Description and evaluation of the process-based forest model 4C v2.2 at four European forest sites

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Abstract. The process-based model 4C (FORESEE) has been developed over the past twenty years to study climate impacts on forests and is now freely available as an open-source tool. The objective of this paper is to provide a comprehensive description of this 4C version (v2.2) for scientific users of the model and to present an evaluation of 4C at four different forest sites across Europe. The evaluation focused on forest growth as well as, carbon (net ecosystem exchange, gross primary production), water (actual evapotranspiration, soil water content) and heat fluxes (soil temperature) using data from the PROFOUND database. We applied different evaluation metrics and compared the daily, monthly and annual variability of observed and simulated values. The ability to reproduce forest growth (stem diameter and biomass) differs from site to site and is best for a pine stand in Germany (“Peitz”, ME=0.98). 4C is able to reproduce soil temperature at different depths in Sorø and Hyytiälä with good accuracy (for all soil depths ME>0.8). The dynamics in simulating carbon and water fluxes are well captured on daily and monthly time scales (0.51<ME<0.983) but less so on annual time scale (ME<0). This model-data mismatch is possibly due to accumulation of errors because of processes that are missing or represented in a very general way in 4C but not with enough specific detail to cover strong, site specific dependencies such as ground vegetation growth. These processes need to be further elaborated to improve the projections of climate change on forests. We conclude that, despite shortcomings, 4C is widely applicable and reliable and is therefore ready to be released to the scientific community to use and further develop the model.

1 Introduction

Forest modelling has a long tradition in forest science and ecology, and is of central importance to understanding forest functioning and dynamics, but also for planning forest management and assessing forest product and service provisioning (Pretzsch, 2010). While climate change impact studies often emphasize long-term forest development, nowadays changes in environmental conditions have provoked a wider interest in the sustainability of various forest ecosystem services. There is also an increasing demand for estimating the sensitivity of forests to disturbance events as well as elucidating forest management options to mitigate climate change. These challenges require accounting for a high degree of complexity in forest ecosystems and thus demand forest models that can capture numerous interactions between air, soil and vegetation. For this reason, stand-scale process-based forest models (PBM) have been developed over the past 30 years that try to explain forest growth and development based on ecological understanding (Fontes et al., 2010; Landsberg, 2003; Mäkelä et al., 2000a; Medlyn et al., 2011). These models can be stand-based or individual-based and many of these models are used to study climate change impacts on forest productivity (see review by Reyer (2015)) or matter dynamics (water, carbon, nitrogen) (Cameron et al., 2013; Constable and Friend, 2000; Kramer et al., 2002), or the effects of forest management (Fontes et al., 2010; Porte and Bartelink, 2002; Pretzsch et al., 2008). These models are typically operating at stand scale and yet include similar process detail as Land-Surface models (Fisher et al., 2015; Naudts et al., 2015) that are typically applied to larger scales. They can also be applied to larger spatial scales but typically without considering interactions among landscape patches, as opposed to landscape models that place particular emphasis on the processes connecting different patches of forests such as dispersal or propagation of disturbances (Seidl et al., 2012). One such model is the forest model "FORESt Ecosystems in a changing Environment", in short 'FORESEE' and even shorter '4C', developed at the Potsdam Institute for Climate Impact Research in Germany.

The development of the forest model 4C started in the 1990s (Bugmann et al., 1997), at a time when environmental change, and especially climate change, had been hypothesized to provoke major changes in forest ecosystems that could not be covered by traditional, statistical forest models. Therefore, the main idea was to develop a forest model that describes individual forest stands and has the following characteristics:

- represents our knowledge of the main mechanisms of forest functioning such as photosynthesis, allocation, water relations etc. (i.e. is process-based)
- is responsive to changing environmental conditions
- is generic in its structure
- is applicable to forests world-wide

The model's objectives include scenario analyses regarding (i) Impacts of climate change and other changing environmental conditions (e.g., CO_2, N-deposition) on forest growth and matter balance (carbon, water, nitrogen), (ii) Effects of forest management on forest ecosystem functioning, and (iii) Impacts of biotic disturbances on forest growth.

The concept underlying 4C and its salient features were outlined by Bugmann et al. (1997) and individual processes of the model by Lasch et al. (2002), Lasch et al. (2005) and Reyer et al. (2010). However, a full description of the model has never been officially published and since the model version 4Cv2.2 has been recently published as an open source tool in a Gitlab repository (https://gitlab.pik-potsdam.de/foresee/4C), we present here the model in more detail and illustrate its main features with model runs compared to observed data using the PROFOUND database (Reyer et al. (2020), Reyer et al. (2019)). We use the PROFOUND database for two main reasons: 1) The PROFOUND Database provides a wide range of data for evaluation and allows us to compare model simulations against stand growth as well as, carbon, water and heat flux data. 2) The database is currently also the basis for a forest model intercomparison within the framework of the Intersectoral Model Intercomparison Project (https://www.isimip.org/) and hence not only 4C will be evaluated at these sites but also a range of other models.

Therefore, the main objectives of this paper are:

(1) To provide a comprehensive description of the structure and the processes of the recently open-sourced version 2.2 of 4C (Lasch-Born et al., 2019)

(2) To evaluate the model's performance in reproducing growth and carbon and water fluxes as well as soil temperature and water content for typical European forest stands with data of the PROFOUND database

(3) To discuss the general applicability of the model and to highlight potential future improvements for scientific users of the open-source version of the model.

This paper and its accompanying detailed model description and Gitlab repository targets scientists that are interested in applying and developing complex forest stand models without necessarily wanting to start building the model from scratch but building on an established model that has been applied widely and can be adjusted to their needs. Therefore, besides the detailed model description and evaluation, we also provide hints on how to best apply and use the model throughout the text.

2 Methods

2.1 Model 4C

In the following, we briefly present the main features of 4Cv2.2. More details on all processes, state variables and parameterization are given in an extensive model description (Lasch-Born et al., 2018) and also on the model's website: http://www.pik-potsdam.de/4c/. Version 2.2 differs from its predecessors by a variety of model extensions and revisions. Amongst others, we enlarged the number of species and species parameters, included new management methods (e.g. short rotation coppice), revised the calculation of the effect of nitrogen availability on growth and implemented the effects of biotic disturbances on stand dynamics.

2.1.1 Overview

4C describes tree species composition, forest growth and structure as well as the whole carbon, water, and nitrogen balance of a forest stand on an area basis. It can be applied for patches of various sizes (varying from 100 m² to several hectares) and mono-and mixed-species forests. The model mechanistically describes forest responses to climate, nitrogen, and CO_2, and accounts for realistic representation of forest management (Bugmann et al., 1997; Lasch et al., 2005). A forest stand is represented by a number of tree cohorts, each of which contains a specific number of trees. All trees within a cohort share the same characteristics which are species, age, tree dimensions (height, height of crown base (or bole height), and diameter at breast height), biomass differentiated into various compartments (foliage, fine roots, sapwood, and heartwood) and stage of phenological development. This allows simulating a representative tree of each cohort instead of each tree of the stand. The model is distance independent and trees within a cohort are horizontally evenly distributed and their position unknown. There are no differences in the growth behaviour of the trees of a cohort and there is no competition between the trees within a cohort. In contrast, the tree cohorts compete for light, water and nutrients. Their relative success in this competition determines their performance in terms of growth and mortality. Establishment of new cohorts is simulated with a regeneration module. The vertical structure of crown space and rooting zone is represented by a resolution into vertical layers. The model requires the following input data: daily meteorological data, a detailed description of the physical and chemical characteristics of each soil layer and an initialization of cohort properties (see section 2.1.4).

Different time scales are used for the sub-models, ranging from a daily time step for e.g. soil water dynamics, phenology, to a weekly time step for photosynthesis (based on weekly averaged daily climate data), and to an annual time step for tree carbon allocation, dimensional growth and mortality (Fig. 1).

Physiologically-based as well as empirical functions were selected and implemented in 4C to provide an understanding of forest functioning that is as general but also as simple as possible (law of parsimony (Coelho et al., 2019)). As an example, the empirical relationship between foliage mass and height used in the model is described with one single function that uses only three species-specific parameters (see Sect. 2.1.3 Eq. (13)). This function was selected after analysing the general applicability across species as well as simple species-specific parameter estimation. Another example is the reduction of the number of parameters in the soil temperature model of 4C. Analyses showed that it is sufficient to use the air temperature of the last three days for the calculation of the surface temperature of the ground and to determine the corresponding three parameters (Suckow, 1985). It should also be noticed that the temporal resolutions of process descriptions is selected specifically for medium- and long-term analyses (from one year up to several hundred years). Therefore, a coarser resolution is preferred for processes such as allocation that may vary at short time scales but still obey general rules on the longer term.

For several key processes, 4C provides alternative descriptions to enable an uncertainty analysis across different model assumptions or for selecting processes at different levels of detail depending on data availability for parametrization or stand initialization. For example, evapotranspiration can be calculated using approaches by Turc and Ivanov (Dyck and Peschke, 1995; DVWK, 1996), Penman-Monteith (Monteith and Unsworth, 1990), or Priestley-Taylor (Priestley and Taylor, 1972). Each of these process descriptions is suited for different applications. The Turc-Ivanov procedure is a simple estimate which requires the least input data whereas Penman-Monteith uses a full range of meteorological variables and is based on physical knowledge which allows for more precise estimates of evapotranspiration (Kingston et al., 2009). Hence 4C is not only a forest model but a forest modelling framework (for details see Lasch-Born et al. (2018)).

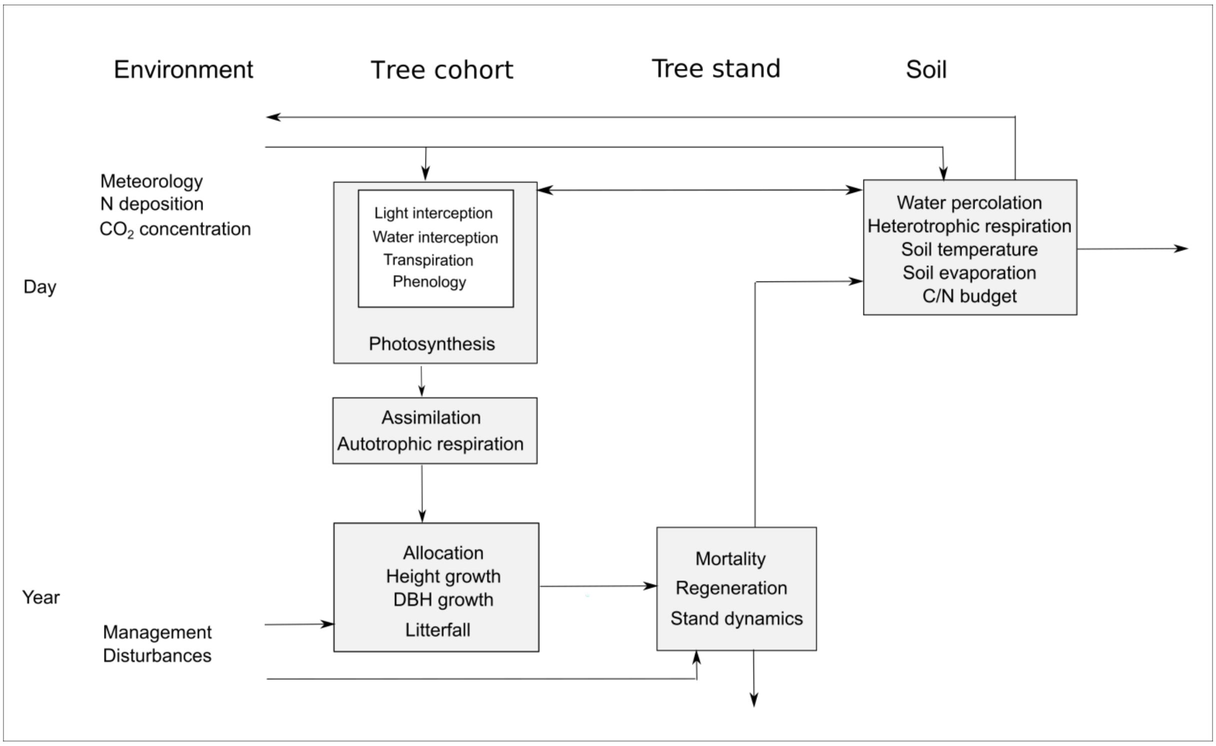

Figure 1. Structural scheme of the model 4C. The individual processes are listed according to the associated model component (horizontally) and their temporal resolution (vertically), the arrows describe information and material fluxes, the boxes assemble processes on the same temporal or spatial level.

2.1.2 Tree species parameterization

4C is parameterized for the most common European tree species: Common beech (*Fagus sylvatica* L.), Norway spruce (*Picea abies* L. Karst.), Scots pine (*Pinus sylvestris* L.), oaks (*Quercus robur* L., and *Quercus petraea* Liebl.), and birch (*Betula pendula* Roth). In addition, parameters for some species that are considered favourable under expected environmental changes or that are used for short-rotation coppices have also been tested and are readily applicable. The considered species include Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), Black locust (*Robinia pseudoacacia* L.), Aleppo pine (*Pinus halepensis* Mill.), eucalypts (*Eucalyptus globulus Labill.* and *Eucalyptus grandis W. Hill ex Maiden)* and poplars (*Populus tremula* (L.), *P. tremuloides* (Michx.)). Moreover, parameter sets for Ponderosa pine (*Pinus ponderosa* Dougl.) and Lodgepole pine (*Pinus contorta* Dougl.) exist but have not been properly tested. The oak, eucalypt and poplar parameters are derived from investigations of two species of the same genus each and are assumed to be valid for both. Besides these tree species, 4C is also parameterized for the hemiparasitic plant Mistletoe (*Viscum album* subsp. a*ustriacum*) and a generic grassy ground vegetation based on properties of *Calamagrostis arundinacea*. For each species, there is a maximum of 95 parameters which are needed to cover all processes available in the 4C modelling framework (see Sect. 2.1.1). Depending on which processes (e.g. which of the evapotranspiration sub-models) are finally included in a simulation, the minimum set of required parameters is 40. Not all parameters differ across species yet, but can be potentially varied further if relevant scientific evidence becomes available. The values and descriptions of the parameters are available in Lasch-Born et al. (2018).

The philosophy of 4C is to rely on processes as close as possible to the underlying principles of forest growth, demography, carbon and water cycling, heat transport etc.. Covering the most important of such processes, one parameter set for each species can be chosen that reproduces species' growth, water and carbon cycling under a wide range of environmental constraints and hence can be kept fix over time and space without need for calibration. Therefore, the values of the 4C parameters were derived from the scientific literature, by expert knowledge or from other published models. If a variety of values were found in this way, the value set for 4C was determined detailed testing and sensitivity analyses (not published). Therefore, re-calibration of the species-specific parameters is not necessary when setting up the model for a new site but is of course possible if data are available and a recalibration is required to achieve the aims of the study.

In recent years, more and more evidence has accumulated that different physiological parameters have been determined in different environments (Kattge et al., 2020), or are dependent on stand density or site fertility (e.g. (Berninger et al., 2005)). To address these issues of parameter uncertainty, we have tested calibrating 4C in systematic Bayesian calibration studies (van Oijen et al., 2013; Reyer et al., 2016). The main goal of these studies was to analyse effects of parameter uncertainty on simulated net primary production (NPP) and forest growth. Reyer et al. (2016) used uniform priors for 42 parameters varying by +/-25 and 50% around their standard value and data from different Scots pine stands throughout Europe to calibrate 4C. The different calibrations showed that even though the output uncertainty induced by the parameter variations is large when projecting climate impacts on NPP, Bayesian calibration in the historical reduced those uncertainties. Most importantly, these tests showed that the direction of NPP change is mostly consistent between the simulations using the uncalibrated, standard parameter setting of 4C and the majority of the simulations including parameter uncertainty. Following a similar simulation set-up but examining results in a multi-model context, 4C was found to be the most plausible out of six established forest models (van Oijen et al., 2013).

2.1.3 Main processes and sub-models

Light competition

The cohorts compete for light and the fraction of photosynthetically active radiation absorbed by each cohort is calculated based on the Lambert-Beer law (Haxeltine and Prentice, 1996b; Monsi and Saeki, 2005).

The absorbed photosynthetically active radiation I_{PAR} is the fraction of global radiation R_g, which is not reflected by the albedo α_{refl}

$$I_{par} = \alpha_{refl}\ \eta_R\ R_g \tag{1}$$

where η_R is a factor which converts the incident radiation from J cm^{-2} to mol m^{-2} under the assumption that only 50 % of incident radiation are photosynthetically active. The share of any cohort in the total stand's net photosynthetic assimilation of carbon is proportional to its share of the absorbed photosynthetically active radiation I_{PAR}. The total fraction f^c_{tot} of I_{PAR} absorbed by each cohort c is calculated each time stand phenology changes, based on the Lambert-Beer law. There are four different models to calculate light transmission and absorption through the canopy, abbreviated by LM1, LM2, LM3 and LM4 in Lasch-Born et al. (2018). Whereas LM1 is based on the classical gap model approach that each tree covers the whole patch with its canopy, this simplistic view is refined in LM2 by attributing each cohort/tree c a specific projected crown coverage area a^c_{cr} depending on its d_{bh}. LM2 and LM3 differ in the way the light is transmitted through the canopy and LM4 additionally introduces an average growing season sun inclination angle β.

Every time phenology changes within the stand, e.g., a species has its bud burst or leaves are colouring, the light transmission through the canopy and accordingly light absorption changes. First, the light routines of the 4C model calculate the leaf area for each cohort c=1,...,n_c and each canopy layer j=0,...,n_l ($l_{a,c}(j)$), respectively, based on the leaf biomass M_f available per year and cohort, total height and height of crown base. This is achieved using a leaf area – leaf dry mass relationship. Because this species specific leaf area (SLA) varies within the canopy from sun to shade leaves, an average SLA (s^c_{av}) is calculated per cohort c depending on the average relative light regime in the cohort's canopy of the previous year

$$s^c_{av} = s^c_{min} + s^c_a \left(1 - \frac{i_c(n_l) + i_c(1)}{2} \right) \tag{2}$$

where s^c_{min} denotes the minimal SLA per cohort c, as it is usually found in sun leaves at the top of the canopy and s^c_a stands for the slope with which s^c_{av} rises according to the average light regime. The calculation of the relative light intensity $i_c(j)$ available in layer j for cohort c depends on the light model and is described below. The s^c_{av} rises with increasing depth of the cohort's canopy. The s^c_a can be approximated when the SLA of shade leaves (s^c_{max}) and the SLA of sun leaves s^c_{min} are known by

$$s^c_{max} = s^c_{min} + 0.5\ s^c_{av} \tag{3}$$

It has to be noted, however, that the average light regime as calculated in Eq. (3) is higher than the relative light in the middle of the canopy because of the concave nature of the light extinction curve and is also usually not 0.5.

All approaches mentioned above calculate the absorbed photosynthetically active radiation for each cohort in each layer of the canopy between height and bole height of the trees, but differ in the way light is transmitted through the canopy and in the consideration of sun inclination (see Lasch-Born et al. (2018)). The daily total radiation absorbed by the canopy is mainly used for calculating photosynthesis and potential evapotranspiration.

Phenology

For deciduous tree species, 4C models bud burst to determine the start of the vegetation period. Bud burst is calculated according to three different approaches driven by temperature and photoperiod (day length) as described by Schaber (2002) and Schaber and Badeck (2003). The most frequently used approach is the promotor-inhibitor-model (PIM) that is based on simple interactions between inhibitory and promotory agents that are assumed to control the developmental status of a plant. The abundance or concentration of certain enzymes in cells is determined by the rates of synthesis and breakdown. Control of these processes is subject to a lot of research; however, it is known that temperature and photoperiod play a prominent role. Temperature, for instance, can act through pure physical mechanisms like its influence on viscosity and diffusion. Moreover, synthesis of proteins usually has activation energy or temperature and an optimal temperature beyond that synthesis rates decrease again (Vegis, 1973; Johnson and Thornley, 1985). Photoperiod has been observed to be the driving force of a biochemical trigger acting through the photochromic system (Wareing, 1956; Perry, 1971; Nitsch, 1957; Heide, 1993b, a). From these simple but basic principles a model for the abundance or concentration of an inhibitory compound I_{phen} and a promotory compound P_{phen} can be formulated as a system of two simple coupled difference equations

$$\begin{aligned} \Delta I_{phen} &= p_1\ f_1(T)\ g_1(d_l) - p_2\ f_2(T)\ g_2(d_l)\ I_{phen} \\ \Delta P_{phen} &= p_3\ f_3(T)\ g_3(d_l)\ (1 - I_{phen}) - p_4\ f_4(T)\ g_4(d_l)\ P_{phen} \end{aligned} \tag{4}$$

where p_i are scaling parameters and the f_i and g_i, $i = 1,..., 4$, are functions of air temperature T_a and photoperiod (day length) d_l, respectively. Temperature T_a and photoperiod d_l are themselves functions of time, in our case of the day of the year. Breakdown of the compounds P_{phen} and I_{phen}, indicated by the negative terms in Eq. (4), is assumed to be a first order reaction, whereas the synthesis terms, indicated by the positive terms in Eq. (4), are formulated as simple forcing terms. The synthesis term of the promotor P_{phen} is coupled to or rather damped by the presence of the inhibitor I_{phen}. P_{phen} and I_{phen} are normalized arbitrarily to vary between one and zero. For each species PIM was determined which model formulations best suited the observed dates of bud burst (BB) and corresponding course of temperature and day length. For more details see chapter 4.1 in Lasch-Born et al. (2018).

The second implemented and parameterized model is the Cannel and Smith model (CSM) that empirically describes the observation that increased chilling in winter decreases the required temperature sum for bud burst in spring. It was developed by Cannell and Smith (1983) and modified by Menzel (1997), see chapter 4.1.2 in Lasch-Born et al. (2018).

The also implemented temperature sum model (TSM) (Menzel, 1997; Wang, 1960; Kramer, 1994) simply integrates daily mean temperatures T_a above a certain threshold T_b starting from a defined date t_1 up to a fixed critical value T_{crit}.

The date of leaf fall is fixed. For coniferous tree species the length of the vegetation period is one year.

Production, allocation and growth

The annual course of net photosynthesis and net primary productivity is simulated for each cohort with a mechanistic formulation of net photosynthesis as a function of environmental influences (temperature, water and nitrogen availability, radiation, and CO_2). The approach for the photosynthesis is based on the mechanistic photosynthesis model of Farquhar et al. (1980) as simplified by Collatz et al. (1991) where the physiological capacity (maximal carboxylation rate) is calculated based on optimization theory (modified after Haxeltine and Prentice (1996b) and Haxeltine and Prentice (1996a)).

Based on this approach is used to calculate the daily net photosynthesis A_{dt} and the leaf maintenance respiration R_d of a tree. The model applied has the important feature that the resulting net photosynthesis is a linear function of the photosynthetically active radiation I_{PAR} (see Sect. 2.1.3). Given this linearity, it is not necessary to integrate photosynthesis explicitly across the canopy, but it is sufficient to calculate the total radiation absorbed by the canopy and then to calculate the total daily net photosynthesis A_{nd} as a function of the absorbed radiation $f(I_{PAR})$ that results for the whole canopy at once.

The total amount of optimum gross (nitrogen limited) assimilation per tree or cohort A_c is then obtained by

$$A_c = A_{sp} \cdot \frac{P_a}{1000} \cdot \frac{1}{c_{part}} \tag{5}$$

where P_a is patch size [m^2]; A_{sp} is the specific gross photosynthesis rate and c_{part} is the part of carbon in biomass and is used to convert A_{sp} from carbon to dry weight. The factor 1000 converts A_{sp} [$g\ C\ m^{-2}\ d^{-1}$] from g to kg. A_c thus is in [$kg\ DW\ m^{-2}\ d^{-1}$].

The rate A_{sp} is calculated from the (nitrogen limited) light use efficiency L_{UE} [$g\ C\ \mu mol^{-1}$], the daily incident photosynthetic radiation I_{PAR} [$mol\ m^{-2}$] and the fraction of the absorbed photosynthetically active radiation f^c_{tot} [-] per cohort.

$$A_{sp} = L_{UE} \cdot f^c_{tot} \cdot I_{PAR} \tag{6}$$

L_{UE} is derived from the optimal light use efficiency $L_{UE,opt}$ (Haxeltine and Prentice, 1996b) reduced by a reduction factor R^c_N which describes the influence of nitrogen availability which is calculated as a function of the C/N ratio of the soil, the ratio of the plant's nitrogen demand and availability and the species-specific photosynthesis response to nitrogen. (see chapter 3.5 in Lasch-Born et al. (2018):

$$L_{UE} = R_N^c \cdot L_{UE,opt} \tag{7}$$

Using the specific daily leaf respiration R_{ds} [g m^{-2} d^{-1}], calculated according to Haxeltine and Prentice (1996a), the nitrogen limited daytime photosynthesis A_{dt} [g C m^{-2}] is calculated by

$$A_{dt} = A_{sp} - \frac{d_l}{24} \cdot R_{ds} \tag{8}$$

with the daily length of photoperiod d_l.

This photosynthesis rate is related to the unstressed stomatal conductance of the tree through the CO_2 diffusion gradient between the atmosphere and intercellular air space and g^c is calculated according to Haxeltine and Prentice (1996a)

$$g^c = \max\left(g_{\min}, \frac{1.56 \cdot A_{dt}}{(1-\lambda) \cdot c_a \cdot c_{mass}} \right) \tag{9}$$

where the factor 1.56 accounts for the difference in the diffusion coefficients of CO_2 and water vapour, $\lambda = c_i/c_a = 0.7$ is the optimum ratio of ambient to intercellular CO_2 concentration, and g_{min} is the minimum conductance (e.g. due to cuticular transpiration). The division of A_{dt} by c_{mass} is required for the conversion of its unit from g C m^{-2} d^{-1} into mol CO_2 m^{-2} d^{-1}.

Summation over all cohorts yields the stomatal conductance of the canopy of the stand g_{tot}.

The realized net daily (water and nitrogen limited) assimilation rate A_{net} is then calculated by

$$A_{net} = I^c_{drps} \cdot (A_c - R_{dc}) \tag{10}$$

where I^c_{drps} is the water limitation of the photosynthesis and is calculated per cohort by the ratio of cohort water supply and cohort transpiration demand (see Chapter 4.2.3 in Lasch-Born et al. (2018)), A_c is the gross assimilation per patch (see Eq. (5)) and the daily leaf respiration rate R_{dc} per patch is defined by

$$R_{dc} = R_{ds} \cdot \frac{P_a}{1000} \cdot \frac{1}{c_{part}} \tag{11}$$

with the parameter c_{part} which gives the part of C in biomass.

Finally, the daily net primary production f_{NPP} is

$$f_{NPP} = A_{net} \cdot (1 - r_{co}) \tag{12}$$

where r_{co} is the (growth) respiration coefficient following the concept of constant annual respiration fraction as proposed by Landsberg and Waring (1997). The total daily NPP of the stand f_{NPP} is summarized over all trees of the cohort, over all cohorts of the forest stand and over all days/weeks of the year to an annual net primary production of the stand.

The nitrogen content in the tree results from constant species-specific C/N ratios separated for fine and coarse roots, twigs and branches, stem, and foliage. The C/N contents are used to calculate the nitrogen demand of the tree and interact with the soil, vegetation and atmosphere due to its influence on the mineralisation of the plant litter (see below).

The competition of cohorts for water and nutrients is modelled via absorption of water and nitrogen by the fine roots in proportion to the fine root mass of the individual cohorts in a specific soil layer. Elevated CO_2 affects photosynthesis by an increase of the internal partial pressure of CO_2 which increases light-use efficiency and gross assimilation and reduces stomatal conductance as well as the potential water demand for transpiration. Therefore, water-use efficiency is increased with increasing CO_2 (Haxeltine and Prentice, 1996a).

The total tree, cohort and stand respiration is calculated as a constant annual fraction of gross primary productivity (GPP) as proposed by Landsberg and Waring (1997). Therefore, the net primary production (NPP) is also a constant fraction of GPP (Waring et al., 1998).

The allocation of annual net primary productivity to different tree organs (sapwood, heartwood, foliage, and fine root biomass) and dimensional tree growth is modelled by combining the pipe model theory (Shinozaki et al., 1964), the functional balance hypothesis (Davidson, 1969), and ideas presented by Mäkelä (1990) to make the model sensitive to resource availability and varying demand with increasing dimensions. The detailed derivation of the allocation parameters are given in chapter 4.4 of Lasch-Born et al. (2018)

Height growth is coupled to the growth of the foliage mass and depends on the shading of the crown (Reyer et al., 2010) and based on this relationship for height H:

$$H = \frac{p_{hv1}}{p_{hv3} + \left(M_f\right)^{p_{hv2}}} \tag{13}$$

with the three parameters p_{hv1}, p_{hv2}, $p_{hv2,}$ and foliage mass M_f. The parameters were derived from a variety of datasets with available tree height and foliage mass.

The diameter is calculated annually after allocation of NPP and height growth using the sapwood and heartwood area and the length of sapwood pipes. For more details see Lasch-Born et al. (2018).

Mortality and senescence

Cohort mortality is described on an annual time scale and two kinds of mortality are considered. The so-called ‘age related’ mortality is based on tree life span and corresponds to the intrinsic mortality described by Botkin (1993). In addition, the reduction of the number of trees due to limitation of resources and resulting growth suppression is described as carbon-based stress mortality according to Keane et al. (1996). If a tree cohort is not able to reproduce foliage biomass losses within a year, this period counts as a stress year. Successive stress years increase the probability of mortality. Stress-related mortality is species-specific, since the sensitivity to stress years is directly related to the parametrized shade tolerance (see Lasch-Born et al. (2018)) of a tree species as well as the abundances of disturbances (see Sect. 2.1.3), see also Lasch-Born et al. (2018). Both types of mortality can be combined or applied separately. Additionally, tree mortality can be superimposed by prescribed mortality events originating from thinning or harvests (see also Sect. 2.1.3)

Annual senescence rates for the biomass compartments foliage, fine roots and sapwood of a cohort are species-specific and calculated from the corresponding fixed parameterized relative senescence rates. They deliver the litter input to the soil and the transformation of sapwood in heartwood.

Water balance

The following processes are considered for the calculation of the water balance: interception of precipitation, actual evapotranspiration, percolation and snowmelt. Snowmelt is estimated from the actual air temperature greater than a threshold temperature with a linear approach suggested by Koitzsch and Günther (1990). Intercepted water of the canopy as well as the ground vegetation is calculated depending on the leaf area and a species-specific interception capacity (Jansson, 1991). The potential evapotranspiration (PET) that is needed to define the evaporation demand of the forest stand is calculated by approaches of Turc and Ivanov from air temperature and global radiation or relative humidity, respectively (Dyck and Peschke, 1995; DVWK, 1996;

Lasch-Born et al., 2015). Further approaches (i.e. Penman-Monteith, Priestley-Taylor) can be selected and are described in more detail in Lasch-Born et al. (2018). The potential evapotranspiration limits the evaporation demand of intercepted and soil water as well as the transpiration of trees and ground vegetation. The actual water uptake of each cohort depends on its transpiration demand and the available water in the soil layers which is proportional to its relative share of fine roots in each soil layer. The potential canopy transpiration demand E_{trd} is calculated from the potential evapotranspiration E_{pot} reduced by the evaporation of intercepted water E_{int} and the unstressed stomatal conductance g_{tot} of the forest canopy (Haxeltine and Prentice, 1996a).

$$E_{trd}(t) = \left(E_{pot}(t) - E_{int}(t)\right) \cdot \alpha_m \cdot \left(1 - e^{-\frac{g_{tot}(t)}{g_{max}}}\right) \tag{14}$$

With the Priestley-Taylor coefficient α_m and the maximum stomatal conductance g_{max}. The unstressed stomatal conductance of the canopy gtot [mol m^{-2} d^{-1}] is calculated as the sum of the stomatal conductances of all trees of all cohorts. The stomatal conductance of a single tree in a cohort is calculated according to Haxeltine and Prentice (1996a) from the net daytime photosynthesis A_{dt} using Eq. (9).

Soil physics, carbon and nitrogen

The transport of heat and water in a multi-layered soil is explicitly calculated, as well as carbon and nitrogen dynamics based on the decomposition and mineralisation of organic matter (Grote and Suckow, 1998; Grote et al., 1998; Kartschall et al., 1990). The soil of a forest stand is divided into different layers with optional thickness defined based on the horizons of the soil profile. Each layer, the humus layer as well as the deeper mineral layers, is assumed to be homogeneous concerning its physical parameters. Water content (W_s – water content per layer, W_s^{FC} - field capacity) and soil temperature of each soil layer are estimated as functions of soil parameters, air temperature, and stand precipitation. A percolation model balances the soil water content of each layer with depth z and time step t:

$$\frac{d}{dt}\left(W_s(z,t) - W_s^{FC}(z)\right) = W_p(z,t) - W_{upt}(z,t) - W_{ev}(z,t) - \lambda_W(z) \cdot \left(W_s(z,t) - W_s^{FC}(z)\right)^2 \tag{15}$$

As input into the soil layer serves the percolating water W_p from the above layer respectively the net precipitation after canopy interception for the first layer. The output is estimated from the soil evaporation W_{ev}, the water uptake by roots W_{upt} and the outflow of gravitational water into the next layer, which is controlled by a soil texture depending percolation parameter λ_W (Glugla, 1969; Koitzsch, 1977).

Water content and soil temperature of each soil layer control the decomposition and mineralisation of organic matter. The carbon and nitrogen dynamics are driven by the litter input which is separated into five fractions for each species (stems, twigs and branches, foliage, fine roots, and coarse roots). The turnover of all litter fractions and of the soil organic matter compartment is described as a first order reaction (Grote and Suckow, 1998; Post et al., 2007). These processes are controlled by matter- and species-specific reaction coefficients and modified by soil moisture, temperature and pH value.

The amounts of nitrogen and carbon from litter (needle and foliage litter, twigs, branches, and stems) entering the soil are added to the N and C pools of the primary organic matter of the first layer. In the same way, the nitrogen and carbon content of dead fine and coarse roots of trees as well as ground vegetation is added to the primary organic matter -pools (C_{pom}, N_{pom}) of the respective soil layer z. The primary organic matter of all species types decomposes to a single humus pool (active organic matter; C_{aom}, N_{aom}) for all matter fractions i and species types j. Depending on the carbon and nitrogen content of the organic matter pools and the matter specific reaction coefficients (k_{pom}, k_{aom}), the carbon pools in the soil are estimated in a system of linked differential equations. Mineralised carbon from the active organic matter (heterotrophic respiration) goes back to the atmosphere as CO_2:

$$\frac{\partial}{\partial t} C_{pom}^{i,j}\left(z,t\right) = -k_{pom}^{i,j} C_{pom}^{i,j}\left(z,t\right) \tag{16}$$

$$\frac{\partial}{\partial t} C_{aom}\left(z,t\right) = \sum_{i,j} k_{syn}^{i,j} k_{pom}^{i,j} C_{pom}^{i,j}\left(z,t\right) - k_{aom} C_{aom}\left(z,t\right) \tag{17}$$

Accordingly, changes of nitrogen, separated into an ammonium N_{NH4} and a nitrate pool N_{NO3}, are considered by the following system of differential equations for each soil layer z:

$$\frac{\partial}{\partial t} N_{pom}^{i,j}\left(z,t\right) = -k_{pom}^{i,j} N_{pom}^{i,j}\left(z,t\right) \tag{18}$$

$$\frac{\partial}{\partial t} N_{aom}\left(z,t\right) = \sum_{i,j} k_{syn}^{*,i,j} k_{pom}^{i,j} N_{pom}^{i,j}\left(z,t\right) - k_{aom} N_{aom}\left(z,t\right) \tag{19}$$

$$\frac{\partial}{\partial t} N_{NH4}\left(z,t\right) = \sum_{i,j}\left(1 - k_{syn}^{*,i,j}\right) k_{pom}^{i,j} N_{pom}^{i,j}\left(z,t\right) + k_{aom} N_{aom}\left(z,t\right) - k_{nit} N_{NH4}\left(z,t\right) \tag{20}$$

$$\frac{\partial}{\partial t} N_{NO3}\left(z,t\right) = k_{nit} N_{NH4}\left(z,t\right) \tag{21}$$

The processes of carbon and nitrogen mineralisation as well as of nitrification depend on soil temperature, soil water content and the pH-value. Under the assumption, that k_{pom}, k_{aom}, and k_{nit} are the reaction coefficients at optimal temperature and moisture and at pH=7 the explicit effect of these environmental conditions can be expressed by reduction functions (Franko, 1990; Kartschall et al., 1990). The product of three reduction functions (R) depending on water, soil temperature, and pH value forms the overall reduction function which modifies the reaction coefficients. Exemplarily, the influence of soil temperature T_S(z,t) on mineralisation and nitrification (R_T) is described by van't Hoffs rule (van't Hoff, 1884):

$$R_T^i = \left(Q_{10}^i\right)^{0.1\left(T_S - T_{opt}^i\right)} \tag{22}$$

with i=mineralisation, nitrification and Q_{10} = 2.9 and the optimal temperature T_{opt} = 35°C in case of mineralisation as well as Q_{10} = 2.8 and T_{opt} = 30°C in case of nitrification. The set of differential equations, with the appropriate initial values, are solved by means of the Laplace transformation. For more details see Lasch-Born et al. (2018).

Management

4C simulates management of mono- and mixed-species forests automatically based on rules that are selected by the user. For this purpose, a variety of management routines are implemented to mimic thinning, harvesting and planting. Thinning is defined mainly by intensity, given by a fixed portion of biomass or stem number removed per year, and type such as thinning from above or below realized by means of stochastic approaches based on a Weibull distribution applied to the cohorts, similar to Lindner (2000); for more details see Lasch-Born et al. (2018).

Planting of seedlings includes the generation of a variety of seedling cohorts of a specific tree species differing in height and number of seedlings. Further seedling characteristics (e.g. biomass and height) are derived from empirical relationships available in the literature (Hauskeller-Bullerjahn, 1997; Schall, 1998; Van Hees, 1997) which are also used for seedling growth. If the height of a seedling cohort exceeds a threshold value, the entire cohort is then transformed into a regular tree cohort. 4C allows the management of short rotation coppices with Aspen and Black locust, see Lasch-Born et al. (2018).

Wood product model and socio-economic analysis

A wood product model (WPM) is integrated in 4C. It is based on a concept introduced by Karjalainen et al. (1994) and further developed by Eggers (2002). The WPM simulates carbon pools and fluxes in the forest sector. The parameters are based on aggregated values of the German timber market reports, available regional data and parameters according to Eggers (2002). The WPM allows the grading of the harvested and standing timber, the processing of the timber and allocation of timber to wood products, and includes the retention period of timber in the final products and later on in landfills. Finally, a socio economic analysis tool (SEA) (Fürstenau et al., 2007) calculates costs, revenues and subsidies of forest management and furthermore the net present value (NPV) and the liquidation value of the standing stock (Fig. 2), see Lasch-Born et al. (2018).

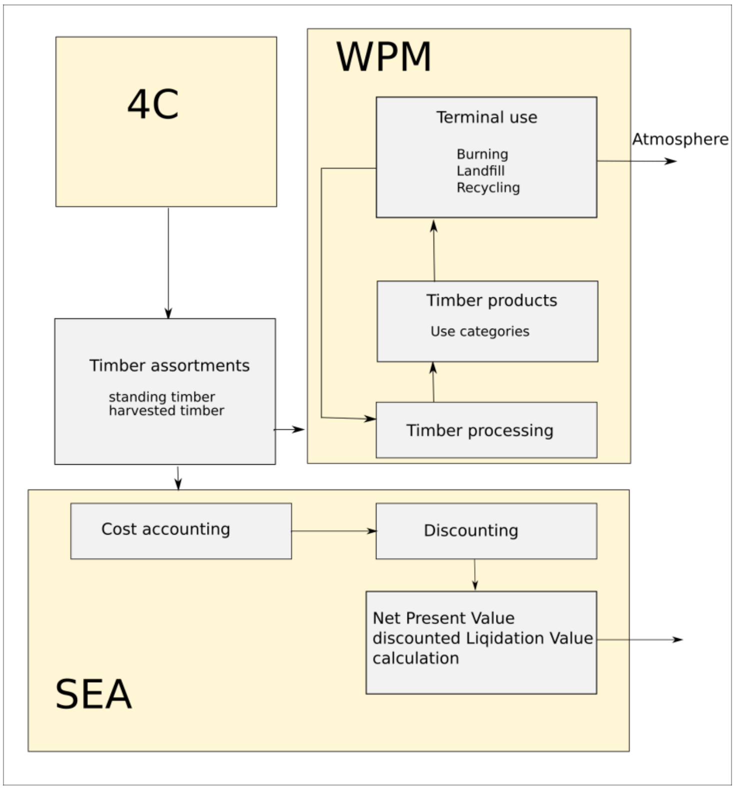

Figure 2. Model framework 4C (as presented in Fig. 1) coupled with the Wood Product Model (WPM) and Socio-economic Analysis-tool (SEA) (Eggers, 2002; Fürstenau et al., 2007).

Disturbances

The implementation of biotic disturbances follows a framework of modelling functional groups of biotic agents proposed by Dietze and Matthes (2014). In this framework, insects and pathogens are clustered upon their pathway of damaging the plant and abstracted on the level of functional groups (defoliators, xylem clogger, phloem feeder, root disturber, stem rot). In addition, we also implemented growth and impacts of the hemiparasitic European mistletoe (*Viscum album* L.) (Kollas et al., 2018). Currently, six pathways of damaging the plant have been implemented: a) foliage loss, b) reduction in water supply rate, c) carbon loss, d) fine root loss, e) increase in tree mortality, and f) combined increase of tree transpiration and carbon loss. The idea of this approach is to connect 4C with dynamic pest and pathogen models as well as disturbance scenarios. Information about the disturbance agents dynamics can stem from process-based models, empirical observations or scenarios. Thus, disturbances have to be prescribed externally as an input time series but their effects on the forest stand are modelled within 4C on a physiological basis. The prescription consists of the functional group of the disturbance, the disturbance year and the damage level (e.g. defoliators imply reductions of foliage biomass between 0% and 100%), which then influences the affected processes within 4C.

If 4C is applied in the disturbance mode, an additional carbon pool is initialized, representing non-structural carbon stored in the tree (so called NSC-pool). This pool is initialized during the tree initialization and its maximum size depends on the carbon stored within the three biomass compartments sapwood, branch/twigs wood, and coarse root wood (differentiated for coniferous and deciduous trees and based on data reported by Hoch et al. (2003)). By default, the simulation then starts with the NSC-pool being completely filled. The surplus of carbon for allocation into damaged tissues is only available at the end of the disturbance year, while refilling of the NSC-pool can continue for many years until the pool's maximum size is reached. For more details see Lasch-Born et al. (2018).

2.1.4 Input data needs

The model requires daily meteorological data (temperature, precipitation, relative humidity, air pressure, wind velocity and global radiation). Furthermore, annual CO_2 concentration and nitrogen deposition are necessary inputs.

The information about the forest can be provided at two levels of detail: At the stand level, average values of diameter at breast height (DBH), height, stem number or basal area, age and species type are needed. From these data, single trees are generated using distribution functions. These functions were derived from (Gerold, 1990) and are based on Weibull distributions. They allow determining DBH values from the average DBH as long as the basal area is reached. The heights corresponding to the derived diameters are calculated with various diameter-height functions from the literature. The generated single trees are grouped into cohorts according to their DBH. The cohorts together represent the average stand values (see chapter 2.4 in Lasch-Born et al. (2018)). At tree level, individual tree measurements (DBH, height, height of the crown base, species and age) are needed and used to aggregate cohort data. Generally, individual tree data are better suited for initializing 4C because the cohorts can be estimated more realistically from individual tree data but also the stand level initialisation yields realistic tree cohorts.

The description of the soil layers follows the soil horizons. At least the thickness and texture of the horizons are required as well as their carbon and nitrogen content. Further important variables are pH, bulk density, pore volume, field capacity, and wilting point. If the last three entries are missing, they can also be estimated via pedotransfer functions from texture (Russ and Riek, 2011; Wösten et al., 2001).

2.2 Previous model evaluations and applications

Since the first applications of 4C, tests, evaluations and model comparisons have been carried out for various forest stands and different processes within 4C (Table 1). The evaluations find 4C applicable to a wide range of environmental conditions and research questions but also highlight deficits. Using these previous evaluations in combination with the detailed results from the selected forest sites of this study, we will draw conclusions for further model development and improvement in the Discussion section.

The earlier applications of the model covered a wide range of research questions and issues. Most relevant objectives were (i) Carbon and water balance of forests under climate change, (ii) Analysis of adaptive management under climate change, (iii) Risks and benefits of climate change in forestry, (iv) Energy potentials from forestry and short rotation coppices, (v) Economic analysis of management units under climate change. A more detailed overview is given in the Supplement (Table S1).

Table 1 Overview of studies in which different species, processes and variables of 4C were evaluated (DBH- diameter at breast height, H height, N- stem number, AET-actual evapotranspiration, NPP- net primary production, NEE- net ecosystem exchange, TER-total ecosystem respiration, GPP-gross primary production)

Process/ variables	Validation data	Site	Species	Results	Publication & model version
Growth (DBH, H, stem volume, N)	Long-term permanent plot measurements; Evaluation using volume growth and survival graphs	Evo (Finland), Fabrikschleichach (Germany)	Scots pine, beech	Satisfactory results for volume growth in tree size classes; underestimation of height growth; underestimation of growth of smaller tree cohorts; overestimation of mortality of smaller tree cohorts;[2]	Mäkelä et al. (2000b)[1] 4Cv0.5
Soil water content, soil temperature	Daily measurements of soil temperature and soil water content in different layers	6 Level II site[3] in Brandenburg (Germany)	Scots pine	Good correspondence of simulated daily soil water content and soil temperature with measured data for four years;[2]	Suckow et al. (2001) 4Cv0.6
Management (DBH)	Long-term permanent plot measurements	Long-term management trials Chorin, Eberswalde	Scots pine, oak	Simulation of thinning preserved the diameter distribution of the residual stand and influenced the stand dynamics in the expected manner;[2]	Lasch et al. (2005) 4Cv0.99
Growth (stem volume, DBH, H, N), climate sensitivity, management	Long-term permanent plot measurements	Fabrikschleichach (Bavaria, Germany), Chorin (Brandenburg, Germany), Eberswalde (Brandenburg, Germany)	Beech, oak, Scots pine	Strong sensitivity of growth to the level of precipitation; sensitivity to drought larger for beech than for oak; simulated diameter development was slightly overestimated by the model, and height growth was slightly underestimated in most	Lindner et al. (2005)[1] 4Cv0.99

Process/ variables	Validation data	Site	Species	Results	Publication & model version
				management scenarios;[2]	
Soil respiration, litter, DBH growth, water balance, soil temperature	Soil water content, soil respiration, growth parameter, tree ring data	Level II sites[3] in Germany	Beech, oak, Scots pine, Norway spruce	Realistic simulation of water balance (correlation coefficient $0.19 < r < 0.9$) and soil temperature ($0.85 < r < 0.95$); leaf mass and leaf litter simulations were valid;	Badeck et al. (2007)[1] 4Cv0.99
Growth and soil processes	Stem biomass, foliage litter fall; soil water content and soil temperature	Level II sites[3] in Germany: Kienhorst, Solling	Scots pine, beech	Good correspondence for stem biomass; slight overestimation of foliage litter fall; good correspondence of simulated and observed soil temperature and soil water content in two depths (Kienhorst); deviation of simulated soil water content from observed data at the end of the dry year 2003 and in 2004;[2]	Lasch et al. (2007) 4Cv0.99
Carbon balance (stem C productivity, soil C)	Stand level inventory data, stem wood productivity derived from yields tables	Forest management unit in the province of Carinthia, southern Austria	Norway spruce	Realistically captured interactions between stand structure and forest floor C as represented in a local empirical model; simulated Norway spruce stem C productivity compared well to the observed values;[2]	Seidl et al. (2008)[1] 4Cv0.99
Management: thinning and conversion strategies	Experience from literature	Forest reserve Galgenberg (The Netherlands)	Scots pine	Effects of different thinning types (from above and from below) and thinning intensities on stand structural characteristics such as tree density, spatial point pattern and diameter and height differentiation, were consistent with reported effects in various Scots pine conversion stands;[2]	Kint et al. (2009) 4Cv0.99

Process/ variables	**Validation data**	**Site**	**Species**	**Results**	**Publication & model version**
Inter-specific competition in a mixed forest	Yield tables	Freienwalde (Germany) Speulderbos (The Netherlands)	Douglas fir, Beech	Model verification: the simulations of DBH yielded similar values and pattern to those displayed in the yield table; the simulated height growth was not always congruent with the yield table values;[2]	(Reyer et al., 2010) 4Cv1.0
Short rotation coppice	Woody biomass experimental data (yields) of SRC from literature	Eastern Germany	Aspen	Good correspondence of simulated yields with experimental data; [2]	Lasch et al. (2010) 4Cv1.0
Forest growth (stem biomass, DBH, H)	Long-term plot measurements	4 Beech stands in forest district Buchfahrt, Thuringia (Germany)	Beech	40 years of growth of the beech stands simulated very well; very good correlations between measured and simulated stem biomasses for a 50-year simulation (r=0.94);	Borys et al. (2013) 4Cv1.1
Height, DBH	Inventory data	12 stands in Austria, Belgium, Estonia and Finland	Scots pine	Good predictive accuracy (a likelihood value from Bayesian calibration approach) for mean tree height and DBH (before calibration);[2]	van Oijen et al. (2013)[1] 4Cv1.1
Water and carbon fluxes, soil	Daily flux measurements (GPP, NPP, TER, AET), soil temperature, soil water content	Flux-sites: Brasschaat (Belgium), Collelongo (Italy), Hesse (France), Hyytiälä (Finland), 5 Level-II sites² in Germany	Beech, Scots pine, Norway spruce	Carbon fluxes: low normalized errors and the Nash-Sutcliffe, model efficiency ME ($0.04<ME<0.78$) and the coefficient of determination are high ($0.73<R^2>0.84$); Hyytiälä: soil temperature follows the annual course of the measured values ($0.63<R^2<0.84$; $0.65<ME<0.74$), no systematic bias exists; the soil water content in the organic layer is mostly not correctly	Reyer et al. (2014) 4Cv1.1

Process/ variables	Validation data	Site	Species	Results	Publication & model version
				simulated;	
Transpiration, soil water, radial stem increment, root water uptake	Xylem sap flux, soil water content, tree ring measurements	Two pure pine stands and two mixed pine-oak stands in Brandenburg (Germany)	Scots pine, oak	For water uptake with low root resistances overestimation of the two year accumulated daily transpiration sum by 45%-85%. Better match of accumulated daily transpiration with high root resistance simulation (-17%). Weak to moderate match of simulated and observed soil water content ($0.35<R^2<0.51$); for water uptake with high root resistance moderate correspondence between observed and simulated tree ring growth indices (54.6%);	Gutsch et al. (2015b) 4Cv1.2
Diameter and height growth	Measurements of DBH and height	4 forest sites in Austria, Belgium, Finland, Estonia	Scots pine	4C simulated without calibration height and DBH with reasonably low NRSME (DBH: 0.06 – 1.0; H: 0.13-0.52);	(Reyer et al., 2016) 4Cv2.0
Carbon and water fluxes	Flux measurements (GPP, NPP, TER, AET)	Euroflux-site Zotino, Siberia (Russia)	Scots pine	Best results of the comparison for GPP; ecosystem respiration and actual evapotranspiration seems not so well captured; satisfactory agreement between simulated and measured data for annual values of GPP (ME=0.83), TER (ME=0.48), NEE (ME=0.75), and AET (ME=0.6) (May-September);	Suckow et al. (2016) 4Cv2.0
Carbon stock in stand and soil		Buchfahrt forest district in Thuringia (Germany), 4 beech stands	Beech	Successfully simulated past growth of four study sites independent of their thinning regime with 4C and WPM; validation on	Borys et al. (2016) 4Cv2.0

Process/ variables	Validation data	Site	Species	Results	Publication & model version
				the level of the forest district: overestimation of the absolute C-stock in the biomass in comparison to the estimates based on inventory (using biomass functions); development of forest stands and harvests at forest district level were depicted;[2]	
NPP	NPP from references	Representative forest stands in Germany	Scots pine, Norway spruce, oak, beech	Static reduced models of NPP were derived from 4C simulations; comparison with results from literature showed that these functions provide meaningful estimates of NPP;[2]	Gutsch et al. (2016) 4Cv2.0
Carbon fluxes	Flux measurements (NEE)	Flux-sites Sorø (Denmark), Vielsalm (Belgium) and Collelongo (Italy).	Beech	Overestimation of NEE in periods of very high carbon uptake and mostly underestimation in periods of carbon release ($0.39<R^2<0.53$); asynchrony between simulations and observations was large in spring and autumn, dropping to lower levels in full summer and full winter; often overestimation of the importance of high frequency variability (inter–monthly to inter-daily) in NEE;	Horemans et al. (2017)[1] 4Cv2.1
Basal area increment and effect of Mistletoe infection	Tree ring measurements	Stand in the forest district Berlin-Müggelsee (Germany)	Scots pine, infected with Mistletoe	Simulated basal area increment (BAI) corresponded well with BAI calculated from measured tree ring width ($R^2=0.61$); ring width indices of both non-infected trees and trees infected from 1994 on were found to run	Kollas et al. (2018) 4Cv2.2

Process/ variables	**Validation data**	**Site**	**Species**	**Results**	**Publication & model version**
				synchronously in relative but also in absolute values; good reproduction of the absolute level of growth, of the general growth trends and the pointer years;	
Timber harvest, stem increment	BWI[3] (forest inventory data Germany No. 3)	Germany	Scots pine, Norway spruce, oak, beech, birch, Douglas fir	Less than 15% deviation of simulated and observed species-specific stem increment for most tree species (spruce, pine, beech, other short-lived broadleaf species); strong underestimation of Douglas fir stem increment (-28%), strong overestimation of oak stem increment (27%); strong match between observed and simulated accumulated species-specific harvested timber volume (R^2>0.9);	Gutsch et al. (2018) 4Cv2.2

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[1] – model comparisons;

[2] – only qualitative evaluation, no quantification of model – data mismatch available;

[3] – ICP Forests intensive monitoring plots

2.3 In which ways is 4C different from other forest models?

Medlyn et al (2011) have developed a classification of models used to project climatic impacts on forest productivity which differentiates process-based stand models, terrestrial biogeochemical models, hybrid models, carbon accounting models, gap models and dynamic global vegetation models. This classification provides a starting point to explain in which ways 4C is different from other forest models: In a narrow sense, 4C can be classified as a ‘process-based stand model’ sharing key elements in terms of process-description (cf section 2.1) with other models from that class such as GOTILWA+ (Keenan et al., 2009) or 3D-CMCC (Marconi et al., 2017). However, 4C also contains elements of ‘gap models’ such as PICUS (Lexer and Hönninger, 2001) and FORCLIM (Bugmann, 1996) especially with regard to the canopy structure (see chapter 2.1. of the model description (Lasch-Born et al., 2018)) and the inclusion of nutrient and water stress through production modifiers (see chapter 4.2. of the model description (Lasch-Born et al., 2018)). Combining the strengths of different model types, is a key feature of 4C and while 4C represents forest complexity by incorporating the key processes of forest growth and dynamics in a mechanistic way, it is also simple enough to run without input data that are challenging to obtain for a larger number of forest stands such as detailed tree positions. Thus, it can be applied relatively easy to a larger number of forests stands as opposed to some of the other models in the same classes and hence 4C can potentially also be applied at larger spatial scales such as at regional or country-level. Moreover, as opposed to other process-based stand models, 4C operates key physiological processes on daily to weekly time scales instead of sub-daily resolution and is thus computationally efficient enough to be applied over longer time frames and can cover many climate and management scenarios. Within the Intersectoral Impact Model Intercomparison Project (ISIMIP - https://www.isimip.org/), 4C will be compared at the sites analysed here and further sites with other mechanistic climate-sensitive forest models. This will yield further insights about model structural uncertainties and how different models address these as well as how different the ensemble of forest models in Europe actually is.

2.4 Test sites, data and simulation setup

To evaluate the current version of 4C regarding long-term growth, as well as water and carbon fluxes we selected four sites Peitz (Germany), Solling (Germany), Sorø (Denmark), and Hyytiälä (Finland) representing the main central European tree species from the PROFOUND database that allows to test forest models against a wide range of observational data (Reyer et al. (2020), Reyer et al. (2019)). Additional data sources (Table 2, Supplement Table S3) for the sites were also used. For Peitz (Scots pine), Solling (Norway spruce) and Hyytiälä (Scots pine with some ingrowing Norway spruce) we evaluated forest growth by stem biomass (BM) and diameter at breast height (DBH) or geometric mean diameter (DG) measurements. These data were not available for Sorø from real measurements in sufficiently long time series. Furthermore, for Hyytiälä and Sorø (Common beech) flux data were available. We did not re-calibrate any parameter for the considered sites.

Table 2 Site and stand characteristics, data source: PROFOUND database (Alt. – altitude, T – annual temperature, P – annual precipitation sum, H –height, DBH – diameter at breast height

Site	**Species**	**Type**	**Lon. [°]**	**Lat. [°]**	**Alt. [m]**	**Meteorological conditions**	**Mean T [°C]**	**Mean P [mm]**	**Simulation time period**	**Soil type**	**Age**	**Mean H [m]**	**Mean DBH [cm]**	**Number of trees per ha**
Peitz (Germany)	*Pinus sylvestris*/ Scots pine	Long-term monitoring site	14.35	51.92	50	continental	9.3	554	1952-2010	Dystric Cambisol	53	7.4	9.1	3860
Solling (Germany)	*Picea abies*/ Norway spruce	Level II	9.57	51.77	504	maritime	6.8	1108	1967-2013	Cambisol (haplic)	85	23.9	30.2	595
Sorø (Denmark)	*Fagus sylvatica*/ Common beech	Euroflux	11.64	55.49	40	warm temperate and fully humid	8.3	848	1996-2012	Cambisol	77[1]	25.0[1]	38.0[1]	426[1]
Hyytiälä (Finland)	*Pinus sylvestris / Picea abies*	Euroflux	24.29	61.85	185	continental	4.4	604	1996-2014	Haplic Podsol	34	10.9	12.7	870

, [1] – source: derived from Horemans et al. (2017)

2.4.1 Climate, soil, stand, and observational data

Climate, stand, soil data, and observational data for model evaluation were available from the PROFOUND database (Reyer et al., 2019) In addition to the gap-filled half-hourly flux data from the PROFOUND database we used the monthly and annual aggregated data from FLUXNET (http://fluxnet.fluxdata.org/data/fluxnet2015-dataset/). We checked the half-hourly flux data and removed implausible data on a daily basis. Some additional data are used for the initialization of the soil profile for Hyytiälä which are based on Haataja and Vesala (1997).

2.4.2 Management

All sites were simulated considering a management which realizes the stem removal according to the inventory records. Therefore, the time of occurrence and the intensity of thinnings have been prescribed for the respective runs. The type of thinning (e.g. thinning from above) was also selected on the basis of available management information. Peitz was managed with moderate thinning from below with a target stem number and 11 management interventions during the whole simulation period. Solling, Sorø and Hyytiälä were managed with thinning from above with the target stem number and 13, 1 and 3 management interventions respectively during the simulation periods.

2.5 Evaluation metrics

To evaluate growth at Peitz, Solling and Hyytiälä, we selected the variables arithmetic mean diameter at breast height (DBH) or the geometric mean diameter (DG) and stem biomass (BM), which were analysed at an annual time step. The choice of different diameter-based variables (DBH, DG) results from the data availability in the PROFOUND-database. We applied regression analysis between observed and simulated values to determine the coefficient of determination R^2 and its significance (with SigmaPlot for Windows Version 11.0), and the model efficiency (ME) (Loague and Green, 1991):

$$ME = 1 - \frac{\sum_{i=1}^{N} \left(O_i - P_i\right)^2}{\sum_{i=1}^{N} \left(O_i - \bar{O}\right)^2} \qquad (23)$$

where O_i are observation values, P_i are simulation values, $\bar{O}$ is the mean of observation values, and N is the number of values. ME estimates the proportion of variance of the data explained by the 1:1 line and is an overall indication of goodness of fit (Mayer and Butler, 1993); a positive value indicates that the simulated values describe the trend in the measured data better than the mean of the observations (Medlyn et al., 2005a; Smith et al., 1997). Furthermore, we calculated the normalized root mean square error (Keenan et al., 2012):

$$NRMSE = \frac{\sqrt{\frac{1}{N} \sum_{i=1}^{N} \left(O_i - P_i\right)^2}}{\sigma_{obs}} \qquad (24)$$

where σ_{obs} represents the standard deviation of the observation values.

Where available, we evaluated carbon (net ecosystem exchange (NEE), gross primary production (GPP)) and water fluxes (actual evapotranspiration (AET)), soil temperature (ST) and soil water content (SWC) in different layers using the same statistical measures on daily and monthly (and annual) time scales.

We also analysed the inter-monthly and inter-annual variability of the carbon and water fluxes. At this end we applied the method described by Keenan et al. (2012) and Vetter et al. (2008) to the monthly and annual time series of observed and simulated GPP, NEE and AET. The inter-monthly variability (IMV) is calculated as follows:

$$IMV_{m,t}^{V} = V_{m,t} - \overline{V}_m \qquad (25)$$

$\bar{V}_{m,t}$ – monthly variable (GPP; NEE, AET) (sum) of month m and year t

$\bar{V}m$ - long-term monthly mean of the variable V for month m (m=1, 12)

The inter-annual variability (IAV) is calculated for the annual time series of the considered variables V:

$$IAV_t^V = V_t - \bar{V} \quad (26)$$

V_t - annual V of year t

$\bar{V}$ - long-term mean of V

The resulting monthly and annual 'normalized' times series (observed and simulated) were compared and subjected to statistical and graphical analyses.

3 Results

3.1 Forest growth

Based on the statistical measures, 4C shows the best performance in terms of ME of DG and BM for Peitz. For Solling the model performance is slightly lower than for Peitz but ME is still well above 0.7 (Table 3). For Hyytiälä, the model performance for DBH of pine (ME=0.557) is better than for spruce (ME=-6.06), however the performance measures for the stem biomass are low. Negative values of ME indicate that the residual variance (observed minus simulated) is greater than the variance of the observed values. For Hyytiälä, 4C overestimated DBH for both pine and spruce, overestimated stem biomass for pine (ME=-6.06) and underestimated stem biomass for spruce (ME=-9.56) (Fig. 5, Supplement Fig. S3).

NRMSE and ME show better results for DBH and DG than for stem biomass for Peitz and Hyytiälä (Table 3). The stem biomass simulations are less precise for all sites because biomass simulation depends on simulated height increment and NPP allocation to sapwood and the sapwood senescence rate. The large negative ME values for DBH (-6.064) and BM (-9.56) of spruce in Hyytiälä indicate a poor performance of the model. 4C underestimated the BM and overestimated DBH of spruce in this forest (Fig. 5, Supplement Fig. S3). The values of R^2 are very high for all variables ($0.933 < R^2 < 0.988$) and sites but are of limited value since they do not provide a comprehensive measure of model performance (Medlyn et al., 2005b).

Table 3 Statistics for the three sites (DG – geometric mean diameter, DBH – diameter at breast height, BM – stem biomass, number – number of values)

	Peitz		**Solling**		**Hyytiälä Pine**		**Hyytiälä Spruce**	
	DG	**BM**	**DBH**	**BM**	**DBH**	**BM**	**DBH**	**BM**
Number of years	13	13	19	18	16	16	16	16
NRMSE	0.119	0.382	0.465	0.338	0.644	1.049	2.574	3.146
ME	0.985	0.842	0.772	0.879	0.557	-6.064	-6.064	-9.560
R^2	0.988**	0.964**	0.984**	0.933**	0.983**	0.939**	0.972**	0.985**

** - p<0.001

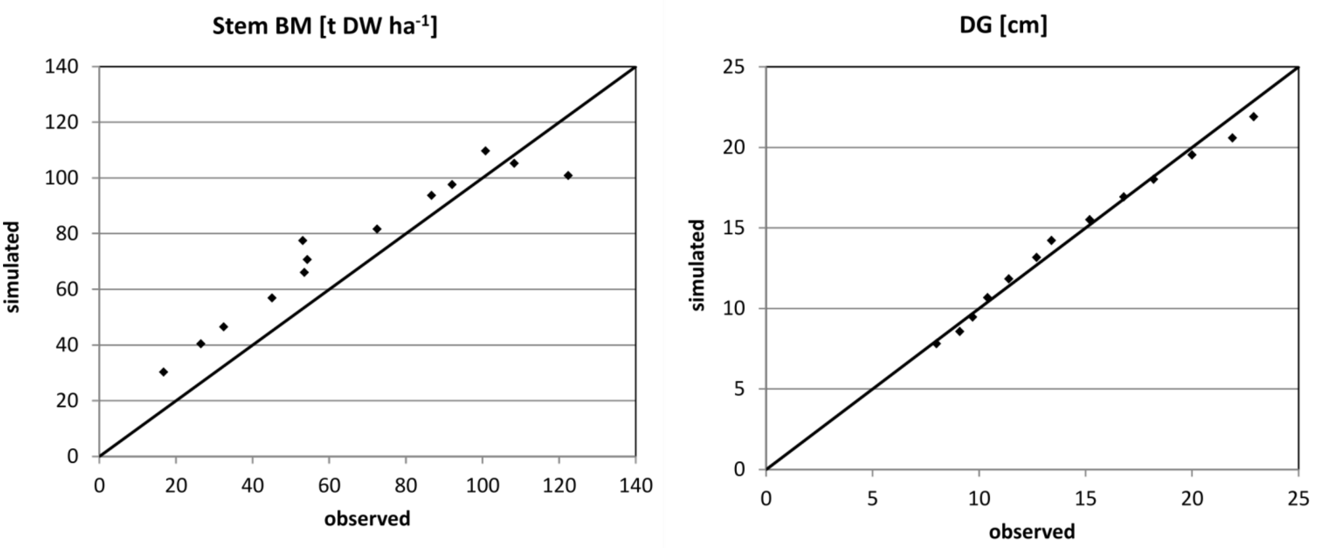

Figure 3. Simulated (sim) versus observed (obs) DG and stem biomass BM for Peitz. The plots show scatter plots with a 1:1 line.

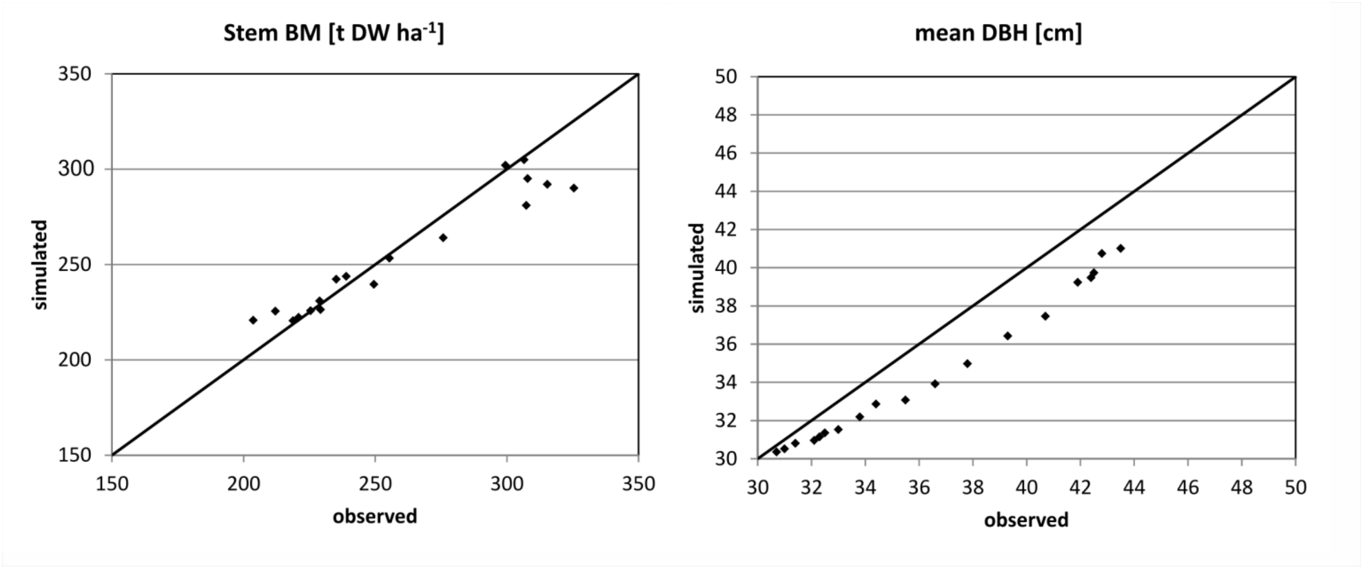

Figure 4. Simulated (sim) versus observed (obs) DBH and stem biomass BM for Solling. The plots show scatter plots with a 1:1 line.

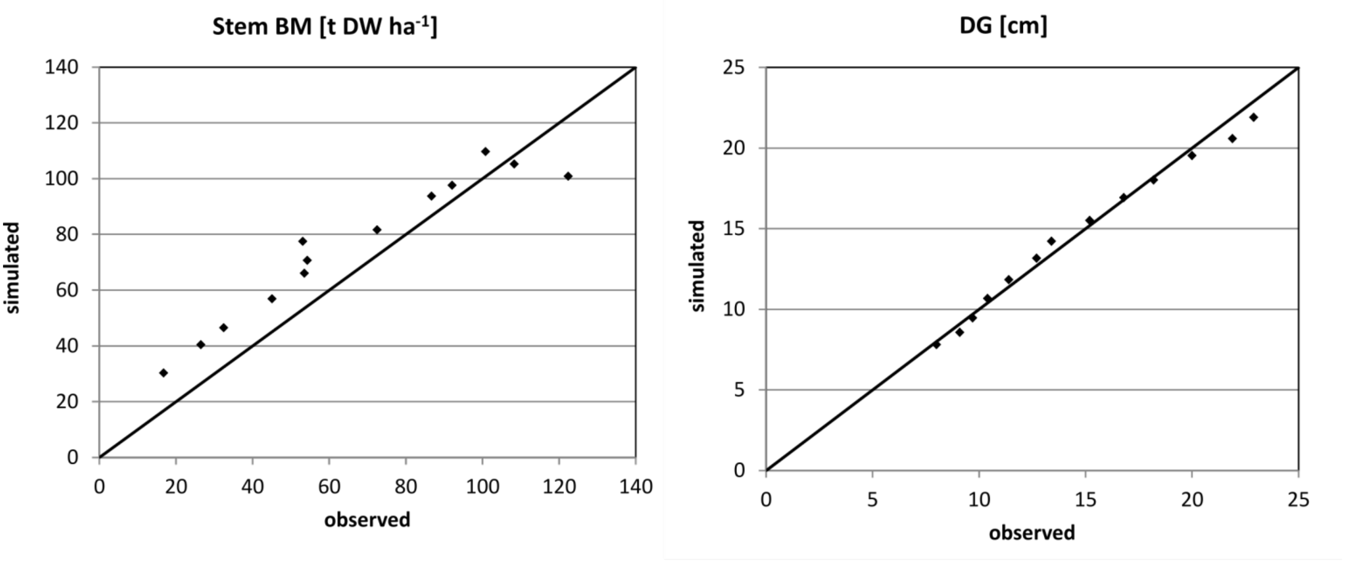

Figure 5. Simulated (sim) versus observed (obs) DBH and stem biomass BM for Hyytiälä (Pisy – pine, Piab – spruce). The plots show scatter plots with a 1:1 line.

3.2 Carbon and water fluxes

3.2.1 Evaluation over long-time scales at different time resolutions

The averages of the simulated annual fluxes in comparison with the observed averages show good correspondence for GPP for Sorø and Hyytiälä (Table 4). In Sorø, 4C overestimates the long-term average of GPP by 3.7 % and in Hyytiälä by 3.5 % (Table 4). NEE is clearly underestimated in Sorø (-148.3 ±130.2 [g C m^{-2} yr^{-1}] observed, -385.8±100.3 [g C m^{-2} yr^{-1}] simulated) and Hyytiälä (-213.65±53.8 [g C m^{-2} yr^{-1}] observed, -348.03±45.4 [g C m^{-2} yr^{-1}] simulated) on long-term average. The same is true for the AET in Sorø (431.3±41.2 [mm] observed, 313.8±22.6 [mm] simulated) but it is slightly overestimated for Hyytiälä (320.6±38. [mm] observed, 381.6±41.0 [mm] simulated). The R^2 (Sorø: $0.0001<R^2<0.437$, Hyytiälä: $-7.1188<R^2<-0.8066$) and ME (Sorø: $-8.453<ME<-0.902$, Hyytiälä: $0.0172<ME<0.3435$) indicate very low correspondence between observed and simulated annual values (Table 5).

Table 4 Annual long-term means (+/- standard deviation) of water and carbon fluxes in Sorø (1997-2012) and Hyytiälä (1996-2014)

Sorø	**Number of years**	**Observed average**	**Simulated average**
Annual AET [mm]	16	431.3±41.2	313.8±22.6
Annual NEE [g C m^{-2} yr^{-1}]	16	-148.3±130.2	-385.8±100.3
Annual GPP [g C m^{-2} yr^{-1}]	16	1892.5±132.4	1972.7±112.5.1
Hyytiälä			
Annual AET [mm]	11	320.6±38.1	381.6±41.0
Annual NEE [g C m^{-2} yr^{-1}]	17	-213.65±53.8	-348.03±45.4
Annual GPP [g C m^{-2} yr^{-1}]	17	1160.80±102.4	1209.2±157.8

For daily and monthly sums of fluxes, the evaluation metrics indicate a much higher agreement between simulated and observed values and the monthly results show an even better agreement with observations than the daily results (Table 5). The evaluation metrics for Hyytiälä are slightly better than for Sorø especially for AET (e.g. Hyytiälä: R^2=0.764, Sorø: R^2=0.734 for daily values) and GPP (Hyytiälä: R^2=0.814, Sorø: R^2=0.743 for daily values). For Sorø, 4C simulates days without any GPP, while GPP values greater than zero were observed. Daily AET is underestimated for days with a high observed AET (greater than 4 mm). For Hyytiälä, 4C clearly overestimates GPP and AET but also NEE for single days by more than 50% (Fig. 6, right). The intra-annual variability on a monthly scale in Sorø for the three variables (Fig. 6, left) shows that 4C underestimates GPP from January to April but during the vegetation period the GPP is clearly overestimated (and NEE underestimated). AET is underestimated throughout the year. In Hyytiälä, 4C overestimates the monthly GPP and underestimates the NEE during the vegetation period from May until July (Supplement Fig. S11). The variability of the monthly GPP from May until August is higher for the simulated values than for the observed values in Sorø (Supplement Fig. S7); for Hyytiälä, it is the other way around. The monthly AET is overestimated throughout the year in Hyytiälä.

Table 5 Evaluation metrics for daily, monthly and annual sums of AET, NEE and GPP for Sorø (1996-2012) and Hyytiälä (1996-2014)

	Daily				**Monthly**				**Annual**			
Sorø	Number of days	NRMSE	ME	R^2	Number of months	NRMSE	ME	R^2	**Number of years**	**NRMSE**	**ME**	**R^2**
AET	6058	0.591	0.651	0.734**	199	0.508	0.745	0.884**	16	2.977	-8.453	0.223 ^{nsN}
NEE	6058	0.691	0.522	0.601**	199	0.513	0.735	0.805**	16	2.403	-5.160	0.437**^{N}
GPP	6058	0.718	0.544	0.743**	199	0.489	0.760	0.877**	16	1.336	-0.902	0.001^{nsN}
Hyytiälä												
AET	3945	0.593	0.649	0.764**	136	0.408	0.833	0.906**	11	2.039	-3.5748	0.0328^{nsN}
NEE	6170	0.643	0.587	0.634**	220	0.514	0.734	0.855**	17	2.764	-7.1188	0.0172^{nsN}
GPP	5398	0.507	0.743	0.814**	188	0.452	0.794	0.877**	17	1.304	-0.8066	0.3435^{ns}

** - $p<0.001$

* - $p<0.05$

^{ns} - not significant

^{N} – normal distribution

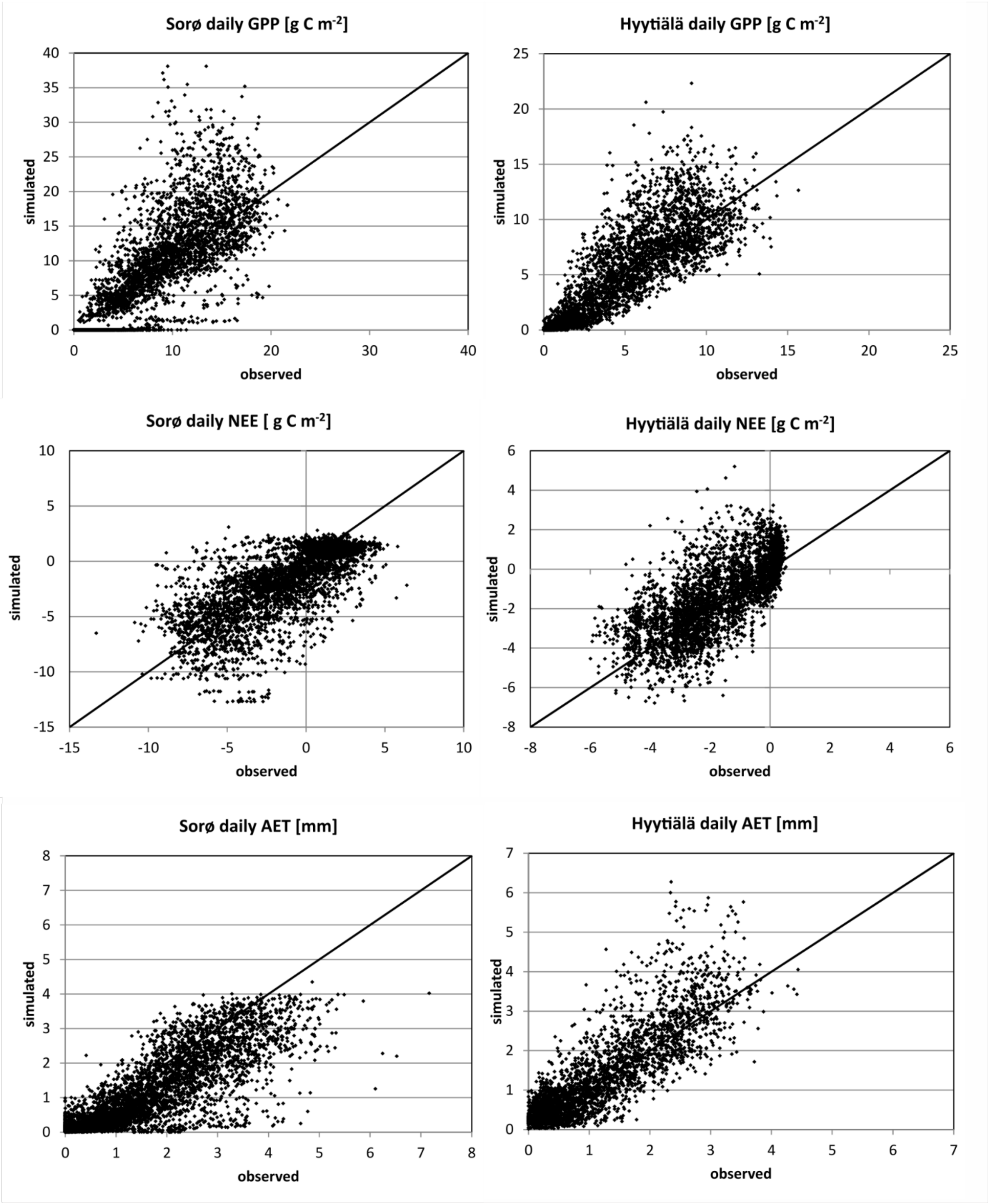

Figure 6. Simulated versus observed daily GPP, NEE and AET in Sorø (left) and Hyytiälä (right). The black line shows a 1:1 relationship.

3.2.2 Inter-monthly (IMV) and inter-annual variability (IAV)

The simulated and observed inter-annual variability is nearly in the same order of magnitude for both sites and for the three variables except for a few years for Sorø (1997: GPP, NEE) and Hyytiälä (1997-1998, GPP, 2006 AET) (Fig. 7). The signs of IAV were best captured for Hyytiälä with 82 % for GPP, 65 % for NEE and 70 % of the years for AET. In Sorø, the signs of IAV of GPP and NEE is not captured by the model, in most of the years the signs are opposite to observed IAV except for AET (63 %).

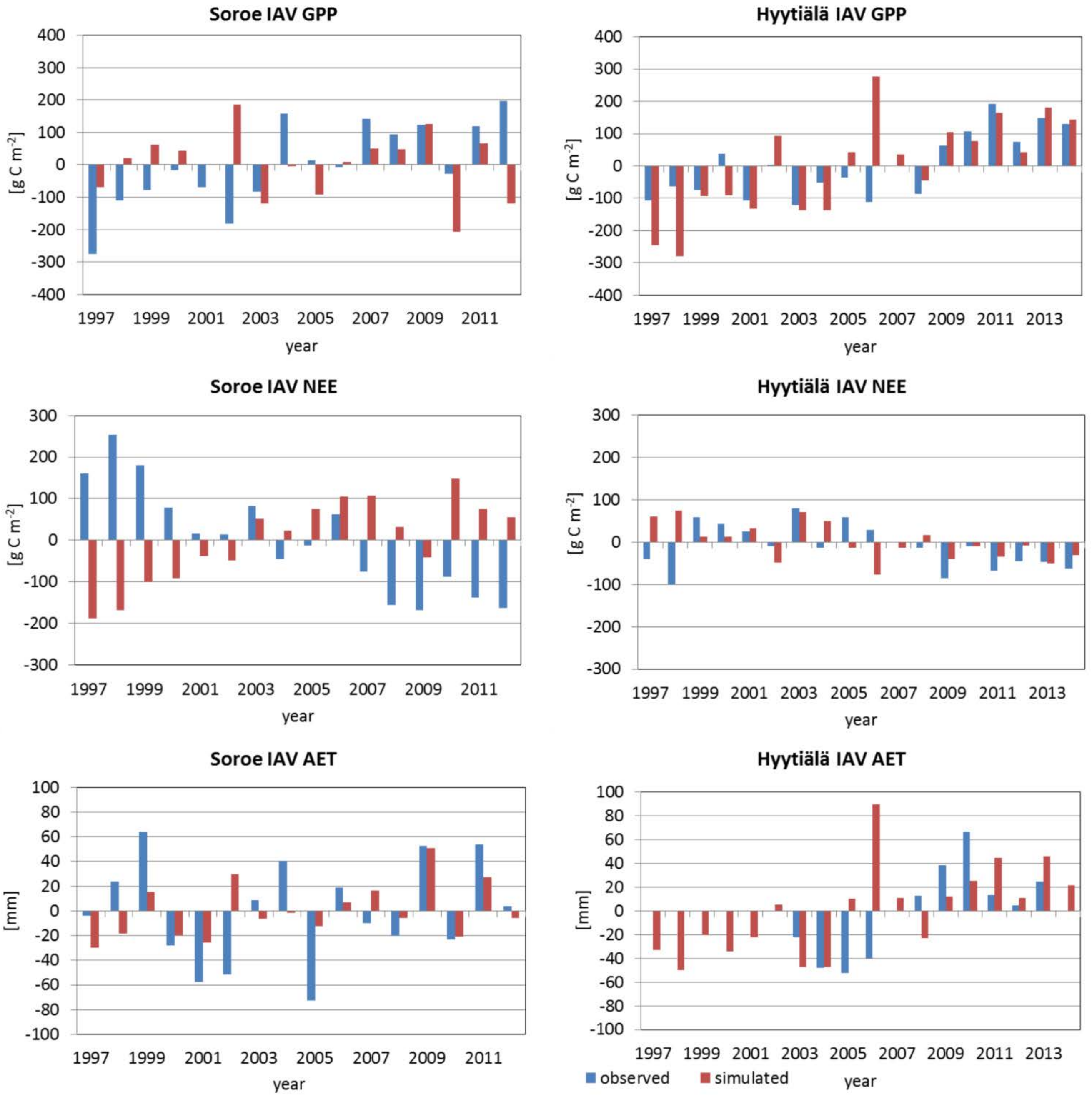

Figure 7. Inter-annual variability (IAV) of GPP, NEE and AET (sim - simulated and obs - observed) in Sorø (left) and Hyytiälä (right).

The analysis of inter-monthly variability with the normalized IMV data shows similar inter-quartile ranges for simulated and observed IMV but a clearly higher range of the IMV of simulated GPP and NEE for Sorø (Fig. 8, left). The IMV of AET differs in the interquartile ranges for simulated and observed data but the range is similar. The simulated variables for Hyytiälä show a lower variability especially for the NEE, and somewhat lower also for the AET. The simulated GPP has a smaller range of the inter-monthly variability than the observed GPP (Fig. 8, right).

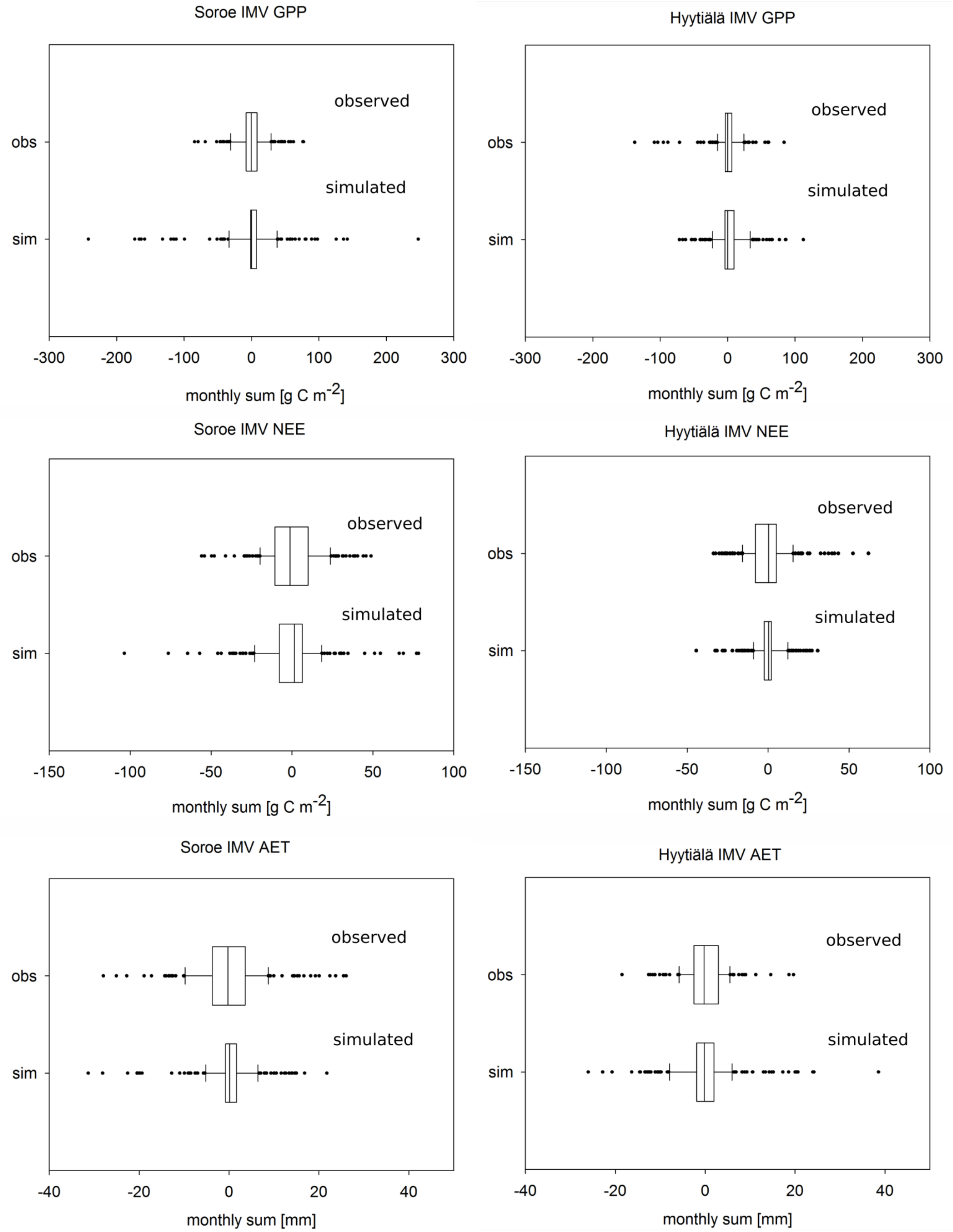

Figure 8. Distribution of the magnitude for the inter-monthly variability values (IMV) of observed (obs, in upper part of the graphic) and simulated (sim, in the lower part of the graphic) monthly sums of GPP, NEE and AET in Sorø (left) and Hyytiälä (right). The graphs show the median, the 25th and 75th percentile (box), the 10th and 90th percentile (whiskers) and the outliers (black dots).

3.3 Soil temperature and water content

The simulated soil temperature (ST) fits very well with the observed data in Sorø (Fig. 9, top) and Hyytiälä (Fig. 10, top) ($0.887<ME<0.974$). With increasing soil depth, the bias between simulated and observed values decreases, which is reflected in a decreasing NRMSE and an increasing ME and R^2 (Table 6). This applies for the daily and monthly statistics with the statistics on monthly level being slightly better than on daily level in most cases. In Hyytiälä, the simulated soil temperature in winter is lower than the observed temperature for the years 1996 until 2005 and consequently also the simulated depth of frost (Fig. 10, top; for more details see Supplement, Fig. S15).

In contrast, the simulations of soil water content (SWC) are less accurate for both sites. Comparing simulated and observed soil water content for all soil layers leads to very low R^2 values (monthly: $0.118 <R^2<0.288$, daily: $0.167<R^2<0.337$) and also to low ME (Table 6). In Sorø, the model underestimates the water content in the upper mineral layer especially in winter time (Fig. 9, bottom). During summer, the model simulates an exhaustion of the soil water content up to the wilting point for several days and more often than observed. Altogether, the model responds to precipitation faster than it is indicated by the measurements.

Table 6 Daily and monthly statistics of soil temperature (ST) and soil moisture (SWC), Sorø 1996-2012 and Hyytiälä (1996-2014)

Sorø	**Daily**				**Monthly**			
	Number of days	**NRMSE**	**ME**	**R^2**	**Number of months**	**NRMSE**	**ME**	**R^2**
ST 2 cm	6073	0.370	0.863	0.942**	199	0.169	0.887	0.959**
ST 10 cm	6073	0.283	0.920	0.951**	199	0.130	0.943	0.972**
SWC 8 cm	5645	1.175	-0.382	0.286**	183	0.261	-0.414	0.288**
Hyytiälä								
ST organic layer	6828	0.338	0.886	0.914**	225	0.259	0.974	0.948**
ST 5 cm	6828	0.346	0.880	0.913**	225	0.253	0.916	0.941**
ST 18 cm	6560	0.250	0.937	0.943**	216	0.178	0.954	0.959**
ST 50 cm	6560	0.263	0.931	0.943**	216	0.167	0947	0.958**
SWC organic layer	6438	0.978	0.043	0.167**	216	0.311	0.062	0.118**
SWC 5 cm	6438	1.196	-0.431	0.176**	216	0.328	-0.299	0.128**
SWC 18 cm	6309	0.861	0.259	0.337**	211	0.261	0.217	0.269**
SWC 50 cm	6438	0.983	0.034	0.129**	213	0.303	-0.192	0.261**

** - P<0.001

ns - not significant

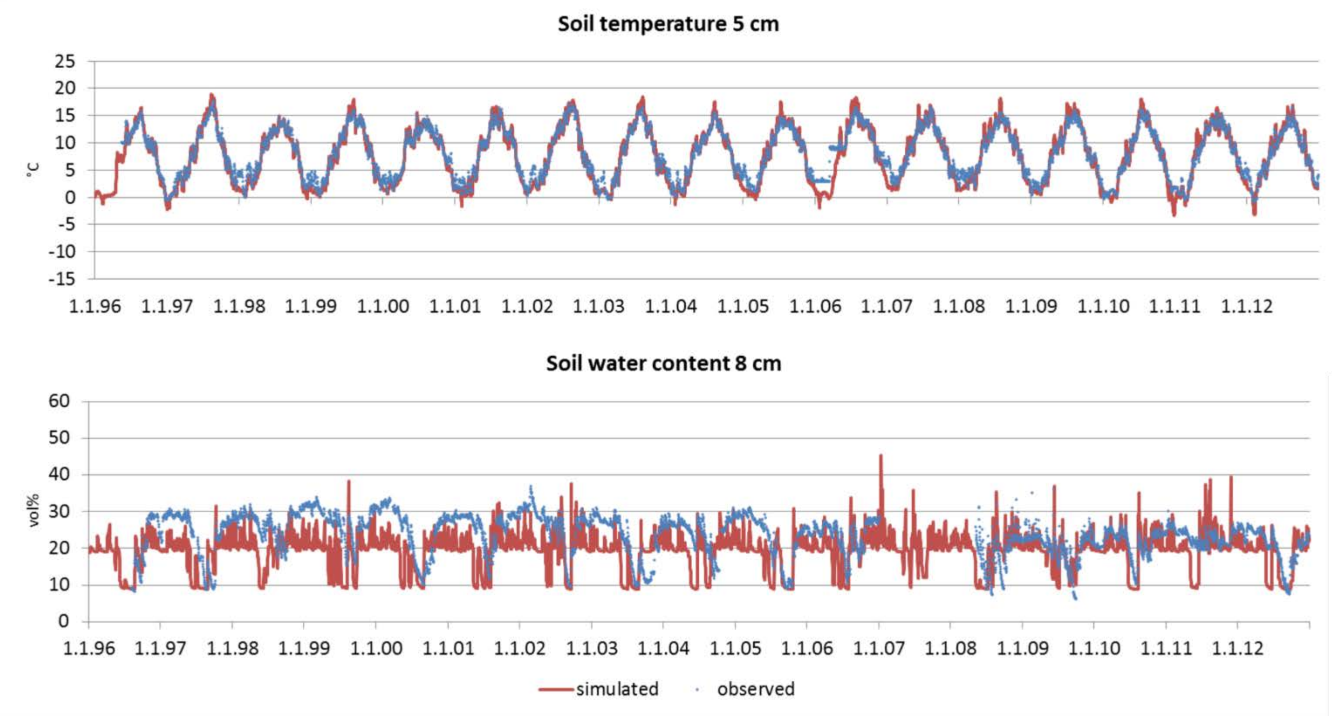

Figure 9. Time series of observed and simulated daily soil temperature at 5 cm depth (top) and time series of observed and simulated daily soil water content at 8 cm depth (bottom) in Sorø for the period 1996-2012.

For Hyytiälä, the results are similar (Fig. 10, bottom). The visual inspection for two layers shows a similar picture than in Sorø: an underestimation during winter time and a more frequent exhaustion of the soil water during summer. The observed water uptake frequently reaches a depth of 50 cm, while the simulated water uptake only reaches a maximum depth of 50 cm in the very dry months of July and August 2006 (Supplement, Fig. S16), with only one third and half of the precipitation sum of the long-term mean, respectively. The interquartile ranges and the ranges of outliers of soil water content are mostly higher for the simulated than for the measured values (Supplement, Fig. S12 right).

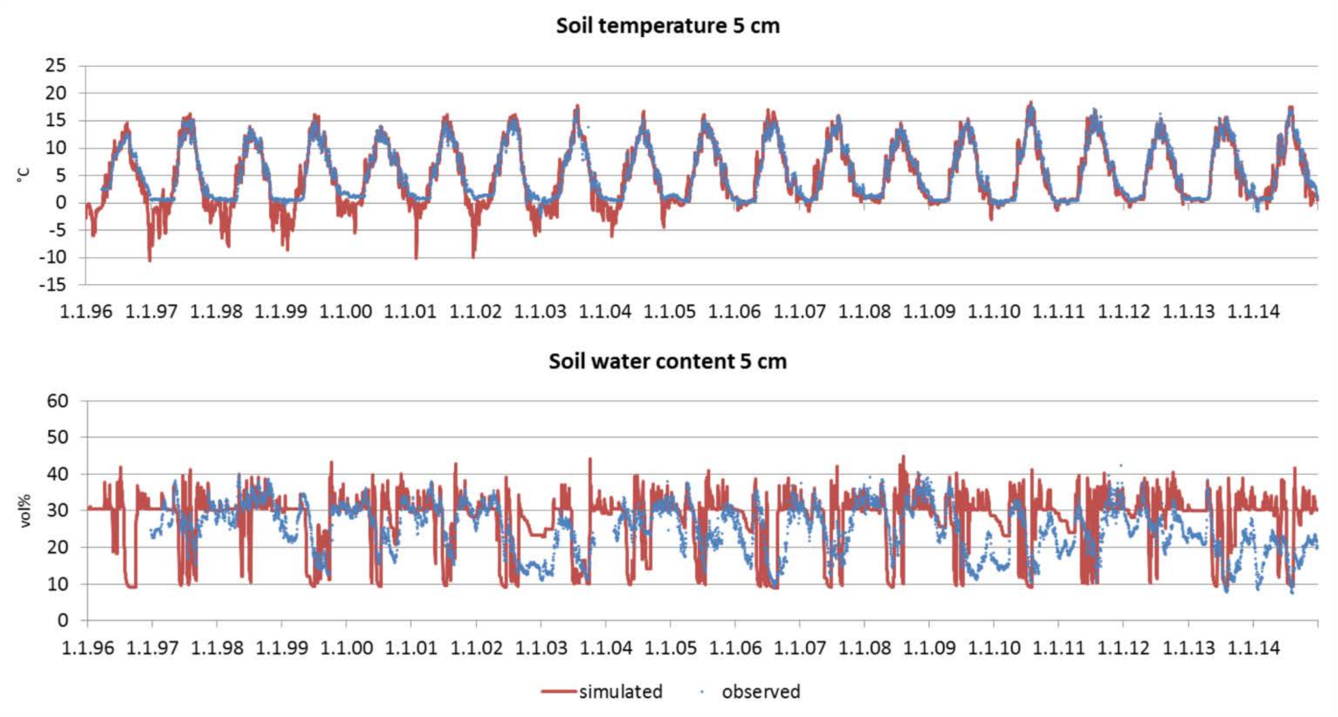

Figure 10. Time series of observed and simulated daily soil temperature (top) and time series of observed and simulated daily soil water content (bottom) at 5 cm depth in Hyytiälä for the period 1996-2014.

4 Discussion

In this paper, we have analysed the capability of 4C to reproduce forest growth, carbon and water fluxes at different temporal resolution as well as soil water content and soil temperature in different soil layers for four forest stands in temperate and boreal regions of Europe. As is often the case when evaluating complex forest models, not all sites and scales can be evaluated in the same way due to different data availabilities. Nevertheless, we present a very comprehensive evaluation of the model which provides important information on the applicability of 4C. In the following, we discuss the evaluation results and provide future scientific users of the model a recommendations of how to best use the model in specific cases and an impression on the reliability of the model results regarding various research questions.

4.1 Evaluation of forest growth

Overall, the ability of 4C to reproduce the dynamics of forest growth differs clearly from site to site. Therefore, we recommend model users to thoroughly evaluate the model before any application. 4C performs best for the mono-specific, coniferous stands Solling and Peitz independent of the evaluation metrics. In particular for Peitz, which features the longest observational time series of Scots pine growth, we observe the best agreement between model and data (Fig. 3, Supplement Fig. S1). For Solling, 4C underestimates the development of DBH (Fig. 4, Supplement Fig. S2). Ibrom (2001) and Ellenberg et al. (1991) found similar carbon storage in this spruce stand in 1967 of 9314 g C m^{-2} as initialized by 4C based on tree dimensions (10840 g C m^{-2}), indicating that basic assumptions about stem form and wood density are appropriate. Our initialization prescribes the same number of trees (595 ha^{-1}) as observed but strongly underestimates foliage (needle) mass (4C: 422.5 g C m^{-2} vs. 868 g C m^{-2} found by Ellenberg et al. (1991)). We applied the fixed parameter η_s (foliage to sapwood area relationship) to estimate foliage mass, which could lead to this underestimation. Furthermore, the estimation of sapwood area from DBH used for initialization is also uncertain. Consequently, our initialization leads to a smaller leaf area index (LAI) of 5.1 m^2 m^{-2} in 1990 compared to a value of 7 m^2 m^{-2} reported by Ibrom (2001) for the same year. In 4C, the initialization of the foliage biomass as well as fine root biomass is estimated via a function depending on sapwood area and a parameter describing the foliage to sapwood area relationship. Therefore, it is possible that 4C's underestimation of DBH growth is due to the underestimation of foliage biomass during initialization. While foliage is underestimated, the initialization works well for DBH. Ibrom (2001) gives the values for mean DBH (35 cm) and mean top height (28 m) which are nearly matched by 4C with a DBH of 35 cm and mean top height of 31.8 m. The initialization of height of tree cohorts uses height-diameter relationships from various yield tables which can lead to deviations in comparison with measured data. We therefore recommend model users to check whether the foliage masses and height-diameter relationships found after initializing the model are comparable to locally/regionally derived relationships.

The quality of growth simulation in Hyytiälä differs for the two species. For Norway spruce, which is present in the understorey of this pine-dominated stand, stem biomass initialization is underestimated but growth is realistic, whereas the stem biomass growth of pine is slightly overestimated (Fig. 5, Supplement Fig. S3). Because thinning is driven by observed stem numbers, stem biomass is overestimated after thinning because other trees were harvested in the model than in the real stand. Comparing simulated biomass data of stem biomass for the mixed stand Hyytiälä with measurements (personal communication by Fredrik Lagergren) for the initialization year 1995 we find that pine stem biomass is in accordance with measurements while spruce stem biomass is clearly underestimated (see Fig. 5, Supplement Fig. S3). Therefore, we recommend model user to always check whether the trees removed in 4C during management are somewhat comparable in terms of size etc. to those removed in reality if such data are available.

Earlier model evaluations of stand dynamics for different species such as pine, spruce and beech in Germany by Lasch et al. (2005); Lasch et al. (2007); Lindner et al. (2005) demonstrated a sufficient ability of the model to reproduce forest growth in terms of DBH, height and biomass. Thus, while in general we have confidence in the ability of 4C to simulate forest growth, it is important to keep in mind that 4C works with a site-independent species parameter set and we did not re-calibrate any of the parameters locally. Thus, matching the absolute observed values could differ between Scots pine stands in Germany and Finland, because of the uncertainty associated with fixed, generic parameters (Collalti et al., 2016). For example, trees in Finland often develop crown shapes that are more adapted to reducing snow damage – this is an example for an adaptive trait that is evolutionary and is not considered in the model. Even though, it is not necessary to recalibrate 4C before moving to a new site, we recommend model users to check whether data relating to the main model parameters have been collected and can be used to explain model-data mismatches.

4.2 Evaluation of carbon and water fluxes

We analysed the model's performance to simulate carbon and water fluxes using statistical measures on different time scales. For Sorø and Hyytiälä, 4C performed best when comparing simulation results with observational data on daily and monthly scales for GPP, NEE and AET (Table 5). The main reason here is the strong dependence of daily and monthly water and carbon fluxes on the daily and seasonal course of temperature and radiation. This clear pattern disappears on the annual scale and small deviations at the daily scale accumulate at the annual scale. Therefore, the relative importance of other variables, besides the meteorological parameters, as leaf area dynamics, transpiration limitation due to water shortage the length of the growing season and, the ground vegetation increases at the annual scale, thus rendering these simulation results more uncertain. Collalti et al. (2016) also found a better performance on a monthly scale than on an annual scale for both sites for their 3D-CMCC-FEM model from the same model family. We therefore recommend model users to evaluate the model across different temporal scales to understand at what temporal scale confidence in the model results is adequate.

For both sites, 4C overestimated GPP and underestimated NEE on long-term average. This could be caused by the simplified simulation of ecosystem respiration in 4C (see Sect. 2.1.3). Because organ-specific, dynamic respiration rates are hard to parameterize due to a lack of data, the respiration rate in 4C is a fixed fraction of GPP following an approach of Landsberg and Waring (1997). The standard deviations of the annual GPP are of similar magnitude for observations and simulation data, which indicates high variability from year to year in both data sets. For Sorø, the standard deviations of NEE are also very high for simulated (130 g C m^{-2} yr^{-1}) and (100 g C m^{-2} yr^{-1}) observed annual values whereas for Hyytiälä the standard deviations are of a lower order of magnitude (54 and 45 g C m^{-2} yr^{-1}). In former model validation experiments with 4C for the site Hyytiälä (Reyer et al., 2014) we concluded that systematic underestimation of NEE at low temperatures causes this deviation between measured and observed fluxes, which is still a problem. We therefore recommend model users to critically evaluate the role of respiration and carbon balances in their applications to ensure the model limitations are clearly spelled out when explaining the model results.

The annual course of GPP and NEE in Sorø shows a sharp increase of GPP with the start of the vegetation period (bud burst) which is faster than the simulated flushing. The phenological model of 4C (Schaber and Badeck, 2003; Schaber, 2002) for beech was derived from long-term observational data in Germany and hence the model parameters might not represent the phenology of beech in Denmark. In fact, the average day of bud break for 1999-2009 in 4C is the day of the year 120, while (Pilegaard et al., 2011) found values between 118 and 134 with a mean being 129. Furthermore, we did not consider ground vegetation because the ground vegetation implemented in 4C is not suitable for beech stands (see Sect. 2.1.2). Therefore, the simulated GPP is underestimated during the early spring time (Supplement Fig. S7). For Sorø, Horemans et al. (2017) discussed in great detail the differences between simulated and observed NEE for 4C and concluded that 4C overestimates the importance of high frequency variability because 4C uses the daily temperature to redistribute the weekly calculated NEE and the applied dependency is possibly too sensitive. Therefore, we recommend model users to assess the role of phenological changes and high frequency variability in their study and, if that amount of detail is required, to adjust the phenological parameters to local conditions.

4C simulates acceptable AET values on daily and monthly time scales (ME≥0.65) but not on the annual scale. For Hyytiälä the statistics show not a systematic bias of observed and simulated AET at daily and monthly time scale as for Sorø, where the long-term annual amount as well as the daily AET values are underestimated (Fig. 6, Table 6). The annual course of AET for Sorø as well as the normalized deviation between simulated and observed values show a large underestimation of AET during the vegetation period and in particular in the months prior to bud break (February to May) (Supplement, Fig. S7, Fig. S13). In contrast, the simulated AET at Hyytiälä does not show such a strong bias (Supplement, Fig. S11, Fig S14). Like for GPP and NEE, the strong systematic bias at the Sorø site is a result of neglecting the observed ground vegetation in 4C. In the model we assume that there is no transpiration when there are no leaves. But in Sorø ground vegetation consisting of *Anemone nemorosa* L. and *Mercurialis perennis* L. exists before bud break (Pilegaard et al., 2001) and in that time the AET is underestimated clearly by the model. Based on reported transpiration values for the ground vegetation comparable to our pine sites Hyytiäla (56 to 76 mm year^{-1} Launiainen (2011)), and Peitz (173 to 185 mm year^{-1}, (Lüttschwager et al., 1999) also the ground vegetation in a beech stand as Sorø explains the simulated deviation of 10 to 20 mm month^{-1} from February to May (Fig. S11). High values of observed AET of more than 4 mm per day show almost no correlation to radiation and only weak correlation to air temperature, but the approach of Penman-Monteith used in 4C calculates the potential evapotranspiration in dependence on radiation and air temperature. Obviously, there are other factors that influence the AET. Furthermore, the soil data for field capacity, wilting point, pore volume and percolation were only estimated by pedotransfer functions. This estimation might explain the underestimation of water supply causing the deviations in AET simulations from observations during the vegetation period of the trees. Unfortunately, in Sorø only the water content at 8 cm soil depth is available. Here we could not perform a simulation run with measured soil water content values as model input to further disentangle probable reasons for the deviations in AET. For Hyytiälä these data were available from measurements leading to a better simulation of AET, but also here the simulation run with measured soil water content values as model input do not change model outputs regarding AET, GPP and NEE compared to the original simulated outputs. So, this model exercise also did not yield any further results other than that the soil water does not play a role for the deviations from the measured AET at Hyytiälä for all time scales. We recommend model users, similar to the evaluation of carbon fluxes to evaluate the model across different temporal scales and to assess the role of ground vegetation for each stand.

Model validation with eddy covariance data is known to suffer from inherent problems (Medlyn et al., 2005b; Robinson et al., 2005). Therefore, we performed an informal interpretation of residual diagrams (Supplement Fig. S4, S8) showing positive correlations between the simulated values and the residual deviation for all variables (GPP, NEE, AET). This reveals a bias towards overestimation at high values simulated by the model at both sites. But since the model efficiency of greater than 0.5 of the daily and monthly values was sufficiently good (Table 5), we also analysed the inter-annual variability (IAV) with so-called normalized time series indicating the variation from year to year between the observed and simulated annual values of GPP, NEE and AET. At both sites the magnitude of inter-annual variability is similar between observations and simulations for all variables except for some years (Fig. 7). Yet, the signs of the IAV differed clearly more often for Sorø than for Hyytiälä. Furthermore, there is a strong trend in Sorø's simulated GPP and NEE opposite to the observed trends. 4C reproduced IAV of GPP, NEE and AET clearly better for Hyytiälä than for Sorø. As a positive aspect with regard to climate sensitivity we note that for both sites the signs of simulated as well as for observed GPP IAV are negative in the extremely dry year 2003 (Granier et al., 2007) which provides some confidecen that 4C is capturing such extreme conditions as were prevalent in 2003. The lower performance in Sorø can be explained by the imprecise simulation of evapotranspiration and available water in Sorø which, in turn, influences the NEE through water limitations. It underlines also a problem in simulating the beech stand, because of missing ground vegetation and imprecise timing of bud burst and leaf unfolding. Keenan et al., 2012 pointed out that terrestrial biosphere models often fail to explain the observed interannual variability in deciduous canopy phenology, which is key to match the IAV of carbon and water fluxes in these kinds of forests. The IAV of the observations is caused by a high number of physical, biological and anthropogenic factors affecting the photosynthesis, respiration and water fluxes of forest ecosystems (Lagergren et al. (2008)). The reproduction of the IAV by the model requires information about these factors and model approaches describing these known but often not measured factors. Overall, our results are in accordance with the finding of Baldocchi et al. (2018) showing from analysis of flux data a clearly higher IAV of NEE in a temperate deciduous forest than in a boreal evergreen forest. They explained the variability in ecosystem photosynthesis as the dominant factor causing IAV in NEE which is confirmed by our results.

The fact that the AET in Sorø cannot adequately be modelled well with 4C is also expressed by the inter-monthly variability, which is simulated lower than measured. For Hyytiälä, the interquartile ranges of observed IMV are larger not only for AET but also for NEE in comparison to simulated IMV. The latter could be caused by the imprecise simulation of ecosystem respiration (soil and stand). The IMV of monthly simulated NEE is clearly lower than the IMV of the observed NEE (Fig. 8) during the vegetation period. In Sorø, it is the other way around (see Fig. 8). GPP shows the same pattern. We suspect that this behaviour could be caused by differences in the length of vegetation period between coniferous and deciduous species as well as different climatic conditions. We recommend model users for studies focussing on carbon exchange to analyse IAV and IMV which helps to detect reasons for low model efficiency at the annual time scale.

4.3 Evaluation of soil water content and soil temperature

Our results show that 4C is able to reproduce soil temperature at different depths in Sorø and Hyytiälä with good accuracy (all ME>0.8) (Fig. 9, top, Fig. 10, top). The implemented soil temperature model (Suckow, 1986) is physically-based and gives trustworthy results, as confirmed in former model evaluations (e.g. Reyer et al. (2014)). The statistics of soil temperature match results obtained in a modelling study with the CoupModel in Hyytiälä (Wu et al., 2011, 2012). In Hyytiälä, 4C did not simulate a snow pack until 2005 potentially because snow cover is underestimated due to unrealistic low winter precipitation (Supplement Fig. S17). Hence the simulated soil temperature of the upper layer is much lower than the observed values and thus the freezing depth is greater than observed. Starting from 2006, winter precipitation data seem more realistic and the model simulated a snow pack leading to a much better fit between the simulated and observed soil temperatures. The evaluation results for Hyytiälä were similar to the results shown by Reyer et al. (2014) (see Table 1). We therefore recommend model users to check whether the climate data properly accounts for snow cover and winter precipitation.

The evaluation of the soil water model is more difficult. Wu et al. (2011) stated that the performance of soil moisture was poorer than soil temperature performance in their modelling study at Hyytiälä with calibrated parameters. The minimum R^2 ranges between 0.03 and 0.27 in the different soil layers and is in the same order of magnitude as in our simulations. The 4C model is able to reproduce the intra-annual cycle of soil water content with low values during vegetation time and clearly higher values during winter time (Fig. 9, bottom, Fig. 10, bottom). The mostly negative ME values for three different depths at both sites (Table 6; $-0.414<ME<0.217$) means that the mean square error exceeds the variance of the observed data and that the model is not consistent with the observed data. In detail, the model reproduced the lowest values during summer time in Sorø and Hyytiälä for the three upper layers caused by the water uptake of the trees, but underestimated the soil water content during winter at both sites. In Sorø, the groundwater table rises in winter up to 20 cm and falls in the summer down to 2 m below the surface (Pilegaard et al., 2011). The model 4C does not consider fluctuating groundwater level and is parametrized with a constant ground water depth of 2 m at this site. Therefore the observed high water content in winter time due to the high ground water level cannot be reproduced by the simulation. In Hyytiälä the observed water uptake reaches up to a depth of 75 cm, but the simulation results show that the water uptake from the deeper layers is not needed to satisfy the simulated transpiration demand with the exception of the dry summer 2006 (Supplement Fig. S16). The uncertainty of simulated soil water content is mainly determined by the parameterization of the soil profile and the approach used to calculate the potential evapotranspiration and the water demand (see section 2.1.3, Water balance). The soil parameters field capacity and wilting point are hard to determine exactly for all soil layers (Supplement Table S3). Furthermore, the parameter rooting depth and the distribution of fine roots in the layers are often not accurately known, but they control the water uptake (Medlyn et al., 2011). Another component of the water balance is the ground vegetation which is not considered in the model for these two sites. Former evaluation of the soil water model of 4C at other sites (e.g. ICP-Forests level II monitoring plots) achieved better statistical results (Reyer et al., 2014) which depend on the soil type, the soil parameterization and the quality of soil water content measurements. A former analysis comparing the applied water uptake approach in 4C with a more process-based approach indeed indicated that missing data on root length densities might be crucial (Gutsch et al., 2015b). When interested in simulating soil water, we recommend model users to focus on sites with stable groundwater levels and detailed soil measurements available for different soil layers.

4.4 Applicability and Reliability of 4C

Analysing the model results for four sites across Europe, Peitz (pine), Solling (spruce), Sorø (beech) and Hyytiälä (pine with ingrowing spruce) underlines the challenge but also the added value of validating tree growth as well as carbon and water fluxes with observational data at different temporal resolution at stand scale. Along with the direct recommendations of how to best use the model and what to consider when applying it spread throughout the sections above, we here provide a summary of the applicability and reliability of 4C for prospective scientific model users (see also FAQ, Table 7). Complete overviews of all applications are given in the Gitlab repository and on the 4C website (http://www.pik-potsdam.de/4c/web_4c/publications/publications.htm).

The temporal development of important forest growth metrics (stem diameter and stem biomass) is represented in the correct order of magnitude with 4C. It reproduces the seasonality of the water and carbon fluxes in principles compared with observations although deviations and distinctions are clear on the daily scale. The model results are sensitive to weather influences and soil properties and all together support the use of 4C as a tool for investigating forest dynamics in managed forest stands. In comparison to former evaluations of the model (Reyer et al., 2014) we not only compared observed and simulated data but used further methods to analyse biases in annual and monthly variability. These methods allowed us also to evaluate the ability of 4C to reproduce extreme years like 2003 as shown for GPP simulated in Hyytiälä (see Sect. 4.2).

We aimed to develop a model which simulates forest growth in terms of height, diameter and biomass as well as the water, nitrogen and carbon fluxes without any site-specific calibration. Even though uncertainties in model parametrization for all species and the uncertainties in model structure contribute to partly insufficient results (Medlyn et al., 2005b) we argue that it is encouraging to see how well 4C performs overall across these very different sites. In agreement with other recent studies with 4C (Borys et al., 2016; Gutsch et al., 2015a; Gutsch et al., 2016), this study underlines the applicability of 4C to its main research areas.

Yet our results clearly show that representation of some processes in 4C should be improved, e.g. the phenology sub-model and the description of ground vegetation as an important element in the water balance. Moreover, the way respiration is modelled was identified as a major uncertainty. A new model version including a non-structural carbohydrates (NSC) pool in a changed allocation scheme is currently under development. This version will allow calculation of the organ-specific respiration and will possibly improve the calculation of ecosystem respiration.

The drought-stress effect on tree growth has to be improved and validated with tree-ring width and isotope data to reflect the mismatch of observed and simulated water dynamics in deeper soil layers. The discussion on tree mortality as an important demographic process (Neumann et al., 2017; Anderegg et al., 2016; Manusch et al., 2012) underlines the need for improvement of mortality modelling in 4C (cf. Bugmann et al., 2019). Further, new stand-level approaches regarding light interception have been published (Forrester, 2014), which may improve the modelling of vertically or horizontally diverse structured mixed forests and ground vegetation.

Although not necessarily needed, parameter calibration is possible with 4C if it is supported by data, as carried out by Reyer et al. (2016) and van Oijen et al. (2013). Application of generic calibration could improve model results at various stands as shown by Minunno et al. (2016) by a site-specific calibration, and Peltoniemi et al. (2015) for the site Hyytiälä. Molina-Herrera et al. (2015) confirmed that site-specific and multi-site calibration leads to a model parameterization that is best suited for simulating daily carbon fluxes with a forest growth model (Pnet). The main calibration studies with 4C have shown that calibration improves the model performance and that 4C was among the best performing model before and after calibration in a study comparing 6 different European forest models (van Oijen et al., 2013). A follow-up study by Reyer et al. (2016) showed that even though parameter uncertainties are potentially large and can be reduced by calibration (as with any other model), the standard parameter set of 4C performs well across different stands spread throughout Europe. Combining recently available data from the TRY database (Kattge et al., 2020) and methods (Bayesian calibration, (Hartig et al., 2012) is a promising avenue to generate deeper understanding of model parametric uncertainties and how the proliferate into model output uncertainty.

Table 7 Frequently asked questions (FAQ) for prospective scientific users of 4C

Question of prospective model user:	**Reply**	**Section in this paper or model description (Lasch et al, 2018) providing details**
For which forests is 4C a good choice?	Most experiences and evaluation studies for even-aged, mono-specific forests, but also mixtures of 2-3 species and uneven-aged stands are possible	Section 2.1-2.2 Full model description: Chapter 1 Overview Example two-species-mixture: Douglas fir-beech (Reyer et al., 2010) Scots pine-oak Gutsch et al. (2015b)
For which species is 4C parameterized?	Common beech, Norway spruce, Scots pine, Common oak, Sessile oak, birch, Douglas-fir, Black locust, Aleppo pine, Southern blue gum, Rose gum, Common aspen, Ponderosa pine, Lodgepole pine	Section 2.1.2 Full model description: Appendix 4 Parameterization of tree
For which soils is 4C a good choice?	All typical forest soils with restrictions on organic soils and alpine soils with high skeleton	Section 2.1.3 Soil physics, carbon and nitrogen Section 2.1.4
For which regions is 4C a good choice?	Temperate and boreal Europe are the main regions in which 4C has been applied but other regions as Mediterranean forests (especially in mountain regions) and tropical regions (only Eucalypts) can be simulated as long as the species are adequately parameterized	Section 2.1.2 Full model description: Chapter 1 Overview Appendix 4 Parameterization of tree species
For which management systems is 4C a good choice	Typically all sorts of even-aged managements with thinning from above, below, planting etc Separate management of	Section 2.1.3 Management Full model description: Chapter 9 Forest Management

	canopy and understory layer in uneven-aged, mixed forests is possible Target diameter harvesting is not feasible	
For which applications can 4C be used?	Scenarios analysis/future projections of the effects of climate and management changes, Historical evaluation and attribution studies Not feasible to analyze natural forest succession	All applications can be found: https://gitlab.pik-potsdam.de/foresee/4C/-/blob/master/publications/4C_publication_overview.pdf
Which simulations should be carefully interpreted given known model deficiencies?	Studies focusing on natural regeneration dynamics and also stress induced mortality need to be interpreted with care, simulations with a strong focus on respiration, simulation of forests with strong contribution of ground vegetation to the matter dynamics	Section 2.1
Which models with similar capabilities (but different strengths and deficiencies) are available?	GOTILWA+, 3D-CMCC-FEM, ForClim, PICUS, FVS-BGC, 3PG	Section 2.3
Can 4C parameters be used everywhere?	Yes, the standard parameter set should be applicable without re-calibration. If needed, 4C can be successfully calibrated to further improve the site-specific precision of the simulations at the expense of generality	Section 2.1.2 Full model description: Appendix 4 Parameterization of tree species

5 Conclusions

The model 4C belongs to a family of process-based forest models operating at stand scale and has been widely applied to simulate climate change impacts on European forests in the last 20 years. The model has been evaluated in a wide range of situations and we here describe the structure and the processes of the recently open-sourced version 2.2 of 4C (Lasch-Born et al., 2019). The evaluation of the models main processes relating to forest growth, carbon, water and heat fluxes against a comprehensive set of observational data at different time scales shows that, despite shortcomings, 4C is widely applicable and reliable. Particular areas for future improvement of 4C are (in no order of importance): refining species-specific model parameters (especially phenological parameters and respiration to enable organ specific respiration and allocation) using recently available data and methods, inclusion of abiotic disturbances especially fire and storm and better representation of ground vegetation, complex mixed forests with more than 2-3 species and their management. We conclude that 4C v2.2 is ready to be released to the scientific community to use and further develop the model in a wide range of climate impact studies on forests.

Code and data availability. The detailed model description (Lasch-Born et al., 2018), the model source code 4C v2.2 (Lasch-Born et al., 2019) and the simulation results are available in the Gitlab repository https://gitlab.pik-potsdam.de/foresee/4C.

Author contributions. P. Lasch-Born wrote the manuscript with contribution from all co-authors, performed simulations, contributed to data analysis and co-developed the model code, F. Suckow contributed to the manuscript writing, co-developed the model code, performed the simulations, and contributed to data analysis. C.P.O. Reyer contributed to the manuscript writing, M. Gutsch contributed to the manuscript writing and co-developed the model code. C. Kollas contributed to the manuscript writing and co-developed the model code. R. Grote contributed to the manuscript writing and co-developed the model code. F.-W. Badeck, H. K. M. Bugmann, J. Schaber, M. Lindner and C. Fürstenau co-developed the model-code. All authors contributed to writing the model description.

Competing interests. The authors declare that they have no conflict of interest.

Acknowledgements. This paper was supported partly by the EU project SilviStrat (Silvicultural Strategies to Climatic Change in Management of European Forests, 2000-2003), the BMBF project OakChain (Nachhaltige Bewirtschaftung von Eichen-Kiefern-Mischbeständen im subkontinentalen Nordostdeutschen Tiefland, 2005-2009), the EU-funded project MOTIVE (Models for Adaptive Forest Management, 2009-2013) of the 7th FP, the BMBF project CC-LandStraD (Climate Change - Land Use Strategies, 2010-2015) the projects WAHYKLAS (Waldhygienische Klimaanpassungsstrategien, 2014-2017) and DENDROKLIMA (Jahrringanalysen auf dem Telegrafenberg (Potsdam) -Nutzung dendrochronologischer Daten Deutschlands zur modell-basierten Analyse der Wirkung von Klimaänderungen auf Waldökosysteme, 2016-2019 both funded by the Waldklimafonds (BMEL, BMU) and the project I-Maestro (Innovative forest management strategies for a resilient bioeconomy under climate change and disturbances, grant no 773324 and 22035418 from 2019-2022) funded by the ERA-NET Cofund ForestValue. We thank Ylva Hauf for her great support in preparing figures and data and Alison Schlums for great editorial help.

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