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RESEARCH

Model based comparison of forest carbon uptake by forest growth and CO_2 Release due to forest operations for case studies in Europe and South Africa

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Abstract

When dealing with CO_2 in- and outflows of forest ecosystems, the CO_2 emissions due to harvest operations have been mostly not included into the analyses, so far. Therefore, to demonstrate an integrative and more holistic view, we used the generic simulation model *care4cmodel* for assessing relevant silvicultural concepts for pine species in different European (*Pinus sylvestris, Pinus pinaster*) and South African (*Pinus pinaster, Pinus radiata*) climatic conditions and management regimes. The concepts covered different thinning and regeneration systems, ranging from clear cut to target diameter harvest. Our focus was on the CO_2 emissions due to forest operations (CEF) and their relation to the CO_2 uptake due to wood increment (CUI). Simulations covered a time span of 50 years and different scenarios of the initial shares of stand development phases on a large virtual forest area. Our simulations suggest that, across all concepts and countries, the CEF are about 2–3 orders of magnitude smaller than the CUI. More importantly, while the initial situation strongly matters for development of the increment and harvest amounts, it does considerably less so for CEF and CEF/CUI. This provides leeway for silvicultural decisions regarding the above-mentioned CO_2 flows.

Keywords Forest simulation · Silvicultural concepts · Forest operations · CO_2 uptake · CO_2 emissions

Introduction

There is no doubt that forestry is required to contribute to reducing society's net carbon emissions. Extensive work has been done worldwide that demonstrates possible CO_2 sink and source effects of forest systems, and how these respond to silvicultural practices (Mäkelä et al. 2023; Anderson-Teixeira et al. 2021; Bravo et al. 2017). In this context, a major carbon flow, that has frequently been accounted for in the past, is the carbon uptake of forest systems due to

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wood or biomass increment (Pardos et al. 2024; Biber et al. 2020; Schwaiger et al. 2019; Noormets et al. 2015). In managed forest systems, however, the C balance is not only influenced by the biological dynamics and their response to silvicultural measures. Machinery is required to actually conduct these operations, importantly harvesting and transporting wood from the stands to forest roads and maintaining the forest road network. These operations release CO_2, predominantly from burning fossil fuels (Kärhä et al. 2023). Clearly, the fuel consumption and the efficiency of forest machines is of great interest even from an economic perspective alone, and has been frequently investigated (Bacescu et al. 2022; Haavikko et al. 2022; Schweier et al. 2019). Studies, however, that bring together the CO_2 uptake due to the biological production in the forest, and the CO2 emissions caused by forest operations seem to be widely missing (Biber et al. 2024). One reason for this gap might be that, so far, tools for such assessments have been developed inside their own scientific realms, i.e. forest growth and yield, and forest operations, independently. With the recently published R-package *care4cmodel*, Biber et al. (2024) provide a generic simulation model that allows the assessment of arbitrary silvicultural concepts with regard to both aspects of the carbon balance. Clearly, these two opposed aspects are only a part of what would be a complete forest carbon balance which would require e.g. including soil and deadwood carbon dynamics; however, they are of special interest, as they can be most directly influenced by silvicultural decisions, and focusing on them does not ask for more data than practitioners usually have available (Biber et al. 2024).

With their model, Biber et al. (2024) have demonstrated that the ratio of CO_2 uptake due to increment (CUI) and CO_2 emissions due to forest operations (CEF) on a given forest area, does not naively and simply depend alone on the forest growth conditions, the technological framework, and the silvicultural concept that is applied. Given all that, it also depends on the area shares of the stand development phases under the silvicultural concept of interest, and the level of risk to be considered. The reason is that forest growth usually strongly differs among different stages of stand development, as do the amounts and dimensions of harvested wood, and the efficiency of harvest operations (Bacescu et al. 2022; Biber et al. 2024; Pretzsch 2009).

For the first time, this study uses the possibilities provided by the new tool, *care4cmodel*, for exploring and comparing CUI and CEF of relevant silvicultural concepts in different places in Europe and in South Africa; the latter allowing us to include highly productive plantation forest systems. Ideally, we would analyze the same species all along the climatic gradient covered by our case studies. However, as none of the commercial species has such a wide range of distribution, we selected three species from the genus *Pinus* for the study at hand. Scots pine (*Pinus sylvestris* L.) was selected, because it is Europe's most widespread major forest tree species (Brus et al. 2012; Pretzsch et al. 2023). As Scots pine is not an option for silviculture in South Africa., we selected Maritime pine (*Pinus pinaster* Ait.) which is also present in Spain as a bridge species between Africa and Europe, and considered both species, Scots pine, and Maritime pine under Spanish conditions. In addition, to reflect some of the typical South African plantation forestry regions, we also included Monterey pine (*Pinus radiata* D.Don).

The idea of our study is neither to provide statistical representativeness nor to make projections for specific forest regions, but to explore a broad range of silvicultural concepts—each associated with typical growth conditions—that are relevant in different parts of Europe and beyond. We do this by taking a dynamic perspective on how these concepts perform when applied in scenarios representing an area with stands in varying developmental stages. This way, we cover close-to-nature forestry as well as fast growth clearcut systems and many approaches in between. We also do not aim to propose an optimal silvicultural concept as the outcome of our study. Rather, our goal is to use silvicultural case studies to explore the range of CUI and CEF values and their ratio, in order to provide an initial indication of the flexibility available for adjusting silvicultural actions. In particular, the research questions are as follows:

1. Do relevant silvicultural concepts of Scots pine and additionally Maritime and Monterey pine, that are relevant in different regions of Europe and South Africa, strongly differ with regard to CUI and CEF and their ratio during a time frame of several decades?
2. To what extent do the initial area proportions of different stand development phases influence the answer to question #1?

We will discuss the findings with a focus on what we can learn about the adaptation potential of forest management with regard to CUI and CEF.

Material and methods

Simulation model

As our central tool, we use the generic simulation model *care4cmodel* (Biber et al. 2024) that is freely available as an R package (Biber et al. 2024, 2023). In what follows, we give a condensed qualitative overview of the model. A formal description would be beyond this article's scope, but is provided in detail in Biber et al. (2024). The core purpose behind this model is to provide a dynamic view on any arbitrary real or hypothetical silvicultural concept a user can provide sufficient information about. Minimizing the amount of required input data to a level that can be reasonably provided by users was a key design principle in the model's development. Without that concept, a study like the one at hand would not be possible, because there exists a fundamental trade-off between the level of detail with which a model represents reality and its practical applicability, as users must supply information at a corresponding level of detail. Biber et al. (2024) discuss that issue specifically with respect to *care4cmodel*, and as far as we are aware, no alternative model frameworks are available that can operate with such streamlined information requirements. This is why *care4cmodel* was made. It is not the purpose of the model to simulate a forest estate or forest landscape where many different silvicultural concepts are applied in parallel with many different species in many different stand types, but to provide deeper insights into one silvicultural concept of interest at a time. This is achieved by populating an imaginary area with different stages of the same concept and simulate its future development under the assumptions of the user.

The structure of the model is based on the idea that any silvicultural concept can be defined as a sequence of distinct stages of stand development which have typical growth and yield properties, including area loss risks due to disturbances, and come with typical silvicultural operations. The same structure, a sequence of stand development phases, is also the usual way practitioner guidelines are set up. Being compatible with that approach was a design requirement when constructing the model. As another important model feature, it is a generic "plugin model", i.e. it provides a mathematical, algorithmical, and technical framework, but no pre-defined parameter values that would have been obtained by statistical fitting or any other kind of research. That means, all information required for making simulation runs has to be provided by the user in form of a standardized concept definition. Hereby, the dwell times, i.e. the average time span a unit area is spending in each stand development phase play a crucial role. Mathematically, each stand development phase is modeled as an n^{th} order exponential delay which is a pronounced negative feedback system (Biber et al. 2024; Sterman 2000).

Given that concept and structure, an arbitrary larger area can be initialized by splitting it into user-defined shares of the different development stages. When a simulation is being run, these area shares move cyclically through the development stages, as the stands grow and finally get harvested. This cycle, however, can be disturbed by random damage events that can throw areas prematurely back into the initial stand development phase. Note that the model is not spatially explicit. That means, the area of a certain stand development phase is the sum of all sub-areas attributed to this phase. It makes no difference to the model whether these sub-areas are small, scattered patches or one big coherent piece of land.

As each development stage has its specific growth and yield properties, e.g. volume, volume increment, harvest, mortality, these can be upscaled *post-hoc* to the whole area. After that step, the amounts and dimensions of the harvested wood are known for the whole area, and the fuel consumption and the corresponding CO_2 emissions are calculated. From the total area size and the forest road density, to be provided by the user, the model also estimates the CO_2 emissions caused by the regular maintenance of the forest road system. Finally, converting the wood increment into CO_2 equivalents allows to oppose the CO_2 uptake by increment to the CO_2 emissions due to the most important forest operations. While this is not a full forest carbon balance, as mentioned above, it is meaningful as it covers the biological production of the raw material wood on the one hand, and the actions required to make that raw material available to society on the other. The model is generic, which means that any silvicultural concept for which a user can provide a small set of essential growth and yield information can be simulated. This model property opens the door to the study at hand. Interested readers find a detailed scientific description of the model in Biber et al. (2024). Readers who want to use the model themselves are referred to Biber et al. (2023). Note that the model itself is freely available for download, see Biber et al. (2023), and all silvicultural concepts used in this study together with the R-script required to reproduce our runs are part the Electronic Supplement S2.

Silvicultural concepts

In the following text, we describe all nine silvicultural concepts that were examined in this study in North South order. Tables 1 and 2 provide a condensed qualitative and quantitative overview, respectively, and Figs. 1 and 2 show the regions where these concepts are implemented in practice. While we have to focus on the most important traits of the concepts here, we provide them in all detail in the Supplementary Table S1. In addition, each concept is also available as an electronic supplement (S2) together with an R script that can be used for reproducing our simulations with the R package *care4cmodel*.

Before we present the single concepts separately, let us give a short synopsis of the concepts. In all European countries included (Sweden, Poland, Germany, Spain), we had one concept with Scots pine as the species of interest. In all these countries, Scots pine is a native species and at the same time one of the most important commercial and

Table 1 Qualitative properties of the silvicultural concepts examined in this study

Country	Species	Goal	Silvicultural System
Sweden	Scots pine	Productivity, pulpwood and timber production	Clear-cut system with thinnings from below
Poland	Scots pine	Productivity, high wood quality, multiple ecosystem services	Clear-cut system with small clear-cuts and selection thinnings with liberation of future crop trees
Germany	Scots pine	Productivity, stand structural diversity, multiple ecosystem services	Shelterwood system with selection thinning and target diameter harvesting
Spain	Scots pine	Productivity, multiple ecosystem services	Group shelterwood system with thinnings from below
Spain	Maritime pine	Productivity, multiple ecosystem services	Shelterwood system with thinnings from below
South Africa	Maritime pine (site index 13 and 17)	Productivity	Clear-cut system with thinnings from below in short rotations
South Africa	Monterey pine (site index 25 and 30)	Productivity	Clear-cut system with thinnings from below in short rotations

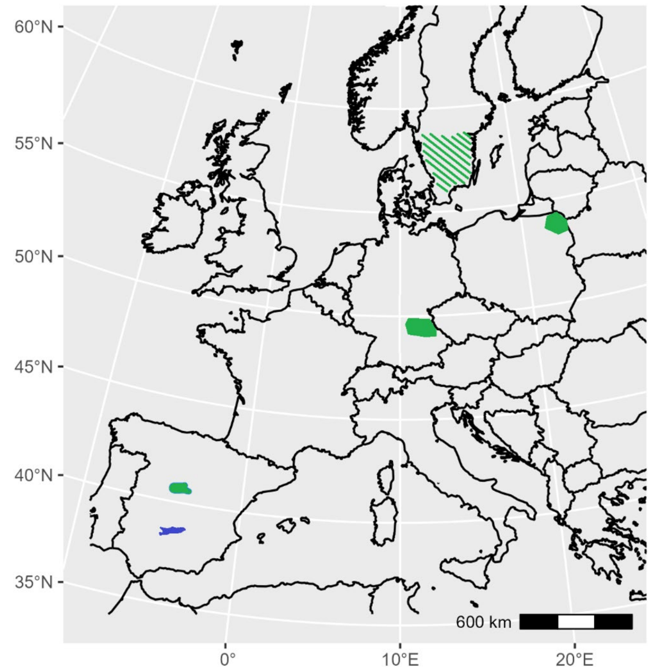

Fig. 1 Areas in Europe where the silvicultural concepts exemplified in this study are in practical use. Green: Scots pine (*Pinus sylvestris*), blue: Maritime pine (*Pinus pinaster*). The Swedish concept is applied in a large region which is, however, only partly covered by pine stands, therefore the hatched marking

widespread tree species in Europe (Pretzsch et al. 2023). For Spain, we had one concept with Maritime pine in addition. Maritime pine is an economically important native tree species in Spain. It is a Mediterranean species known to be more drought resistant than Scots pine (Sánchez-Salguero et al. 2010). Obviously, maritime pine in South Africa is an introduced tree species. Its economic significance is declining as it is considered invasive (Martin et al. 2025), however, we included it in this study in order to have an overlap species between the European and South African case studies. Monterey pine, originating from a small area in the Californian coast region, is among the most important commercial tree species in South Africa. Monterey pine is considered less drought resistant (Smith et al. 2014) but also less invasive (Martin et al. 2025) than Maritime pine.

Table 2 Important quantitative properties of the silvicultural concepts examined in this study

Country	Species	Area (ha)	T (°C)	P (mm/a)	Rotation Time (a)	N Phases	Road Density (m/ha)	Max. Volume (m^3/ha)	Max. PAI (m^3/ha/a)	Total Surv. Rate
Sweden	Scots pine	390,000	6.0–8.0	600–1,000	95	7	20.0	307	9.8	0.93
Poland	Scots pine	114,000	6.6	600	127	7	14.1	459	11.1	0.71
Germany	Scots pine	96,000	8.0	750	155	6	20.0	446	10.7	0.79
Spain	Scots pine	10,600	8.3	1027	121	6	20.0	624	18.0	0.89
Spain	Maritime pine	35,000	14.9	662	70	4	26.0	512	22.3	0.95
South Africa	Maritime pine (site index 13)	4,000	17.5	850	31	6	20.0	81	10.5	0.79
South Africa	Maritime pine (site index 17)	6,000	17.5	900	31	6	20.0	148	18.7	0.79
South Africa	Monterey pine (site index 25)	21,000	17.5	900	26	6	20.0	293	25.9	0.82
South Africa	Monterey pine (site index 30)	19,000	17.5	950	26	6	20.0	471	39.0	0.82

Area: Area of the region (ha), where a concept is in practical use; T, P: Mean annual temperature (°C) and annual precipitation (mm/a) in the region of interest. Rotation Time: Rotation time implemented in the concept of interest; N Phases: Number of the subsequent stand development phases in the concept; Road Density: Density of forest roads assumed for the simulation (m/ha); Max. Volume: Greatest standing wood volume (m^3/ha) in a stand development phase; Max. PAI: Greatest periodic annual increment in a stand development phase; Total Surv. Rate: Probability of a stand to survive from its establishment to the end of the last development phase

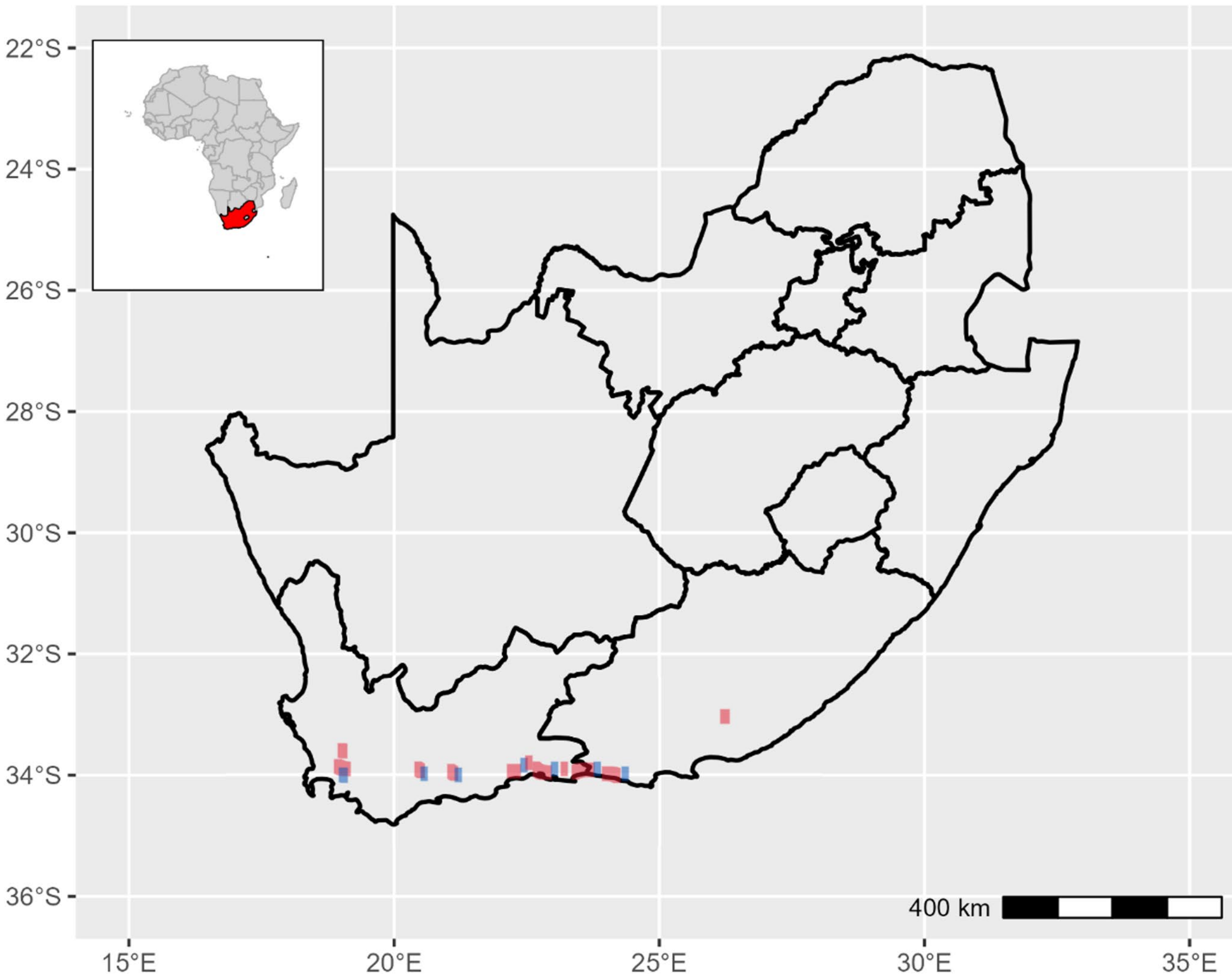

Fig. 2 Areas in South Africa, where the silvicultural concepts exemplified in this study are in practical use. Blue: Maritime pine (*Pinus pinaster*), red: Monterey pine (*Pinus radiata*)

All silvicultural concepts implemented in our study have in common that productivity (in terms of sustainable wood provision) is an important goal (Table 1). The emphasis on productivity is most significant in the South African concepts which represent a highly rationalized plantation forestry with comparably short rotation times (Table 2). Among the European concepts considered here, productivity is the most dominant goal in Sweden, while in Spain, Poland and Germany also the provision of other ecosystems (conservation, recreation) is explicitly aimed for. In the German concept, creating stands with a high structural diversity is an explicit goal, too. The silvicultural systems covered a range from more or less intensive and frequent classic thinnings from below and final harvest by clearcut (South Africa, Sweden) to future crop tree selection and promotion followed by a long-term target diameter harvest (Germany). The Polish and the Spanish concepts are in between this range (Table 1). Rotation times are lowest with the South African concepts with Monterey pine (26 years) and Maritime pine (31 years), while the Scots pine rotation times cover a span of 95 (Sweden) to 155 years (Germany). The Spanish concept for Maritime pine has an intermediate rotation time of 70 years (Table 2).

Sweden – Scots pine (*Pinus sylvestris*)

The Scots pine management concept selected for Sweden is common on better sites in the southern part of the country (Fig. 1). Besides Norway spruce (*Picea abies* (L.) H. Karst.) Scots pine is the most used tree species in forestry in Sweden. In comparison to spruce, pine is usually planted towards drier sites. The silvicultural concept presented in this study is implemented on roughly 390,000 ha (Swedish National Forest Inventory 2021), and its main goal is the production of pulpwood and timber for multiple uses. The focus lies on an economic forestry with a high productivity and an adequate quality throughout the whole stand. Pine is typically managed in a clearcuting system. After a soil preparation, stands are established by planting approx. 2500 trees/ha, but also natural regeneration with seed trees is common. In the period between an age of 25 and 85 years, three thinnings from below take place, typically at about 30, 45, and 60 years. After the last thinning follows a period without harvest up to an age of 95 years. After that, the stand is harvested by clearcutting. The maximum standing volume and wood increment that can be achieved on stand level with this concept are 307 m^3/ha and 9.8 m^3/ha/a (Table 1). Lacking survival rate data from Sweden, we used the risk functions published by Staupendahl (2011) for estimating the development state wise survival rates of such stands.

Poland – Scots pine (*Pinus sylvestris*)

The selected Scots pine silvicultural concept for Poland represents the boreal climatic conditions of the Augustów Forest (NE Poland, Fig. 1). However, this approach, with minor modifications, is also commonly used for Scots pine-dominated forests throughout Poland. The Augustów Forest covers about 160 000 ha, of which 114 000 ha are in Poland (Table 1). Over the last 200 years, the presented silvicultural programme has been used very successfully in this region to manage stands dominated by Scots pine with only minor admixture of silver birch and Norway spruce, on oligotrophic sites with sandy podzolic soils. The main goal of this management system is to achieve high quality stands and productivity. Stands are established by planting 10,000–12,000 trees/ha on clearcut areas up to 4 ha. After establishment, early and late cleanings are carried out until the stand is about 20 years old. During this time, the negative selection is used to reduce density and competition in the upper storey and to remove low quality trees. Later, in the subsequent early and late thinning phases, the positive selection is used to promote 350–400 future crop trees per hectare. The Polish thinning concept, called selection thinning, is a combination of thinning from above and below. The main competitors are selected for felling within the cohort of dominant trees that hinder the growth of future crop trees, but some suppressed trees that would die before the next thinning are also removed. While the early thinning cycle is 5–7 years and focuses on the upper layer, the late thinning cycle lasts 10 years and concentrates mostly on suppressed trees. The thinning intensity is between 15 and 20% of the stocking volume. When the stand age exceeds 100 years, the phase without any silvicultural operation begins. Finally, at the age of 120–130 years, the stand is harvested in areas of up to 4 ha. The maximum standing volume and the periodic annual increment at stand level are approximately 460 m^3/ha, and 11 m^3/ha/a, respectively. In the Augustów Forest, according to Bednarski and Miscicki (2016), the survival rate of a stand throughout the rotation is 71%.

Germany – Scots pine (*Pinus sylvestris*)

The German Scots pine management concept we selected has only recently been defined. It was taken from the current silvicultural guideline issued by the Bavarian State Forest Enterprise, BaySF (Bayerische Staatsforsten 2014). As such, it is in use on about 96,000 ha (Table 1) in the state forest areas in the regions of Upper and Middle Franconia, and the Upper Palatinate (Fig. 1), where Scots pine is the dominating tree species (Brosinger and Baier 2007). The main idea of the concept is an early selection of about 150 vital and good quality future crop trees. These trees are strongly supported by removing competitors. At higher ages, when the goal trees are established as dominant, only moderate but continuous thinnings take place in order to keep the goal trees' crowns in good condition. This phase is followed by a target diameter harvest of the goal trees when these reach breast height diameters of 45 cm. At the same time, this harvest regenerates the stand with the intention to create less homogeneous initial stands in the subsequent generation. While, in practice, other tree species are regularly introduced in that phase in addition to Scots pine, we do not take this into account in this study for the sake of clarity. In the main areas of interest, the age class distribution of Scots pine is heavy towards older stand ages. Many of these older stands, however, can be managed under this concept, as it has been explicitly designed to be also useful for lateral entry (Bayerische Staatsforsten 2014). The highest standing volume and volume increment on stand level amount to 446 m^3/ha and 10.7 m^3/ha/a. The survival probability of a stand throughout a whole rotation is 79%, the survival probabilities of this concept were estimated after Staupendahl (2011).

Spain – Scots pine (*Pinus sylvestris*)

The Spanish Scots pine management concept is the business-as-usual management regime applied in the Valsaín forest (located in the Central Mountain Range of Spain), over an area of ca. 10,000 ha (Fig. 1, Table 1). Between 1400 and 1900 m a.s.l., the forest area is dominated by *Pinus sylvestris*, whose stable presence has been proven during millennia under different climate scenarios (Morales-Molino et al. 2017). In these stands, the management has been traditionally focused on the production of valuable timber, while maintaining a satisfactory level of other ecosystem services (Pardos et al. 2017). For instance, in recent years, conservation objectives (highlighting birdlife conservation) are rapidly gaining importance (Ezquerro et al. 2024). Its strategic planning is based on classic European management methods, although more flexible methods have been applied in the last 20 years. The silvicultural systems has shifted from a traditional uniform shelterwood to a group shelterwood system for stand regeneration (Pommerening et al. 2024). Three light thinnings from below of moderate intensity are applied at ages 40, 60 and 80. Regeneration fellings start by opening patches of 0.5–1.0 ha spread over the compartment, taking into account the existing advance regeneration. In total, four regeneration fellings are applied, starting with a seeding cut in the selected patches, where 80% of the volume is removed. In a second step, the gaps are enlarged, removing 30% of the residual volume in the initial gaps, 70% in the enlargements and 40% in the rest of the compartment. In the third step, the volume is generally reduced by 50%, both in the gap areas and the rest of the compartment. In the final regeneration cut after 20 years, a few residual trees per hectare are left standing to provide a nesting habitat for birds. Rotation length is 120 years. The highest standing volume and volume increment on stand level amount to 624 m^3/ha and 18 m^3/ha/yr. The survival rate for these stands throughout the whole rotation period is 95%, estimated from Staupendahl (2011) as baseline and modified based on mortality statistics and local damages.

Spain – Maritime pine (*Pinus pinaster*)

The management concept for maritime pine is coming from the current silviculture that could be applied in the inner south part of Spain (autonomous communities Castilla-La Mancha and Andalucía) on approximately 38,500 ha (Fig. 1, Table 1). These pinewoods are mainly even-aged, monospecific and come from afforestation. The management is summarized in (Rodriguez-Soalleiro et al. 2008). The objective is to achieve a final stocking density of 300–400 trees/ha through 3–4 thinnings from below with moderate or heavy intensity, including a pre-commercial thinning depending on the initial density. The maximum stand volume and periodic annual increment at stand level are 512 m^3/ha, and 22.3 m^3/ha/a, respectively. Natural regeneration is usually established by the seed-tree or shelterwood method, although other alternatives as group selection systems are being studied to diversify the species composition and stand structure (de Frutos et al. 2023). The survival rate for these stands throughout the whole rotation is 95%, estimated from fire and mortality statistics and modified by local expertise.

South African pine plantations – Monterey pine (*Pinus radiata*) and Maritime pine (*Pinus pinaster*)

The South African concepts for *Pinus pinaster* and *Pinus radiata* plantations were based on a short rotation with a 2-step thinning. A very standard silvicultural regime was selected, with 6 phases in total, roughly based on the summary provided by Kotze and Du Toit (2012) which can be described as follows for both species:

Phase 1 (Temporary unplanted) – period after clearcutting the previous stand, when harvesting debris (slash) is managed, and site is prepared for planting in the next rainy season. Phase 2 (Establishment)—Stand is planted after site preparation using 1111 seedlings/ha and subjected to intensive weed control up to canopy closure; Phase 3 (Young growth)—stand is pruned in 3 pruning lifts up to approximately 6 m height and thinned (from below) to 500 stems/ha at the end of the phase; Phase 4 (Immature timber)—Stand undergoes second thinning (from below) down to 300 stems/ha by the end of the phase; Phase 5 (Mature timber) diameter growth remains rapid due to recent thinning at the end of the previous phase and stand starts to produce mature, denser timber; Phase 6 (Final crop phase) – This phase spans the period until clear felling where tending is usually restricted to fire protection operations only.

The only major difference between the two regimes studied lies in phase 6, where *P. pinaster* is grown for 12 years within phase 6 before clear felling at plantation age 30 and *P. radiata* is grown for only 6 years within phase 6 before clear felling at plantation age 25 years. The site index in all the South African pine concepts is the average height (in meters) of the 20% of trees with biggest dbh in the population, as measured at 20 years of age (hence abbreviated as SI_{20}). Where the two species occur in the same region, *P. pinaster* is usually planted on compartments with shallower, more infertile soils (with poorer site indices) thereby reserving *P. radiata* for the better site qualities, as it is a more responsive species to growth resource availability. The rotation in *P. radiata* is thus generally shorter than that of *P. pinaster*. To approximate this reality, we chose stands with SI_{20} of 13 and 17 m in *P. pinaster* and stands with SI_{20} of 25 and 30 m for *P. radiata*. The climatic conditions listed in Table 1, as well as the site index ranges for *P. radiata* were taken from Fischer and Du Toit (2019). The volume growth estimates per phase for two *P. pinaster* concepts were approximated from Loveday (1983), and that of *P. radiata* from Kotze et al. (2012). Risk estimates are based on averaged figures of plantation damage (total loss of stand category) for the entire area of South Africa's pine plantation forest estate, by Godsmark and Oberholzer (2019). It was assumed that these country-wide figures are equally applicable to the two species in question, and that slightly longer rotations carry a larger risk by virtue of being exposed to damaging agents for longer periods of time. The size of the forest estate (Table 1) was based on 2010 data where the two species grew in the Cape Forest regions (Fig. 2). Note that since that time, *P. pinaster* has largely been phased out of plantation forests within the aforementioned regions, partly due to its invasive tendencies (Martin et al. 2025), and partly due to poor productivity of Maritime pine on some of the marginal afforestation areas (Kotze et al. 2012). The phasing out process started before 2010, and for this reason the 2010 population of *P. pinaster* had a predominance in the older age classes, because clear felled stands already were being replanted with other pine species or pine hybrids at that time. We represent the carbon model as if the area was replanted, for comparative purposes with the European case studies of *P. pinaster*.

Simulation approach

Each of the silvicultural concepts was simulated on a virtual forest area of 1000 ha for a simulation time span of 50 years. We considered this time span long enough to cover essential forest dynamics, and short enough for being not fully outdated by technical progress in the field of forest machinery. For each concept, we calculated three scenarios that differed in the distribution of the initial area proportions that were attributed to the concept of interest's stand development phases. We called these scenarios "new start", "normality", and "reality". The "new start" scenario assumes that the whole area of 1000 ha is planted at the same time. As such, it represents the most unbalanced initial situation possible, which will generate the widest amplitudes of our goal variables. The "normality" scenario, in contrast, starts at about the situation, where the forest area is in an equilibrium, where the total wood volume, the increment, and the harvest remain virtually constant, and the annual increment equals the sum of harvest and mortality. In contrast to the "new start" scenario, the "normality scenario" represents the most balanced situation possible under the given disturbance regime. In managed forests, such an equilibrium is the traditional benchmark for assessing sustainability. To achieve this initial situation for a given concept, a 500-year spinup run was made, and the situation achieved at the end of the run was taken as the initial situation. The "reality" scenario reflects an estimate of the current phase area distribution in the region where the concept is applied. These area proportions were obtained from the available forest inventory data. As such, the initial phase-area distribution of a "reality" scenario, lies usually between the two corresponding extremes "new start" and "normality".

We did not consider different risk scenarios, though. For each silvicultural concept we used the risk level, i.e. area loss probabilities, which were considered normal under current conditions. The random number generator that controls the severity of potential damaging events for each simulation year (see Biber et al. 2024), was identically initialized for each simulation run, i.e. the sequence of the annual damage potential was the same in each run. The effect of a given damage potential could, however, differ strongly due to the specific risk settings in the concept definitions and the area distribution of the stand development phases when a damaging event hits. Despite these random components, the deterministic part of the simulated dynamics dominated the outcomes of the simulations at the risk levels we applied. Therefore, we deemed single simulation runs per scenario sufficient for producing the patterns we wanted to explore in this study. In the Supplementary Information S2, we provide an R script and all files that are required for reproducing the simulation runs presented here. For the conversion of wood volume into CO_2 equivalents, we assumed a raw wood density of 520 kg/m^3 at 12% moisture for all three tree species of interest, as the average wood density values reported for these species are not substantially different (Réjou-Méchain et al. 2017) and wood densities in general show a broad variation even on species level (Auty et al. 2014). When converting standing wood volume to harvested wood volume, we accounted for a bark share of 12% and a harvest loss of 10%. For calculating the fuel consumption of harvesters and forwarders we used the standard option that is implemented in *care4cmodel* based on Bacescu et al. (2022), and Grigolato and Cadei (2022). The annual fuel consumption per ha for maintaining the forest road network as a function of the forest road density is estimated in care4cmodel after Enache and Stampfer (2015). All simulation outcomes were carefully checked for plausibility, including sensitivity to the different scenarios and risk settings by all authors.

Results

Simulated area development

The Figs. 3, 4, 5, 6, 7, 8, 9 and 10 show the simulated phase-area dynamics for each silvicultural concept on a virtual forest area of 1000 ha. For interpreting the C-related outcomes in Sect. "CO2 Flows due to increment and forest operations" this information is useful, as the model obtains whole-area values by upscaling from the areas covered by specific stand development phases. Each figure is structured in the same way, i.e. panel a, b, and c show the normality, new start, and the reality scenario, respectively. Evidently, the area shares in the normality scenarios remained almost constant over the whole simulation time span; they were only slightly disturbed by damaging events. Such random disturbances were generally stronger in the South African scenarios with both Maritime and Monterey pine (Figs. 8, 9 and 10). While the normality scenarios started with about equilibrium area shares where the area shares of each phase mirrored that phase's duration, the new start scenarios began,

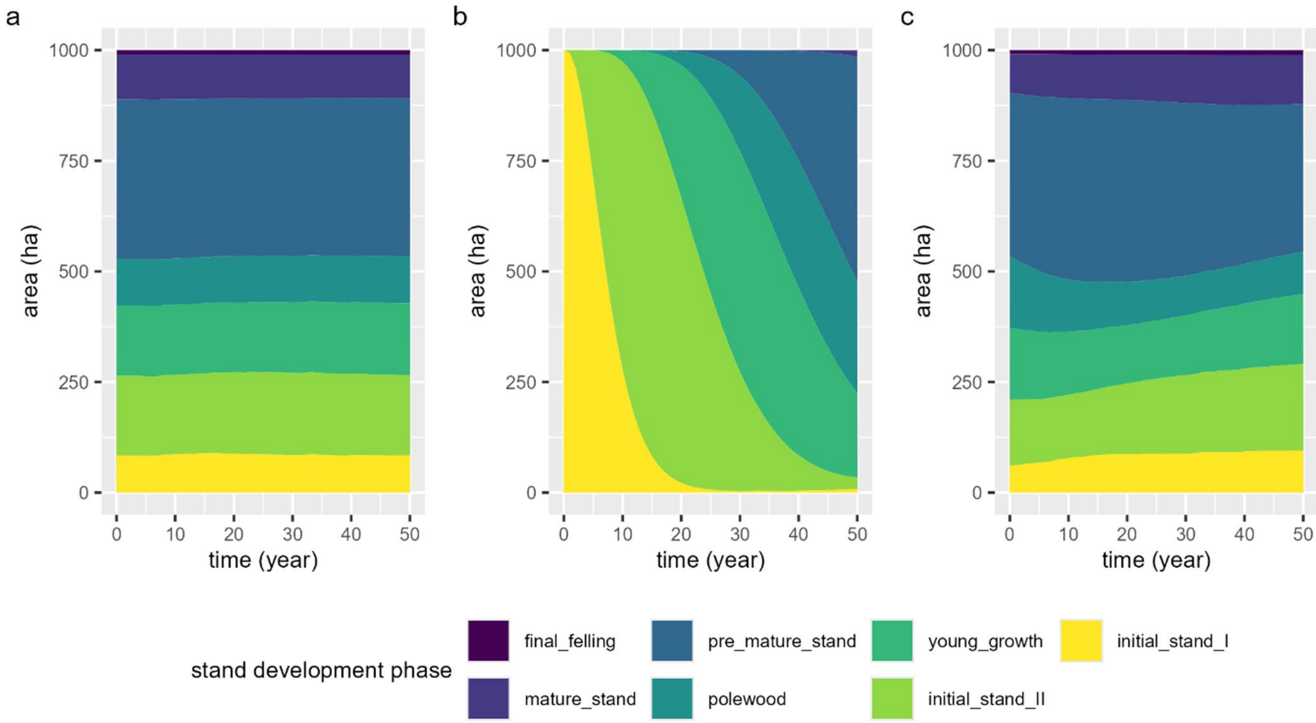

Fig. 3 Simulated phase area shares for the Swedish Scots pine (*Pinus sylvestris*) concept on a 1000 ha forest area. **a** normality **b** new start, and **c** reality scenario. Lighter and darker colours indicate earlier or later stand development phases

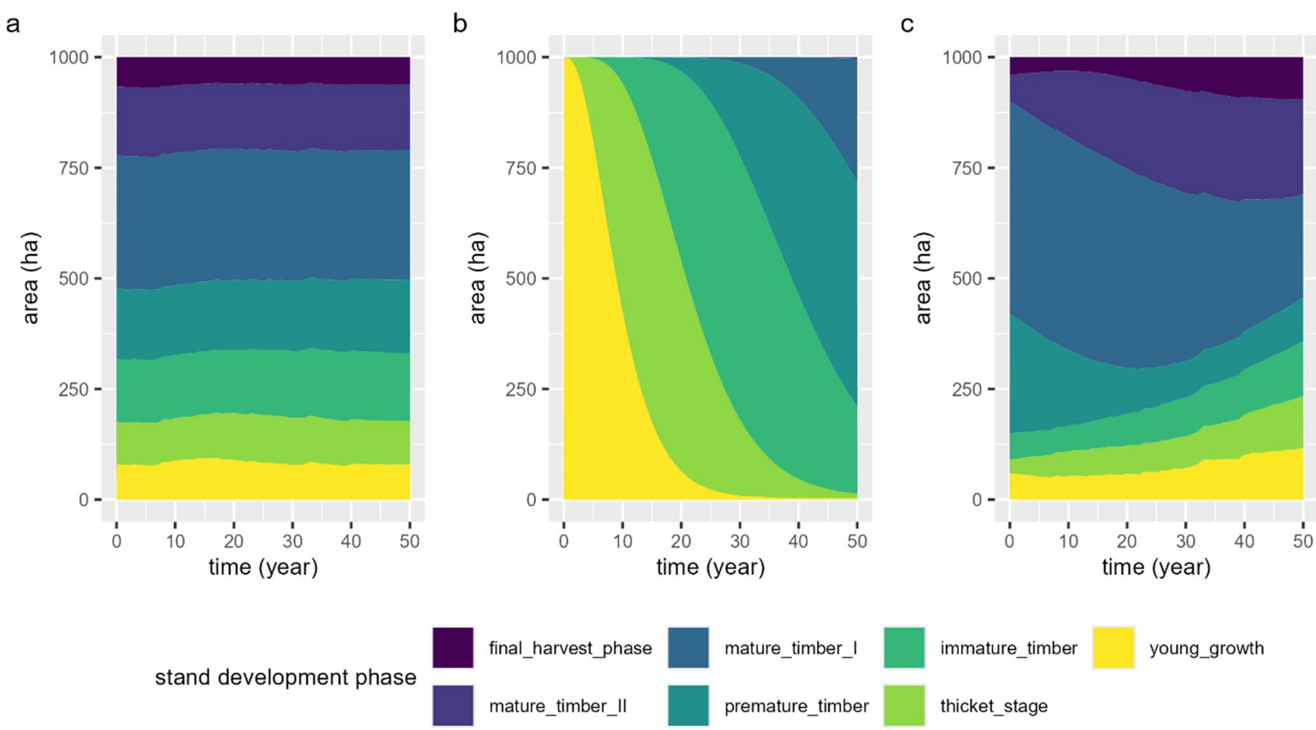

Fig. 4 Simulated phase area shares for the Polish Scots pine (*Pinus sylvestris*) concept on a 1000 ha forest area. **a** normality **b** new start, and **c** reality scenario. Lighter and darker colours indicate earlier or later stand development phases

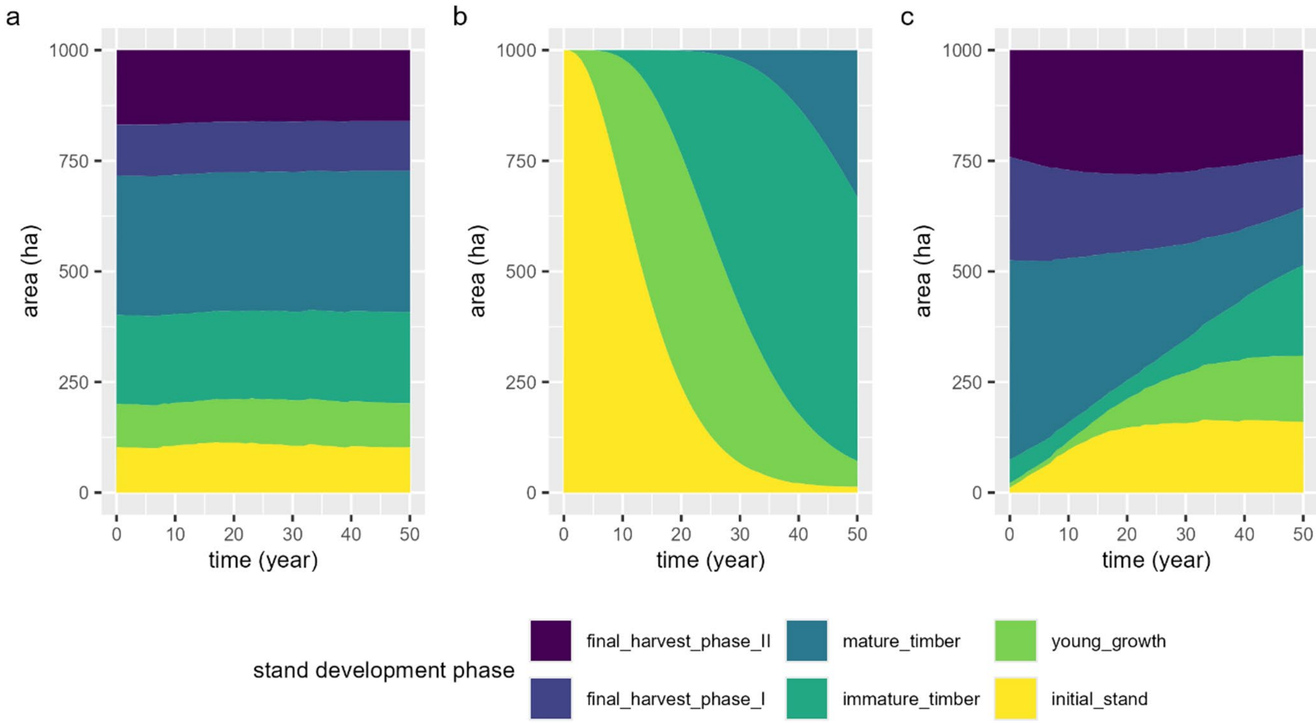

Fig. 5 Simulated phase area shares for the German Scots pine (*Pinus sylvestris*) concept on a 1000 ha forest area. **a** normality **b** new start, and **c** reality scenario. Lighter and darker colours indicate earlier or later stand development phases

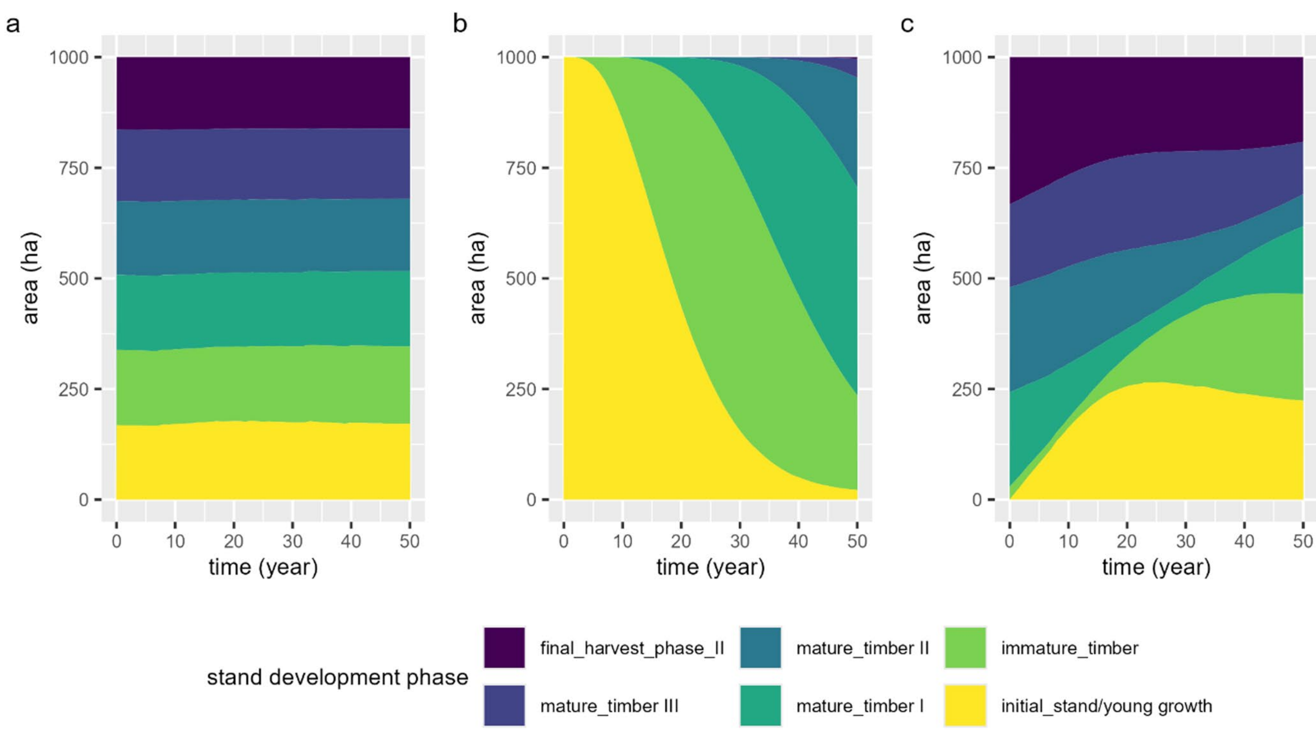

Fig. 6 Simulated phase area shares for the Spanish Scots pine (*Pinus sylvestris*) concept on a 1000 ha forest area. **a** normality **b** new start, and **c** reality scenario. Lighter and darker colours indicate earlier or later stand development phases

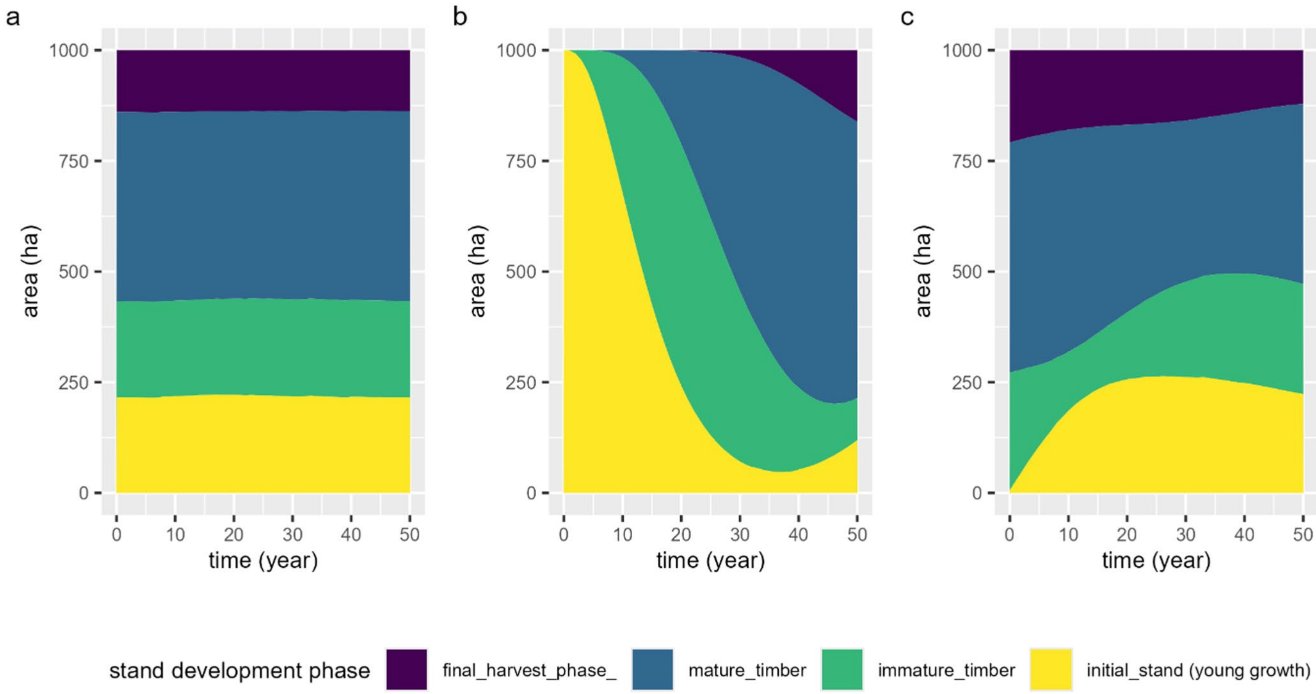

Fig. 7 Simulated phase area shares for the Spanish Maritime pine (*Pinus pinaster*) concept on a 1000 ha forest area. **a** normality **b** new start, and **c** reality scenario. Lighter and darker colours indicate earlier or later stand development phases

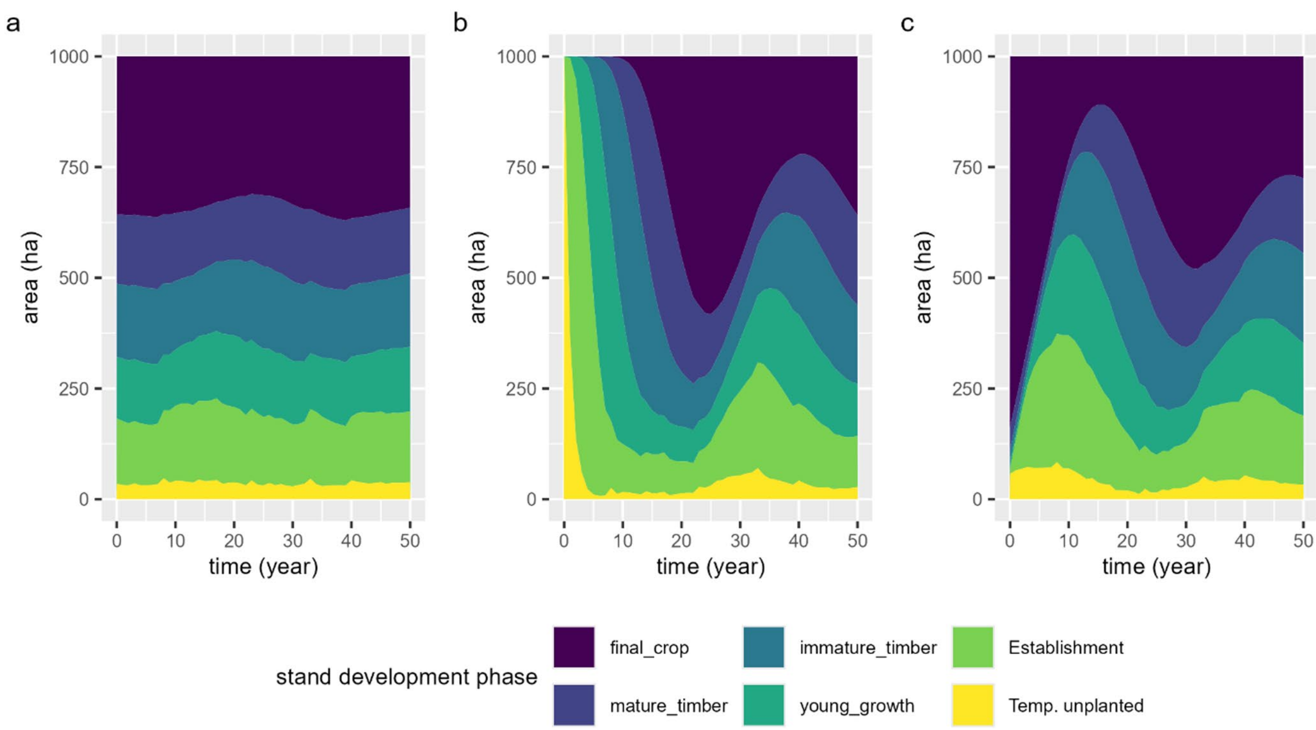

Fig. 8 Simulated phase area shares for the South African Maritime pine (*Pinus pinaster*), site index 13 and 17, concepts on a 1000 ha forest area. **a** normality **b** new start, and **c** reality scenario. Lighter and darker colours indicate earlier or later stand development phases. Both site indexes are covered by the same figure as the durations of the phases and the phase-specific risks are the same

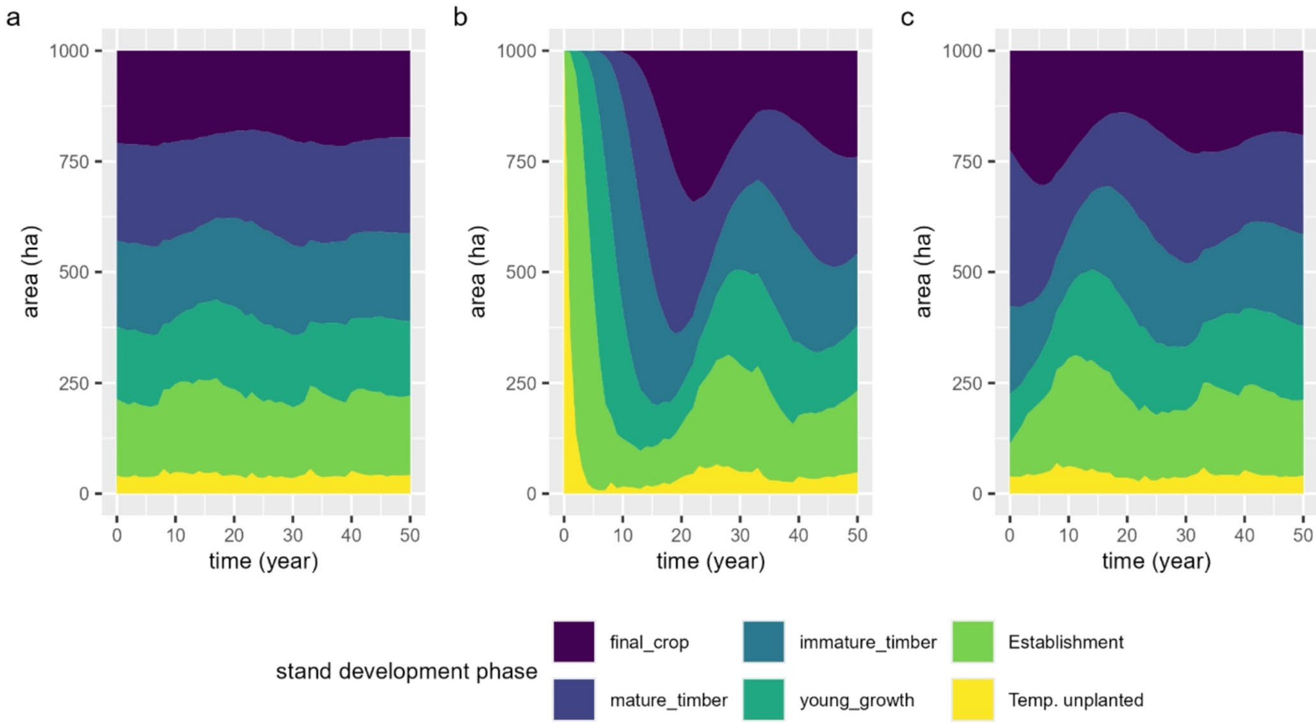

Fig. 9 Simulated phase area shares for the South African Monterey pine (*Pinus radiata*), site index 25, concept on a 1000 ha forest area. **a** normality **b** new start, and **c** reality scenario. Lighter and darker colours indicate earlier or later stand development phases

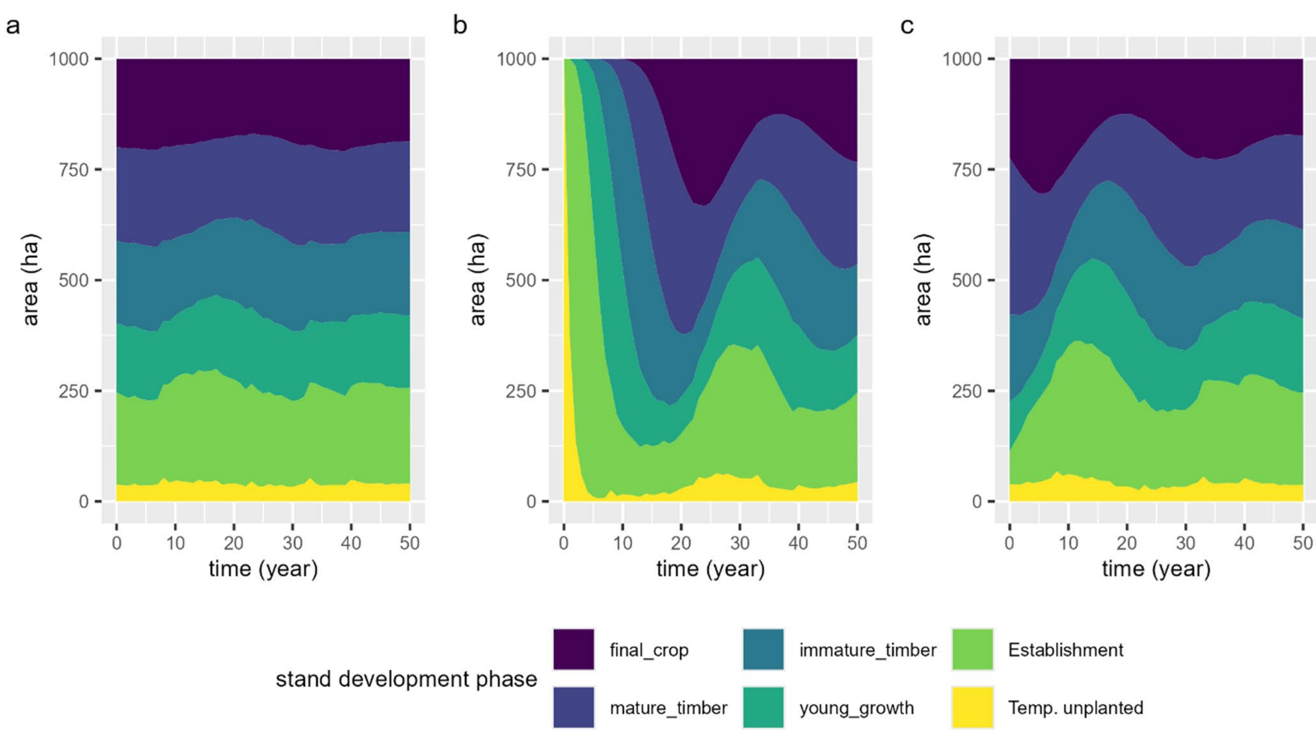

Fig. 10 Simulated phase area shares for the South African Monterey pine (*Pinus radiata*), site index 30, concept on a 1000 ha forest area. **a** normality **b** new start, and **c** reality scenario. Lighter and darker colours indicate earlier or later stand development phases

by definition, with an extreme imbalance, i.e. the whole area being initialized with the initial stand development phase. With the ongoing simulation, this imbalance propagated subsequently through the area shares of the stand development phases. On the long run, the area shares would exhibit long-term dampened oscillations, gradually approaching conditions as in the corresponding normality scenarios. For all European concepts, the simulation time span of 50 years was too short to cover that behavior. Therefore, at the end of the new start scenarios, advanced stand development phases were either not represented at all or strongly underrepresented (Figs. 3, 4, 5, 6 and 7). This was strikingly different for the South African concepts (Figs. 8, 9 and 10). Here, due to the short rotation times, more than one complete rotation was covered by the simulations. This is evident by the dampened oscillations of the area shares as visible in Figs. 8b, 9b, and 10b. For the reality scenarios, the initial situation for the Swedish concept was very close to the normality equilibrium (Fig. 3c). For all other European concepts, the real initial phase area shares showed an underrepresentation of early stand development stages, in the case of the Polish concept also an underrepresentation of the oldest stages leading to a heavy initial overweight of the intermediate phases (Fig. 4c).

CO_2 Flows due to increment and forest operations

We show the overall outcomes for the CO_2 uptake due to the increment of merchantable wood (CUI) on a 1000 ha forest area in Fig. 11. Note that the numbers provided are not kt C but kt CO_2 (equivalents). The diagrams in the Figure are arranged as a 3 × 3 matrix, each column representing a species (Scots pine, Maritime pine, Monterey pine), and each row representing one scenario (normality, new start, reality). As a logical consequence of the area shares, the CUI in all normality scenarios was almost constant over time. For Scots pine (Fig. 11a) almost all runs indicate an annual CUI of about 5 kilotons CO_2. The Spanish Scots pine concept made a clear difference with almost 10 kt, underlining the high productivity of Scots pine in Spain (Pardos et al. 2017; Montero, 1994). Also for Maritime pine, the Spanish concept showed the highest CUI with about 12 kt/a (Fig. 11b). With 8 kt/a, the South African concept for Maritime pine with site index 17 was still on a higher level than most of our Scots pine concepts, while, for site index 13, it was comparable to the majority of the Scots pine runs. Expectedly the highest CUI level of all simulations was obtained for Monterey pine, site index 30, in South Africa with an annual CUI of almost 20 kt CO_2 (Fig. 11c), while the same species with site index 25 was at about the same level (12 kt/a) as Maritime pine in the Spanish concept.

The new start scenarios (Fig. 11d, e, f) clearly showed wavelike dynamics of CUI with the maxima at times when the biologically most productive stand development phases have the highest shares. In this scenario, we see clear differences among the Scots pine concepts for Sweden, Poland, and Germany (Fig. 11d) which behaved virtually equal under normality conditions. The earliest maximum is obtained for Poland (~8–9 kt/a) after 20–25 years, followed by Germany (~7–8 kt/a) at 25–35 years, and Sweden (~6–7 kt/a) at 35–40 years. The Spanish concept, again, is an exception with ~ 14 kt/a at 30–35 simulation years. Maritime pine in the Spanish concept (Fig. 11e) showed the same basic dynamics as did the Scots pine runs; here the level is slightly higher than observed for the Spanish Scots pine, and the maximum occurs pronouncedly earlier (~ 15 kt/a after 20 simulation years). For both site indexes (13, and 17), Maritime pine in the South African runs shows two maxima of CUI after 15 and 45 simulation years, the second one being less pronounced due to the more balanced area shares obtained after one whole rotation. The absolute levels of CUI for the South African Maritime pine runs were clearly below what we obtained in the Spanish run. They differ, as expected, between the two covered site indexes. For Monterey pine in South Africa, we obtained the most pronounced oscillations in CUI (Fig. 11f). At a site index of 30 we observed a first peak after 13 simulation years at 26 kt/a, a second, much weaker peak occurred after 42 simulation years. For site index 25 the same rhythm was evident as for site index 30, just on a much lower level (10 kt/a less at the first peak) and the maxima occurring slightly, i.e. one or two years, earlier.

Evidently, CUI estimates obtained for the reality scenario runs of Scots pine (Fig. 11g) were by far closer to what we observed for the normality scenarios than to the new start scenarios. The Swedish, Polish, and the German concept show a virtually constant CUI at 5 kt/a, slightly diverging only towards the end of the simulation runs. The Spanish concept, in the reality run, however, had a constant CUI of ~ 8 kt/a for the first 20 years, and after that showed a linear increase towards 10 kt/a at the end of the simulation. This was due to the initial underrepresentation of the most productive stand development phase “immature timber” (cf. Figure 6c). Maritime pine in Spain (Fig. 11h) showed just a slight wavelike, almost constant trajectory with a CUI of about 12 kt/a. As the South African Maritime pine starts very imbalanced in the reality scenarios it shows similarly strong oscillations as in the new start scenarios (Fig. 11h). The peaks, however, are delayed by 5 to 10 years, as the last stand development stage covers most of the area in the initial situation. While the South African reality runs for Monterey pine also show oscillations (Fig. 11i), these are

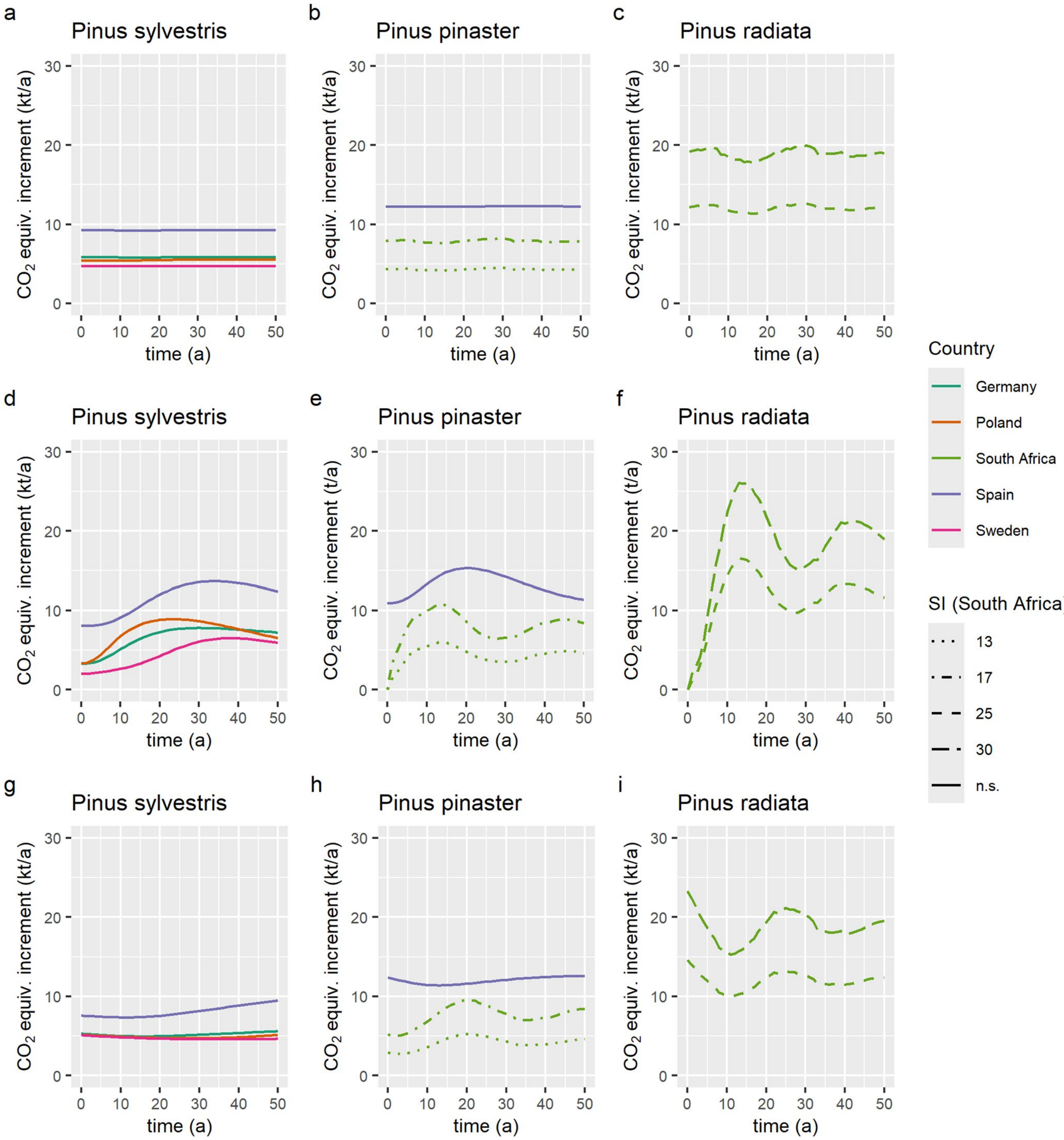

Fig. 11 Simulated CO_2 uptake due to the annual increment of merchantable wood (CUI) on a 1000 ha forest area; **a**–**c** normality scenario, **d**–**f** new start scenario, **g**–**i** reality scenario. Dashed and dotted lines represent different site indexes (SI) of the South African concepts

much more dampened and closer to normality than in corresponding new start scenarios.

As an interim information that helps to understand the CO_2 emissions caused by harvest operations, we show the annual amounts of harvested wood (in CO_2 equivalents) in Fig. 12. The structure of this figure follows exactly Fig. 11. Expectedly, the harvest amounts in the normality scenarios (Fig. 12a, b, c) did not reveal any time trend, comparing them to the corresponding increments in Fig. 11a, b, c, the influence of random disturbances on the harvest amount was much more visible than on the increment. The random fluctuations in all simulation runs were synchronous due to the constant initialization of the random generator (see Sect. "Simulation approach"), but the extent of their

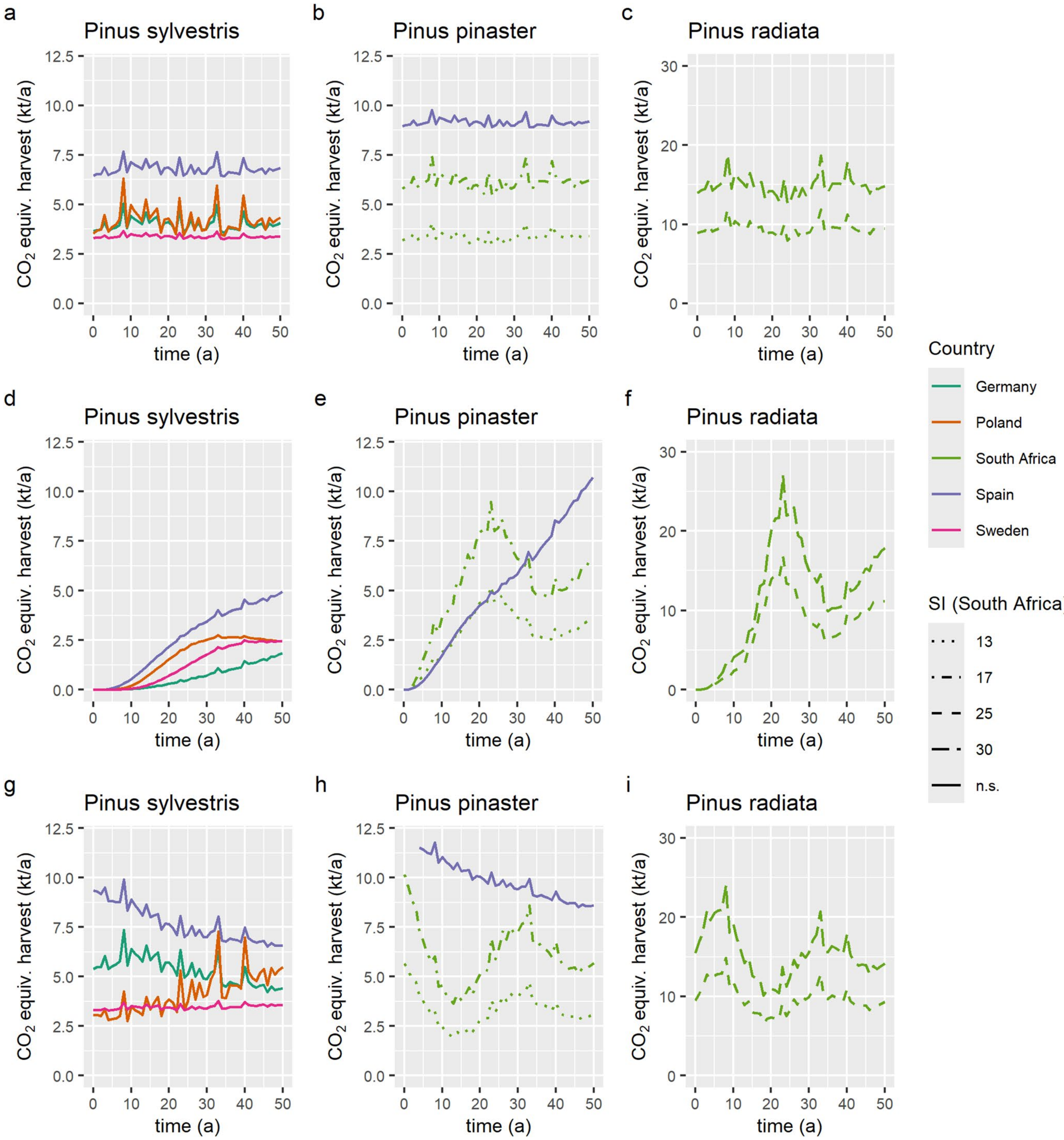

Fig. 12 Simulated amounts of harvested wood, expressed in CO_2 equivalents, on a 1000 ha forest area; **a**–**c** normality scenario, **d**–**f** new start scenario, **g**–**i** reality scenario. Dashed and dotted lines represent different site indexes (SI) of the South African concepts. Note that the vertical scale for the *Pinus radiata* runs (**c, f**) differs from the other for the sake of clarity

effect differed strongly due to the specific concept settings and prevalent shares of development phases. While in the normality scenarios the harvest matched the increment, the numbers displayed for the harvest in Fig. 12 are somewhat smaller, as the harvested wood does not include the bark and the harvest losses, most prominently the stumps that remain in the forest.

Considering the new start scenarios (Fig. 12d, e, f) the Scots pine runs for Sweden and Poland showed maxima (Fig. 12d), these occurred, however, considerably later than the maxima of the increment for the same runs (Fig. 11d).

The same is true for the South African concepts for Maritime and Monterey pine (Fig. 12e, f). The harvest amounts for the Spanish and the German Scots pine and the Spanish Maritime pine concept kept increasing throughout the simulation time span. The reason is that, in general, harvest is comparably low in the stand development phases of highest increment. The phases with high harvest come later, after the increment has accumulated in standing volume.

The harvest amounts in the reality scenarios developed quite differently, dependent on the initial situations. For Scots pine (Fig. 12g), the Spanish concept showed a constant decrease, resulting from the initial overweight of advanced stand development phases changing towards a more balanced situation (Fig. 6c). This was very similar for the Spanish Maritime pine run (Fig. 12h, 7c). In the German run, we observed a slight initial increase of the harvest amount, followed by a consistent reduction (Fig. 12g), which is due to an initial increase of the final phase embedded in a general trend of decreasing overrepresentation in the advanced stand development phases (Fig. 5c). For the conditions of the Polish concept, the harvest amounts increased consistently (Fig. 12g) due to an increase of the final harvest phase's area share throughout the simulation (Fig. 4c). In the Swedish run, where the initial situation was already close to a balanced representation of the stand development phases (Fig. 3c), the harvest amounts stayed virtually constant throughout the simulation. For Maritime pine in the reality runs (Fig. 12h), the Spanish concept marks the upper boundary of the obtained values, despite its continuous decrease. Of the South African runs, only the better site index, at its peaks (initially, and after about 30) years comes close. Marked oscillations of the annual harvest are also visible for Monterey pine in South Africa (Fig. 12i), the general development is, however, closer to the corresponding normality scenarios than to the new start runs.

The simulated CO_2 emissions due to forest operations (CEF) are presented in Fig. 13. The CEF comprise both, a variable component due to cutting and processing trees, and transporting them to landings at forest roads, and a fixed component due to maintaining the forest road network. In general, it can be taken from Fig. 13 that the CEF are by two to three orders of magnitude smaller than the corresponding CO2 uptake due to wood increment (CUI). It is also important to understand that the machines' fuel consumption, and therefore the CEF, increase with the amount of wood to be harvested, but decrease with the size of the trees that make up a given harvest lot (Bacescu et al. 2022; Biber et al. 2024).

The normality scenarios (Fig. 13a, b, c) showed the expected constant CEF per scenario with undirected random disturbances. For the Scots pine runs (Fig. 13a), the emissions on a 1000 ha forest area were lying between 0.025 and 0.050 kt/a. For Maritime pine (Fig. 13b), the above-mentioned tree size effect was obvious: While the harvest amounts for South Africa, site index 13 were lowest (Fig. 12b), the corresponding CEF were highest at about 0.075 kt/a. While the harvest amounts for the Spanish Maritime pine concept were highest, the CEF are at about the same level as for the South African concept with site index 17 (0.05–0.06 kt/a). For Monterey pine, the order of CEF along the site index did not reverse as it did for Maritime pine in South Africa, however, the CEF due to both site indexes came closer together (Fig. 13c).

The effect of tree size was clearly visible in the new start scenarios for Scots pine (Fig. 13d), most pronouncedly in the Spanish concept. While the harvest amount is consistently increasing there (Fig. 12d), the CEF show a distinct maximum at about 30–35 simulation years due to the increasing size of the trees being harvested. The curves obtained for the Swedish, the Polish and the German concepts are to be interpreted in the same way. For Maritime pine, the South African concept with site index 13 was on the highest level of CEF with extreme amplitudes, the maxima occurring with intermediate harvest amounts at comparably small tree sizes (Fig. 13e). We did not observe such strong oscillations for the better Maritime pine site index in South Africa, however the tree size effect completely flattened out the strong oscillations we observed for the corresponding harvest (Fig. 12e). For the Spanish Maritime pine concept, the model predicted a strong increase of the CEF during the first 20 years, followed by just slightly increasing values (0.05–0.06 kt/a) for the remaining simulation time (Fig. 13e). This is in a pronounced contrast to the steep linear increase of the corresponding harvest amounts (Fig. 12e). For Monterey pine, again, the tree size effect due to the different site indexes did not reverse the order of CEF levels related to the harvest amounts, but brought both site index closer together and dampened the amplitudes (Fig. 13f).

Remarkably, the CEF obtained for the reality scenarios (Fig. 13g, h) seem very similar to the outcomes for the normality scenarios, i.e. almost no time trends and similar values, while – except for Sweden – the harvest amounts show quite different and pronounced trends (Fig. 12g, h). The clearest example is the Spanish Scots pine concept, where the harvest amounts consistently decrease due to an increasing representation of younger stand development phases (Fig. 12g). However, as this comes with decreasing harvest tree sizes, the CEF in this scenario are virtually constant (Fig. 13g). For Maritime pine (Fig. 13h) and also for Monterey pine (Fig. 13i), the CEF of the reality scenarios are also in between the two extreme scenarios.

The outcomes of relating the CO_2 emissions due to forest operations (CEF, Fig. 13) to the CO_2 uptake due to wood increment (CUI, Fig. 11) are displayed in Fig. 14. In general,

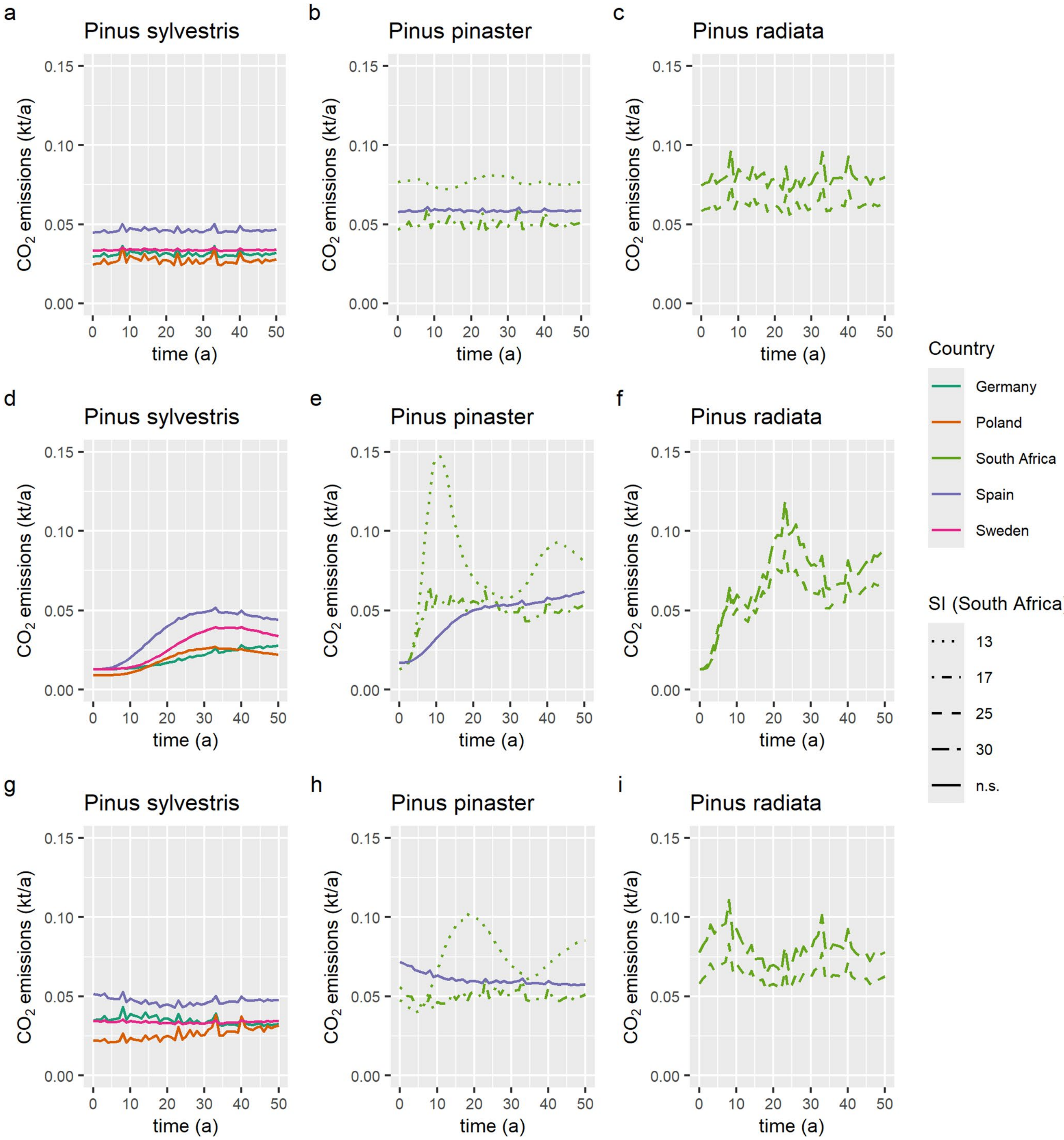

Fig. 13 Simulated CO_2 emissions due to forest operations (CEF) on a 1000 ha forest area; **a**–**c** normality scenario, **d**–**f** new start scenario, **g**–**i** reality scenario. Dashed and dotted lines represent different site indexes (SI) of the South African concepts

the ratios we obtained are between 0.20% and 0.80% with just a few exceptions. As apparent, the runs for the normality scenarios (Fig. 14a, b, c) resulted in virtually constant values for the CEF/CUI ratio. Interestingly, among the Scots pine concepts (Fig. 14a), Sweden was on the highest level with almost 0.75%, due to the comparably low increment rates. All other runs were considerably below (~0.5%) and close to equal. Maritime pine in the Spanish concept and the site index 17 concept of South Africa performs virtually the same (0.5–0.6%, Fig. 14b). The same applies to both Monterey pine runs (Fig. 14c). Only Maritime pine with the South African site index 13 concept showed by far the highest level of all runs at about 1.8% which is due to its low

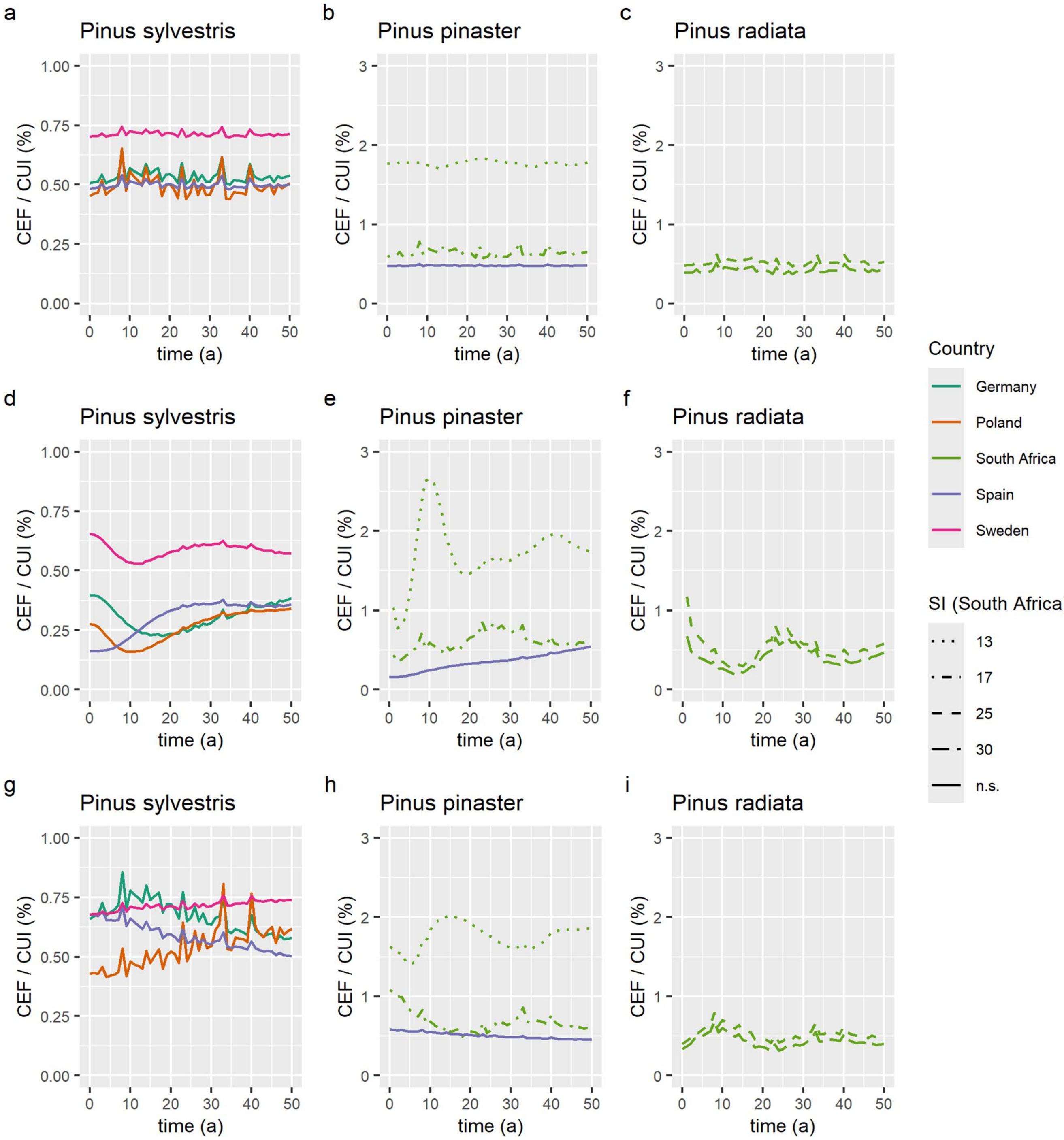

Fig. 14 Simulated ratio of the CO_2 emissions due to forest operations (CEF) and the CO_2 uptake due to wood increment (CUI) in % on a 1000 ha forest area; **a**–**c** normality scenario, **d**–**f** new start scenario, **g**–**i** reality scenario. Dashed and dotted lines represent different site indexes (SI) of the South African concepts. Note that the vertical scale for the *Pinus sylvestris* runs (**a**, **d**, **g**) differs from the other for the sake of clarity

increment (Fig. 11b) coming along with high emissions due to the tree size effect (Fig. 13).

The Swedish concept was on the highest level for Scots pine also in the new start scenarios (Fig. 14d). All runs except Spain, however, showed a swing down to a minimum after 10–15 simulation runs and seemed to swing back and converge later. However, the values at the end of the simulation time span were still considerably below what we observed for the corresponding normality runs (Fig. 14a). For Maritime pine in the Spanish concept, we obtained a linear increase from about 0.2% up to the same values as observed in the normality scenario (~0.5%, Fig. 14b). The South African concept with site index 17 reaches the normality values even earlier, but with more pronounced variations. The lower site index of South Africa showed a distinct and early peak at about 2.7% (Fig. 14e), clearly resulting from the simultaneous emission peak (Fig. 13e). Later, the CEF/CUI ratio moved quickly towards the normality value of about 1.8%. As in the normality runs, the CEF/CUI ratios of Monterey pine are virtually the same for both site indexes (Fig. 14f), both curves have troughs at the times when the increment peaks.

We observed heterogeneous outcomes for the reality scenarios (Fig. 14g, h). The Swedish Scots pine concept converged quickly to its value under normality conditions (~0.75%) which is expected, as this run started with considerably balanced area shares (Figs. 14g, 3c). The runs for the Spanish and the German concepts started at about the same value but showed a consistent decrease down towards their corresponding normality values. For the Polish concept, the CEF/CUI ratio increased throughout the simulation period soon overshooting normality. The Spanish concept for Maritime pine developed similar to the Spanish Scots pine concept (Fig. 14h). Overall, despite their different initial conditions the CEF/CUI ratio in all European runs stayed inside the range of 0.3–0.8%. For both, Maritime pine in South Africa (Fig. 14h) and Monterey pine (Fig. 14i), the results of the reality scenarios were plausibly between the corresponding normality and the new start runs.

Discussion

It might be considered a positive outcome of this study in general, that the CO_2 emissions by forest operations are by two or three orders of magnitude smaller than the amount of CO_2 sequestered by wood increment. This is in line with recent studies (Bacescu et al. 2022; Haavikko et al. 2022; Kärhä et al. 2023) and therefore not unexpected. However, a more detailed scrutiny of our results with regard to both research questions of this study provides a few interesting insights.

Variation of the outcomes among different concepts and species

Clearly, our results for the increment and the harvest amounts are plausible consequences of the concept settings across all concepts and species. This is most obvious to see with the normality scenarios but applies to all others as well. Both, increment and harvest are generally highest for Monterey pine in South Africa, while these are considerably lower for Scots pine in Europe, and Maritime pine. When considering the emissions due to forest operations, the piece-volume principle (cf. Heinimann 2007) has a mitigating effect. This principle states, in our context, that the harvesting effort, and therefore, the fuel consumption per unit of wood volume decreases with increasing volume per piece. Therefore, while on poorer sites the harvest amounts are smaller than on better sites, they typically come with smaller tree sizes, and vice versa. The same is true when comparing harvest amounts and average harvested tree size for earlier and later stand development phases. Therefore, the emissions due to forest operations are not as different as the harvested amounts across different concepts, but also inside the concepts over time. In general, this effect also determines the ratio of CO_2 emissions due to forest operations (CEF) and the CO_2 equivalents of the increment (CUI). With only one exception (Maritime pine on poorer sites in South Africa), these ratios are very similar even in a cross-continental and cross-species comparison.

How far does the initial situation matter?

From the different scenarios (normality, new start, reality) we simulated for each concept, it is evident that for the development of the increment and the harvest amounts the initial situation definitely matters. The more imbalanced the initial situation, the stronger the fluctuations will be in the long run. However, total afforestation of larger areas, as assumed in the new start scenarios, is an extreme that is not most probable in practice. The initial situations as used in the reality scenarios do certainly provide a more realistic picture of the variation that exists in the field. Especially regarding the increment, these scenarios show results that are considerably closer to the normality than to the new start scenarios. While this is less the case for the harvest amounts, the piece-volume principle as mentioned above brings the CO2 emissions due to forest operations remarkably close to the results of the normality scenarios with almost constant values over time. This is somewhat less so for the ratio of CEF and CUI. Nevertheless, while here the general variation among the concepts is higher than observed for the CEF alone, even the new start scenarios seem quite balanced over time, and stay inside a comparably narrow corridor, the only exception being maritime pine on poorer sites in South Africa.

Relevance for carbon taxation

Carbon tax laws are structured in many countries to be punitive when the total level of C sequestration in the forest decreases. Enterprises that plant trees for C sequestration purposes in climates with fast-growing stands may find that they are liable for high levels of carbon taxation during times that carbon stock levels fluctuate, as visible, for example, in Fig. 12f. The developed model can be used to run scenarios where peaks and troughs are minimized, for the sake of consistency in forest product supplies, and to minimize unnecessary taxation.

Implications for practice and outlook

As a résumé, the outcomes of our study suggest, that regarding the CO_2 emissions due to forest operations (CEF) and their relation to the CO_2 uptake by wood increment (CUI), there is considerable leeway in terms of the choice between different silvicultural options. While the outcomes in terms of increment, and even more harvest amounts are strongly dependent on silvicultural actions, the piece-volume law has a strong buffering effect on the transition from these quantities to CEF and CEF/CUI. That means, when making decisions about silvicultural concepts and pondering their consequences, it seems most important to focus directly on the increment and the amounts to harvest, or in other words, forest productivity expressed by total yield. This is also underlined by the fact that the amount of CO_2 set free when harvesting 1 m^3 of wood is very small compared to the CO_2 equivalents represented by that same m^3 of wood.

One could rightfully argue that our simulations assume constant growth conditions and disturbance regimes, and no development towards more efficient technology in the future. While our model has the possibility to deal with growth trends and changing risks (Biber et al. 2024), we decided to leave out this very speculative element. Especially with regard to the disturbance regimes, it turned out challenging to obtain the small amount of information required even for the present conditions. The buffering effects we observed about our goal variables CEF and CEF/CUI, make the problem of assuming constant environmental conditions seem moderate from a *post-hoc* view. Given the second development, there seems to be considerable potential in future precision forestry (Holopainen et al. 2014; Hoppen et al. 2025). Indeed, there are also developments of increasing electrification in forest operations, but there seem to be still substantial hurdles to take before a widespread application of the technology becomes feasible (cf. Hamilton et al. 2024). Trivial as it might be, electrification of forest operations would mean substantially lower CO_2 emissions only if the electric energy is generated with low or zero CO_2 technology. For that case, the CO_2 emissions due to forest operations as predicted in our study could still be useful as a measure for the required energy. We feel that to significantly reduce CO_2 emissions from forest operations, more effort might be put into the carbon footprint of new machines such as harvesters and forwarders than into reducing their fuel consumption only.

Conclusions

- Due to the buffering effect of the piece-volume principle, CO_2 emissions due to forest operations (CEF) and their ratio with the CO_2 uptake due to wood increment (CUI) are relatively similar across the investigated silvicultural concepts and scenarios
- This opens a broad leeway for silvicultural decisions regarding the goal variables CEF and CEF/CUI
- There is less leeway when the focus is on the increment and the harvest amounts to be obtained from a larger forest area
- For a 1000 ha forest area, our simulations suggest annual CO_2 emissions in a range of about 0.02–0.15 kt, and annual uptakes by wood increment of 2–25 kt. The ratios between emissions and uptakes vary between about 0.1 to 2.5%.
- The software *care4cmodel* will allow investors who grow trees for carbon sequestration goals with the necessary information to plan and manage carbon credits, product flows and carbon taxation situations.

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Author contributions P.B.: Conceptualization, methodology, formal analysis, software, writing—original draft E.A., K.B., M.d.R., B.d.T., S.G., M.P., H.P., R.R.-P., J.S., E.U.: Resources, investigation, validation, writing—review & editing In addition: H.P., E.U. contributed to conceptualization, E.U.: project administration.

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Data availability All silvicultural concept data together with an R script that allows to reproduce all simulation runs shown in the manuscript are provided within the Supplementary Information S2.

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