic modelling of wind damage risk to forests. Forestry 81, 447–463. https://doi.org/10.1093/forestry/cpn022.

Grigolato, S., Cadei, A., 2022. Full-mechanized CTL production data in Scots pine forest in Poland [WWW Document]. URL https://researchdata.cab.unipd.it/659/ (accessed 11.21.23).

Grüneberg, E., Ziche, D., Wellbrock, N., 2014. Organic carbon stocks and sequestration rates of forest soils in Germany. Glob. Chang. Biol. 20, 2644–2662. https://doi.org/10.1111/gcb.12558.

Haavikko, H., Kärhä, K., Poikela, A., Korvenranta, M., Palander, T., 2022. Fuel consumption, greenhouse gas emissions, and energy efficiency of wood-harvesting operations: A case study of Stora Enso in Finland. Croatian J. For. Eng. 43, 79–97. https://doi.org/10.5552/crojfe.2022.1101.

Hanewinkel, M., 2002. Comparative economic investigations of even-aged and uneven-aged silvicultural systems: A critical analysis of different methods. Forestry 75, 473–481. https://doi.org/10.1093/forestry/75.4.473.

Hanewinkel, M., Hummel, S., Albrecht, A., 2011. Assessing natural hazards in forestry for risk management: A review. Eur. J. Forest Res. 130, 329–351. https://doi.org/10.1007/s10342-010-0392-1.

Hanewinkel, M., Kuhn, T., Bugmann, H., Lanz, A., Brang, P., 2014. Vulnerability of uneven-aged forests to storm damage. Forestry 87, 525–534. https://doi.org/10.1093/forestry/cpu008.

Heinimann, H.R., 2017. Forest road network and transportation engineering – state and perspectives. Croatian J. For. Eng. 38, 188.

Heyer, C., 1883. Die Waldertrags-Regelung. Teubner.

Hundeshagen, J.C. 1848. Die Forstabschätzung auf neuen, wissenschaftlichen Grundlagen. Laupp.

Jandl, R., Vesterdal, L., Olsson, M., Bens, O., Badeck, F., Roc, J., 2007. Carbon sequestration and forest management. CABI Reviews 2007, 16 pp. doi: 10.1079/PAVSNNR20072017.

Kärhä, K., Haavikko, H., Kääriäinen, H., Palander, T., Eliasson, L., Roininen, K., 2023. Fossil-fuel consumption and CO2eq emissions of cut-to-length industrial roundwood logging operations in Finland. Eur. J. Forest Res. 142, 547–563. https://doi.org/10.1007/s10342-023-01541-4.

Knigge, W., Schulz, H., 1966. Grundriss der Forestbenutzung Verlag Paul Parey. Hamburg and Berlin, Germany.

Knoke, T., Paul, C., Gosling, E., Jarisch, I., Mohr, J., Seidl, R., 2021. Assessing the Economic Resilience of Different Management Systems to Severe Forest Disturbance (SSRN Scholarly Paper No. ID 3844645). Social Science Research Network, Rochester, NY. doi: 10.2139/ssrn.3844645.

Kouba, J., 2002. Das Leben des Waldes und seine Lebensunsicherheit. Forstw. Cbl. 121, 211–228. https://doi.org/10.1046/j.1439-0337.2002.02026.x.

Lecina-Diaz, J., Martínez-Vilalta, J., Alvarez, A., Banqué, M., Birkmann, J., Feldmeyer, D., Vayreda, J., Retana, J., 2021. Characterizing forest vulnerability and risk to climate-change hazards. Front. Ecol. Environ. 19, 126–133. https://doi.org/10.1002/fee.2278.

Lundbäck, M., Häggström, C., Nordfjell, T., 2021. Worldwide trends in methods for harvesting and extracting industrial roundwood. Int. J. For. Eng. 32, 202–215. https://doi.org/10.1080/14942119.2021.1906617.

Mäkelä, A., Minunno, F., Kujala, H., Kosenius, A.-K., Heikkinen, R.K., Junttila, V., Peltoniemi, M., Forsius, M., 2023. Effect of forest management choices on carbon sequestration and biodiversity at national scale. Ambio 52, 1737–1756. https://doi.org/10.1007/s13280-023-01899-0.

Manner, J., Nordfjell, T., Lindroos, O., 2016. Automatic load level follow-up of forwarders' fuel and time consumption. Int. J. For. Eng. 27, 151–160. https://doi.org/10.1080/14942119.2016.1231484.

Matthews, D.M., 1939. The use of unit cost data in estimating logging costs and planning logging operations. J. For. 37, 783–787. https://doi.org/10.1093/jof/37.10.783.

Nguyen, T.T., Biber, P., Pretzsch, H., 2012. Analysis and management of stand dynamics of Vietnamese dipterocarp forests by applying a dynamic growth model. Ann. For. Sci. 69, 581–601. https://doi.org/10.1007/s13595-011-0176-x.

Pretzsch, H., 2009. Forest Dynamics, Growth and Yield: From Measurement to Model, 2010th ed. Springer, Berlin.

Pretzsch, H., Biber, P., Ďurský, J., 2002. The single tree-based stand simulator SILVA: Construction, application and evaluation. For. Ecol. Manage. 162, 3–21. https://doi.org/10.1016/S0378-1127(02)00047-6.

Pretzsch, H., Biber, P., Schütze, G., Uhl, E., Rötzer, T., 2014. Forest stand growth dynamics in Central Europe have accelerated since 1870. Nat. Commun. 5 https://doi.org/10.1038/ncomms5967.

Pretzsch, H., Poschenrieder, W., Uhl, E., Brazaitis, G., Makrickiene, E., Calama, R., 2021. Silvicultural prescriptions for mixed-species forest stands. A European review and perspective. Eur. J. Forest Res. 140, 1267–1294. https://doi.org/10.1007/s10342-021-01388-7.

Pretzsch, H., del Río, M., Arcangeli, C., Bielak, K., Dudzinska, M., Forrester, D.I., Klädtke, J., Kohnle, U., Ledermann, T., Matthews, R., Nagel, J., Nagel, R., Ningre, F., Nord-Larsen, T., Biber, P., 2023. Forest growth in Europe shows diverging large regional trends. Sci. Rep. 13, 15373. https://doi.org/10.1038/s41598-023-41077-6.

Prodan, M., 1965. Holzmesslehre. J.D. Sauerländer's Verlag, Frankfurt am Main.

Reventlow, D.O.J., Nord-Larsen, T., Biber, P., Hilmers, T., Pretzsch, H., 2021. Simulating conversion of even-aged Norway spruce into uneven-aged mixed forest: Effects of different scenarios on production, economy and heterogeneity. Eur. J. Forest Res. 140, 1005–1027. https://doi.org/10.1007/s10342-021-01381-0.

Río Gazteluurrutia, M.del, Bravo Oviedo, J.A., Pretzsch, H., Löf, M., Ruiz-Peinado, R., 2017. A review of thinning effects on Scots pine stands: From growth and yield to new challenges under global change. For. Syst. 26, 9.

Schmied, G., Pretzsch, H., Ambs, D., Uhl, E., Schmucker, J., Fäth, J., Biber, P., Hoffmann, Y.-D., Šeho, M., Mellert, K.H., Hilmers, T., 2023. Rapid beech decline under recurrent drought stress: Individual neighborhood structure and soil properties matter. For. Ecol. Manage. 545, 121305 https://doi.org/10.1016/j.foreco.2023.121305.

Schmitz, F., Polley, H., Hennig, P., Kroiher, F., Marks, A., Riedel, T., Schmidt, U., Schwitzgebel, F., Stauber, T., 2014. Der Wald in Deutschland : ausgewählte Ergebnisse der dritten Bundeswaldinventur. Bundesministrium für Ernährung und Landwirtschaft, Bonn.

Schwaiger, F., Poschenrieder, W., Biber, P., Pretzsch, H., 2019. Ecosystem service trade-offs for adaptive forest management. Ecosyst. Serv. 39, 100993 https://doi.org/10.1016/j.ecoser.2019.100993.

Schweier, J., Magagnotti, N., Labelle, E.R., Athanassiadis, D., 2019. Sustainability impact assessment of forest operations: A review. Curr. For. Rep. 5, 101–113. https://doi.org/10.1007/s40725-019-00091-6.

Shifley, S.R., He, H.S., Lischke, H., Wang, W.J., Jin, W., Gustafson, E.J., Thompson, J.R., Thompson, F.R., Dijak, W.D., Yang, J., 2017. The past and future of modeling forest dynamics: From growth and yield curves to forest landscape models. Landscape Ecol. 32, 1307–1325. https://doi.org/10.1007/s10980-017-0540-9.

Soetaert, K., Petzoldt, T., Setzer, R.W., 2010. Solving differential equations in R: Package deSolve. J. Stat. Softw. 33, 1–25. https://doi.org/10.18637/jss.v033.i09.

Speidel, G. 1972. Planning in forestry. Planning in forestry.

Staupendahl, K., 2011. Modellierung der Überlebenswahrscheinlichkeit von Waldbeständen mihilfe der neu parametrisierten Weibull-Funktion. Forstarchiv 82, 10–19.

Staupendahl, K., Möhring, B., 2011. Integrating natural risks into silvicultural decision models: A survival function approach. Forest Policy Econ. 13, 496–502. https://doi.org/10.1016/j.forpol.2011.05.007.

Sterman, J., 2000. Business Dynamics, 1st ed. McGraw-Hill Inc, USA.

Strigul, N., Florescu, I., Welden, A.R., Michalczewski, F., 2012. Modelling of forest stand dynamics using Markov chains. Environ. Model. Softw. 31, 64–75. https://doi.org/10.1016/j.envsoft.2011.12.004.

Thom, D., Seidl, R., Steyrer, G., Krehan, H., Formayer, H., 2013. Slow and fast drivers of the natural disturbance regime in Central European forest ecosystems. For. Ecol. Manage. 307, 293–302. https://doi.org/10.1016/j.foreco.2013.07.017.

Usher, M.B., 1969. A matrix model for forest management. Biometrics 25, 309–315. https://doi.org/10.2307/2528791.

Wickham, H., 2016. In: ggplot2: Elegant Graphics for Data Analysis. Springer International Publishing, New York. https://doi.org/10.1007/978-3-319-24277-4.

Wickham, H., 2019. Advanced R, 2nd ed. Chapman and Hall/CRC, Boca Raton.