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Further development of indicators for sustainable forestry in Sweden

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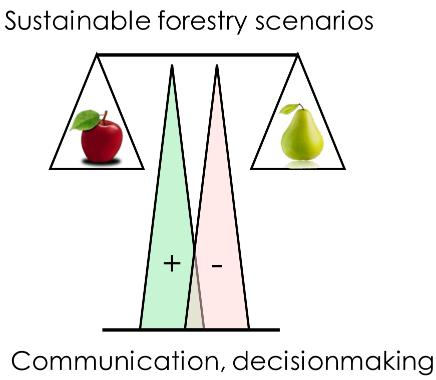
Delivery 2.5.1 from the Mistra Digital Forest research program, phase 2.

This report describes new progress regarding indicators for sustainable forestry in Sweden that has been developed in dialogue with a scientific advisory board.



Preface

The Mistra Digital Forest (MDF) research program aims to contribute to the transformation of the Swedish society to a sustainable bioeconomy. MDF is financed by The Swedish foundation for strategic environmental research (Mistra) in collaboration with the industrial partners BillerudKorsnäs, Holmen, SCA, Stora Enso, Sveaskog, Södra, IVL, Skogforsk as well as the universities Swedish University of Agricultural Sciences (SLU), Umeå university and Royal Institute of Technology (KTH).

This technical report describes methods that can be used for integrated assessments of to what extent one scenario for future Swedish forestry is overall more sustainable compared to another scenario. Methods are described in detail to allow other scientists to replicate the calculations. Therefore, an extended summary is provided for readers that are not interested in all details.

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Summary

Activities within the Mistra Digital Forest (MDF) research program, WP2 task 2.5, aims to develop methods for describing, from an integrated sustainability perspective, alternative scenarios for the production and use of forest raw materials for current and future forestry in Sweden. The development of quantitative indicators to describe different aspects of sustainability for Swedish forestry represents an important part of this work.

The aim of the study was to further develop methods that can be used to assess to what extent one scenario for future forestry is overall more sustainable, compared to other scenarios in the same area. The study will not answer which future scenario that is most sustainable. Instead, the study aims to contribute to the development of standardized and transparent methods for sustainability assessments that can be used as a common basis for future discussions among different stakeholders. The methods presented represents a framework methodology, that has to be further developed and specified, particularly concerning reference scenarios and target values. The methods are intended to be applied for large forest owners or forest owner associations as well as nation-wide assessments.

The methodology for sustainability impact assessments is developed in dialogue with different stakeholders in the Swedish society, as well as with scientific experts. New progress regarding the methodology has been developed in dialogue with a scientific advisory board. The authors of this report are grateful to the advisory board that has provided valuable suggestions, as well as criticism. However, the authors have the full responsibility for the methods that have been developed.

To test the performance of the suggested methodology, different future forestry scenarios were developed for two Swedish counties, Västernorrland (boreal zone) and Kronoberg (boreonemoral zone), over a 100-year period using the Heureka PlanWise software. Five different test scenarios were simulated and analyzed; 1, Current forestry ("CUR"); 2, Increased growth and harvests ("INCR"); 3, Doubled conservation areas and additional biodiversity promoting measures ("DOUBLE+"); 4, Terminated forestry ("STOP") and 5, Standard forestry ("STAND"). The scenario "STOP" simulated that all forest management practice was terminated in 2010. However, forests will still be affected by the forest management activities conducted prior to that year. The scenario "STAND" was aiming to reflect the overall average forestry for the entire Sweden, seeking to minimize the influence of factors such as, e.g., stand age distribution and varying growth conditions.

It should be emphasized that these scenarios are not intended as predictions for future Swedish forestry, they are only used to test the performance of the suggested sustainability assessment methods.

Eight different sustainability indicators were implemented: 1. production of wood-based raw materials; 2. impact on biodiversity; 3. impact on carbon stock change; 4. impact on fossil fuel emissions; 5. impact on recreation values; 6. impact on forest owner economic net income; 7. impact on regional work opportunities; 8. impact on reindeer husbandry. The indicators were generally calculated based on the total area of productive forests under the control by the forest owner, which enables the comparison of different sized forest owners.

The absolute values for the eight, widely different sustainability indicators were transferred to a common, normalized scale with values between -1 and +1, where the value +1 represents the most positive aspects from a sustainability point of view. The absolute values were transferred to normalized values using reference-, preference- and indifference values. The preference (target) value defined the normalized

value +1 while the indifference value defined the value -1. The reference value defined the normalized zero value.

Two different approaches were tested to define the reference scenarios.

1. The current situation in the specific county, as represented by the mean value for each sustainability indicator for the scenario “CUR”, average for periods 1-2 (year 1-10).

2. The standard forestry, as represented by the nationwide mean value for each sustainability indicator for the scenario “STAND”, average for periods 1-20 (year 1-100).

The preference values were in this study set to three times the reference value, unless stated otherwise. This value was set as a “dummy” value for the purpose of testing the suggested methodology and has no real sustainability basis. The indifference value was set to 0.1 times the reference value. Eventually, relevant preference and indifference values will need to be determined through future scientific and policy discussions.

The area-based, relative **production of wood-based raw materials** was calculated relative to the mean “site quality” (“bonitet”) in the respective county. The relative production was higher in Västernorrland compared to Kronoberg. The relative production of forest raw materials was approximately 30-40% higher in the scenario “INCR”, compared to “CUR”, and about 20% lower in the scenario “DOUBLE+”. Obviously, in the scenario “STOP”, there was no production of wood-based raw materials. These relatively modest differences in production implied that the selected scenarios for future forest management in Sweden were relatively realistic, except for the scenario terminated forestry.

The indicator for the **impacts on biodiversity** was calculated as the summed forest areas that comply with some selected structural characters that could be regarded as potentially positive for biodiversity, divided by the forest owner's total productive forest area. Double accounting was allowed, so that the ratio could be higher than 1.0. The development of the indicator values over the 100-year period is shown for the different scenarios in Figure S1. The indicator values for “CUR” scenario increased over time in both counties. The indicator increased progressively more for the scenarios in the order “INCR”, “CUR”, “DOUBLE+” and “STOP”.

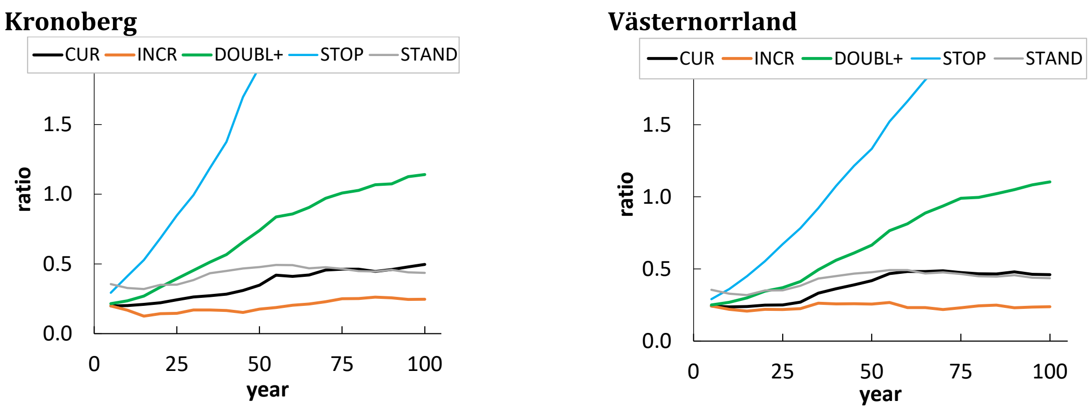

Figure S1. *Indicator values for impacts on biodiversity. Scenarios: Current forestry (CUR); Increased growth and harvests (INCR); Doubled conservation areas and additional measures (DOUBL+); Terminated forestry (STOP). Standardized forestry for entire Sweden (STAND).*

The indicators for area-based **changes in forest carbon stocks** were calculated based on the methodology used in international reporting within the sector land use, land use change and forestry (LULUCF) sector and can take both positive and negative values. The forest ecosystems shifted considerable between being a carbon sink or source over a period of 100 years. Over longer time periods, there was a net uptake of carbon dioxide (CO_2) for forests in both counties and for most scenarios. The CO_2 uptake was highest in the scenario “STOP”, followed by “DOUBL+” and the lowest for the scenario “INCR”. The uptake in the scenario “STOP” might, however, have been overestimated due to uncertainties in the tree mortality rates.

The indicator for area-based **fossil fuel emissions** from forestry was calculated based on the extent of various forest management practices multiplied by emission factors. The fossil fuel emissions were related to the forest management activity and, consequently, to production levels. The area-based fossil fuel emissions from forestry were higher for Kronoberg compared to Västernorrland, due to the longer rotation periods in the latter county. The fossil emissions were highest for the scenario ”INCR”, followed by the scenario “CUR” and with less emissions from the scenario “DOUBLE+”. There were no emissions from scenario ”STOP”.

The **recreation values** were calculated as the cumulative area of forest land meeting certain structural requirements favorable for recreation purposes, divided by the total area of productive forests. Again, double accounting was allowed. The recreation values were lowest in the scenario “INCR” and increased gradually in the scenarios “CUR”, and “DOUBL+”. The values for the scenario “STOP” were overall similar to the scenario “DOUBL+”.

The indicator for forest owner’s area-based net **economic revenue** was estimated by the Heureka model for each forest stand and 5-year period based on the estimated income and costs. Mean values for all stands and for each 5-year period within the respective county were then calculated. In this respect, the calculations assume that the county was one large “forest owner”. The timing of the economic net revenue changed considerably in the different scenarios. The area-based net economic revenues were between 16 and 90 % higher in the scenario “INCR”, compared to “CUR”. The revenue for the scenario DOUBL+ varied considerably over time but was mostly lower than for the “CUR” scenario.

The indicator for local **job opportunities** was based on county-level statistics from the Swedish Forest Agency for annual work units (AWU) that could be related to forestry. The county AWU was related to the production of forest raw materials during the same years and expressed as AWU ha^{-1} yr^{-1}. In Kronoberg, there were considerably more area-based AWU connected with forestry than in Västernorrland. The AWU per productive forest area was highest in the scenario “INCR” and least in the scenario “DOUBLE+”. There was no AWU for the scenario “STOP”.

The indicator for **reindeer husbandry** was intended to reflect forest conditions that are favorable for the growth of ground-based lichens. This was defined as forests dominated by Scots pine, with a share of standing stock for pine >65% of the total standing stock and with a total forest basal area <18 m^2 ha^{-1}. This indicator was calculated for Västernorrland only. The share of the productive forests that fulfilled the criteria to be favorable for ground-based lichens was generally very small since none of the tested scenarios were optimized for reindeer husbandry. Among the scenarios included in the present study, the indicator value was lowest in the scenarios “DOUBL+” and “STOP” and highest in the scenarios “CUR” and “INCR”. Hence, there is a conflict between the impacts on reindeer husbandry and the impacts on biodiversity. It should be emphasized that there were only minor differences between the scenarios with respect to reindeer husbandry and that future forestry in this part of Sweden will have to be much more adapted to reindeer husbandry than the scenarios tested in this study.

All indicators described above were recalculated as characterization factors for each indicator, with a normalized scale between -1 and +1, using reference values together with preference- and indifference values. As described above, we tested two different possibilities regarding the reference scenario, either county-specific current situation or a 100-year mean value for standardized forestry scenario common for entire Sweden. The characterization factors were calculated as mean values for two different periods during the 100-year period, 10-30 and 80-100 years.

The results can be visualized as continuous values between -1 and +1 in for example spider diagrams. Below (Figure S2), results for the mean values for the first period, 10-30 years, for Kronoberg are presented in spider diagrams. The results are shown with either the current situation reference ("initial CUR") or the 100-year mean standard forestry ("STAND"). The center point of the spider diagram represents the indifference value, the middle circle represents the reference value and the outer circle the preference value. In other words, values that are positioned further from the center point are "better" values from a sustainability perspective. For clarity, results are shown only for the three scenarios "Increased production" (INCR), "Doubled conservation areas+" (DOUBL+) and "Terminated forestry" (STOP).

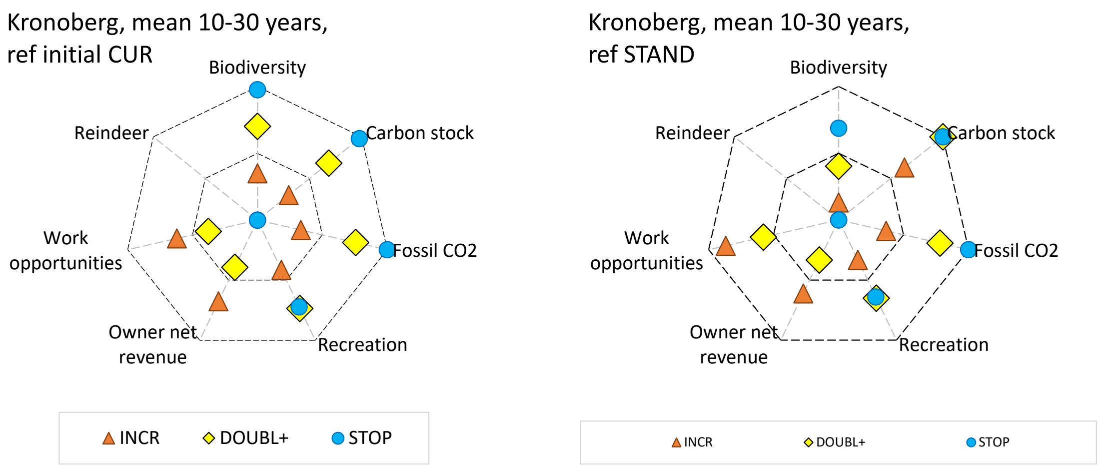

Figure S2. *Spider diagrams illustrating the mean characterization factors for the time period 10-30 years for Kronoberg county based on county-specific current situation (initial CUR) as well as based on a 100-year mean value for a standardized forestry scenario common for all Sweden (STAND). The different forestry scenarios were calculated over a 100-year period, starting in 2010. Values on the middle circle represent characterization values of zero. The outer circle represents characterization values of +1 and the middle point of the diagram represent characterization values of -1. Hence, values that are further out from the midpoint represents "better" values from a sustainability point of view. Note that the indicator for reindeer husbandry is not relevant and hence not calculated for Kronoberg.*
Scenarios: Increased growth and harvests (INCR); Doubled conservation areas and additional measured (DOUBL+); Terminated forestry (STOP).

The order between the different scenarios on the scale from the center point towards the outer circle was overall similar, independently of which reference scenario that was used. For the indicators of biodiversity, changes in forest carbon stocks, fossil CO_2 emissions and recreation values, the most positive values from a sustainability point of view were, as expected, observed for the scenario “STOP” followed by “DOUBL+”, while the scenario “INCR” yielded the least favorable values. For the indicators for the owners net economic revenue and for the work opportunities, the order between the scenarios was reversed. The least favorable values were for the scenario “STOP”.

The overall conclusion from this study is that the suggested methodology results in reasonable values for the different sustainability indicators and the forestry scenarios tested.

The scenario with a 30-40% increased wood production, compared to the current forestry scenario, was related to lower indicator values for biodiversity, forest carbon stock changes and recreation values as well as higher fossil emissions of CO_2. On the other hand, forest owner net economic revenues as well as the creation of local job opportunities were higher in the increased production scenario.

The scenario with doubled conservation areas and additional biodiversity promoting measures, compared to the current forestry scenario, resulted in a 20% decreased wood production, but higher indicator values for biodiversity, forest carbon stock changes and recreation values as well as lower values for fossil emissions of CO_2. The forest owner net economic revenues as well as the creation of local job opportunities were lower in the doubled conservation areas scenario.

The indicator value for reindeer husbandry was a special case with highest values for the current forestry scenario and lowest in the scenario with doubled conservation areas. Hence, there was a conflict between the impacts on reindeer husbandry and the impacts on biodiversity. It should be emphasized that the share of the productive forests that fulfilled the criteria to be favorable for reindeer husbandry was generally very small since none of the tested scenarios were optimized for reindeer husbandry.

The methods need further development, particularly concerning the choice of reference and preference values.

Mistra Digital Forest

1. Introduction

The Mistra Digital Forest (MDF) research program, work package WP2 task 2.5, aims to develop methods for describing and visualizing alternative, future scenarios for the production and use of forest raw materials, for current and future forestry, from a sustainability perspective. It also aims to develop methods that can be used to assess the extent to which one scenario for future forestry in Sweden can be regarded more sustainable, compared to an alternative scenario.

Sustainability impact assessments represent a proactive and holistic evaluation method, aimed at evaluating the potential consequences of policy actions and facilitating life-cycle assessments of forest industry products (Lindner et al., 2010). However, these assessments are complex and encompass a variety of different aspects. There is an urgent need for standardized and transparent methods and tools that enable integrated assessments, balancing environmental, social and economic impacts and analyzing synergies and trade-offs between different management goals (Lundmark, 2023).

The methodology presented in this report represents the development from methods that have been presented earlier (Karlsson et al 2021; Nilsson et al., 2022; Mattsson et al., 2024). The methods presented represent a framework methodology, that needs to be further developed and specified in terms of reference scenarios and preference (target) values.

1.1 Definitions of sustainable forestry

Sustainable development was originally defined as a “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (UN, 1987). Sustainable forest management has been defined by Forest Europe (2020) as “the stewardship and use of forests and forest lands in a way, and at a rate, that maintains their biodiversity, productivity, regeneration capacity, vitality and their potential to fulfil, now and in the future, relevant ecological, economic and social functions, at local, national, and global levels, and that does not cause damage to other ecosystems”.

In the Swedish Environmental Objectives (**https://www.sverigesmiljomal.se/miljomalen/levande-skogar/**) it is stated: "The value of forests and forest land for biological production must be protected, at the same time as biological diversity and cultural heritage and recreational assets are safeguarded." Furthermore, some specifications for sustainable forests are made:

- the physical, chemical, hydrological, and biological qualities and processes of forest land are maintained,
- ecosystem services of forests are preserved,
- the biodiversity of forests is preserved in all natural geographical regions and species have the opportunity to spread within their natural range as a part of a green infrastructure,
- habitats and naturally occurring species associated with forest areas have a favorable conservation status and sufficient genetic variation within and between populations,
- threatened species have recovered and habitats have been restored in valuable forests,
- alien species and genotypes do not threaten the biodiversity of forests,
- genetically modified organisms that can threaten biodiversity are not introduced,
- the natural and cultural heritage values of forests are preserved and the conditions for continued preservation and development of these values are in place, and
- the value of forests for outdoor recreation is safeguarded and maintained.

In general, the number of indicators used in forestry sustainability assessments should be limited in order to avoid too complex and confusing results. On the other hand, relevant and important indicators must be included.

On the basis of the basic considerations described above, we have for the purpose of this study chosen to define sustainable forestry in Sweden as follows:

- The conditions favorable to biodiversity are maintained at an acceptable level
- The increases in the forest ecosystem carbon stocks contribute to a reasonable extent to the mitigation of climate change
- The fossil fuel GHG emissions are minimized to a level consistent with other work machines
- The recreational values of the forests are maintained at an acceptable level
- The net economic revenues for the forest owners are kept at a reasonable level
- The local and regional work opportunities associated with forest operations is contributing to a sustainable rural population
- Forest conditions in relevant parts of the Swedish forests are as far as possible favorable for reindeer husbandry

The definitions of the different sustainability criteria listed above are on purpose kept very broad. The exact definitions must be developed in future dialogues between the scientific community, governmental policymakers, and the forest industry.

The specific indicators used in this study are further described in section 4.3 below.

1.2 What drives the development of sustainability assessment methodologies to be applied for Swedish forestry?

Forests provide both market-traded goods and services, as well as non-market benefits, such as various environmental and climate-related impacts (Konjunkturinstitutet, 2021). It can be argued that an unregulated market will not inherently result in the optimal use of forest resources to maximize societal benefits. Consequently, a key role of the political framework is to address these market failures. Forest and environmental policies must therefore be grounded in robust, well-founded data that offer guidance and facilitate trade-offs between the diverse dimensions of sustainability (Konjunkturinstitutet, 2021).

Key actors in the forestry sector are independently developing methods to assess various aspects of sustainability within their own forest operations, driven primarily by marketing objectives. This is problematic since a fundamental principle of environmental performance assessments is that evaluations should be conducted using standardized methods to enable fair comparisons across similar products from different manufacturers. Hence, there is a need to standardize methods and target values for calculating sustainability in Swedish forestry, in close consultation with a wide range of stakeholders both nationally and internationally.

There is a strong need for consensus about methods, assumptions and reporting of results to be used for sustainability assessments of the production of forest-based raw materials. It is important to consider the details since minor differences in the definitions of concepts, formulations of hypotheses, methodologies and input data used can explain why different conclusions can be reached, for example regarding the climate impacts from forestry (Englund et al., in preparation).

2 Aims

The overall aim of this study is to further develop methods that can be used for integrated assessments of to what extent one scenario for future forestry is overall more or less sustainable compared to another scenario for future forestry in the same area.

The aim of this report is to further develop methods to deepen the discussions about basic principles for methods to be used for sustainability assessments of forestry, with a focus on Swedish forests. It should be emphasized that the study will not try to answer which choice for the future Swedish forestry that is most sustainable. Instead, the study aims to contribute to the development of standardized, transparent and integrated sustainability assessments methods that can be used as a common basis for future discussions among different stakeholders. The methods are intended to be applied for large forest owners or forest owner associations as well as nation-wide assessments.

3. Methodology overview

3.1 What are the intended applications for the methods?

In general, the suggested methods are intended to be applied for large forest owners or forest owner associations, alternatively to large regions or nationwide assessments. The methods for assessing sustainability in Swedish forestry are intended to be possible to use in a wide range of applications, such as

- Strategic planning for large forest owners or forest owner associations, for example Sveaskog and Södra
- Swedish Forest Agency forestry impact assessment (SKA)
- A basis for a geographical region, e.g., a county, to assess its overall impacts on the climate, now and in the future

The user can start the analysis based on Heureka model outputs for all its productive forests, or use its own forest inventories, with an output format suitable for the calculations of the sustainability indicators described here. The input values that are needed are describe in Appendix 1.

The other possibility would be to create a ”library” with a large number of sustainability indicator calculations made for representative regions for different parts of Sweden and made for a large selection of future scenarios for Swedish forestry. A forest owner might use a relevant selection of these examples as a basis for own decisions.

3.2 The need for a reference scenario

In the general context of systems analysis of biological systems, a reference scenario is used to facilitate the assessment of how the studied “system” influences the aspects of interest (Soimakallio et al., 2015, Brander, 2015; Schulte et al., 2022). Since major parts of Swedish forest land are managed, it is useful to compare the performance of one forest owner in comparison with the general performance of all forest owners in the relevant surrounding geographical region, i.e. “business as usual” (Mattson et al., 2022; 2024). Moreover, a reference scenario is needed to transfer absolute values for different sustainability indicators to a common normalized scale, se further below.

In this study, we assess two different basic choices for reference situations; 1, the current situation of the forest in the respective counties **(“county-specific, current situation”**) and 2, the situation in a hypothetical standard forestry scenario as a nationwide mean value over an entire 100-year time period (“**Nation-wide standard forestry**”).

The “Current situation” reference scenario is calculated separately for each indicator and each county, based on the mean values in the forestry scenario “Current forestry” for the first 10 years of the assessed 100-year period. The advantage of the “Current situation” reference scenario is that it is relatively easy to understand what it represents. The disadvantage is its strong dependence on the status of the forests in the county during the time 2010-2020, such as the age distribution of forest stands, meaning the comparison with the reference scenario will be heavily influenced by this initial condition. For example, the forests in Kronoberg county were severely affected by the storm “Gudrun” in 2005, which has consequences for the age distribution of the forest stands even today. A further disadvantage is that this reference scenario will be different between the two counties.

The “Standard forestry” reference scenario is based on a hypothetical, “average” forestry in Sweden and its development over a 100-year time period. The aim was to avoid the influence of the initial conditions of the forests as much as possible, while still being reasonably realistic. A nation-wide reference scenario could be constructed that could be used for both counties. The disadvantage was that it was difficult to understand what this “Standard forestry” reference scenario in fact represents.

3.3 Transfer to a common normalized scale

In order to transfer absolute values for the different sustainability indicators into normalized values between -1 and +1, preference and indifference values had to be used for each indicator and county, in combination with the reference values (Karlsson et al., 2021; Mattsson et al., 2024). The preference value will define the limit for the normalized value +1, while the indifference values will define -1 (Figure 1). Based on the nomenclature used in system analysis, the normalized value is named “**Characterization factor**”, (CF). Hence, the CF factor is the normalized value on a common scale and calculated separately for each sustainability indicator.

So far in this study, we are using “dummy” preference and indifference values with the purpose to test the performance of the suggested methodology. Relevant preference and indifference values will need be suggested later, based on a consensus between scientific and policy-related perspectives. One possibility would be to base the preference values based on Environmental Quality Objectives (EQO), such as the EQO “Living forests” in the case of Sweden. One question would be whether the preference values should vary geographically across Sweden, depending on differences in climate and other edaphic factors.

The choice of the preference and indifference values will have a profound influence on the normalized value that is calculated. As can be seen in Figure 1, the slope between the normalized (-1 - +1) characterization factor and the absolute value for the sustainability indicator will depend on the choice of the preference value. The same is true also for the choice of indifference value (not shown).

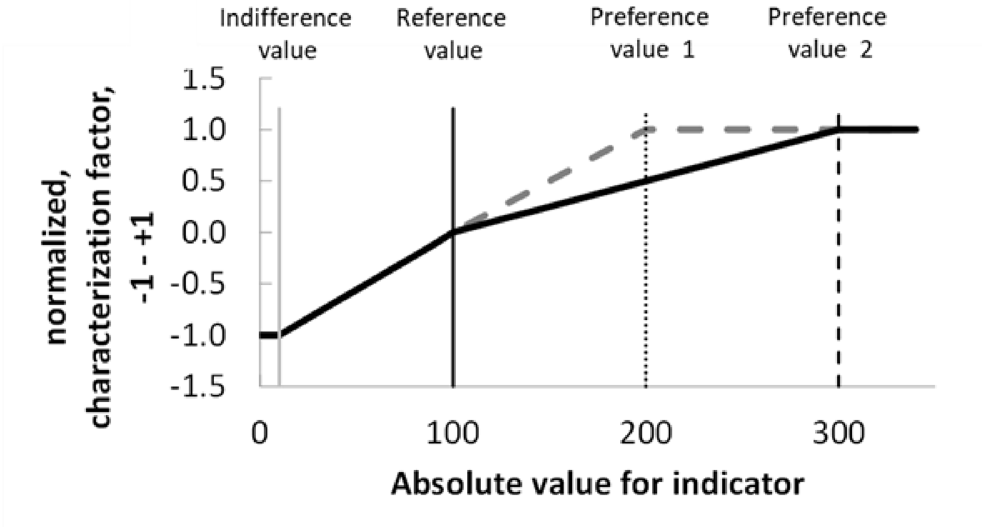

Figure 1. *Theoretical relationships between absolute values for any sustainability indicator (on the x-axis) and the corresponding calculated normalized (-1 - +1) characterization factor (on the y-axis) for two cases with different preference values. In both cases the reference value was set to an absolute value of 100 and the indifference value was set to 10. In the first case (shown with broken grey line), the preference values were set to twice the reference value, i.e. 200. In the second case (shown with a continuous black line), the preference value was set to three times the reference value, i.e. 300.*

In the following, for model test purposes, the "dummy" preference values were set to three times the reference value as a guiding principle, unless stated otherwise. The indifference value was set to 0.1 times the reference value.

The reference-, preference- and indifference values that were used in this study are presented for Kronoberg and Västernorrland using the reference scenario based on initial current forestry scenario in Table 1 and based on the reference scenario for a nationwide standard forestry in Appendix 2.

Mistra
Digital Forest

Table 1. *Reference, preference and indifference values used for Kronoberg, (value before the slash) and for Västernorrland (value after the slash) based on initial current forestry scenario. The principles used for the calculation of the values are indicated in the three columns to the right. Note that double accounting of areas that fulfil several of the defined characteristics is permitted.*

	Unit	Reference	Preferens	Indiffe-rens	Principle, reference	Principle, preferens	Principle, indifferens
Biodiversity	fraction of total productive forest area	0.20/ 0.24	0.60/ 0.72	0.02/ 0.002	Current forestry, average periods 1-2	3 * reference value	10% of reference value
Change carbon stocks	ton CO_{2e} ha^{-1} yr^{-1} (uptake negative value)	-3.69/ -3.34	-11.08/ -10.02	0.00/ 0.00	Current forestry, minimum periods 1-20	3 * reference value	zero (carbon neutral)
Fossil fuel emissions	ton CO_{2e} ha^{-1} yr^{-1}	0.01/ 0.02	0.001/ 0.002	0.04/ 0.05	Current forestry, avg periods 1-2	10% of reference value	3 * reference value
Recreation	fraction of total productive forest area	0.31/ 0.28	0.92/ 0.85	0.03/ 0.03	Current forestry, avg periods 1-2	3 * reference value	10% of reference value
Job opportunities	AWU, ha^{-1} yr^{-1}	0.0012/ 0.0006	0.0035/ 0.0019	0.0001/ 0.0001	Current forestry, avg periods 1-2	3 * reference value	10% of reference value
Net economic income	SEK ha^{-1} yr^{-1}	613/ 772	1840/ 2315	61/ 77	Current forestry, avg periods 1-2	3 * reference value	10% of reference value
Reindeer husbandry	fraction of total productive forest area	-/ 0.05	-/ 0.16	-/ 0.01	Current forestry, avg periods 1-2	3 * reference value	10% of reference value

4. Revised calculations

The revised calculations used in this study are described in detail in Appendix 3. The calculations are described in brief below, with a focus on comparisons with previously published calculations (Karlsson et al., 2021; Nilsson et al., 2022; Mattsson et al., 2024).

4.1 Scenarios for future Swedish forestry

Heureka PlanWise software, version 2.18.3 was used to calculate different result parameters from forestry over a 100-year time period, based on simulations for two counties with large forest cover in Sweden: Västernorrland in the northern part of Sweden (boreal zone) and Kronoberg in the southern part of Sweden (boreonemoral zone). In principle, the calculations include areas voluntarily set aside for nature conservation, with no forestry performed. However, in this study information about areas voluntarily set aside was not available and had to be simulated.

This study's planning horizon extends from the year 2010 to the year 2110, with outcomes presented in 20 distinct 5-year intervals. The simulations will depend strongly on the initial conditions of the forests in the year 2010, depending for example on the distribution of stand ages.

Five different scenarios were simulated and offer realistic representations of the potential future trajectory of Swedish forestry (Table 2), except for the scenario “STOP” which was included to illustrate the possible consequences if all forestry operations were suddenly terminated 2010.

The scenarios were developed based on different aspects of optimization and should not be seen as predictions for the development of future Swedish forestry.

Table 2. *Scenarios for future Swedish forestry during 100 years, 2010-2110 used in the present study.*

Scenario	Acronym	Short description
1. Current forestry	“CUR”	Reflects a development in which Sweden's forests are used and managed as they are today
2. Increased growth and harvests	“INCR”	Increased timber production (growth) and harvest rates given reasonable but high investment levels in forestry
3. Doubled conservation areas and additional measures	“DOUBL+”	Double the areas that are set aside, primarily for conservation reasons, compared to Scenario 1, in combination with increase areas with continuous forestry and prolonged rotation periods
4. Terminated forestry	“STOP”	All forestry practices were terminated 2010; however, the forests will continue to be influenced by the forestry activities that were conducted prior to that year.
5. Standard forestry	“STAND”	Aiming to reflect the overall average forestry for the entire Sweden, with the aim to eliminate as far as possible the influence of the stand age distribution, etc

The scenario “STAND” was used as a reference scenario in one of the used approaches to estimate normalized characterization factors.

4.2 Indicators

The methods used to calculate the different indicators are described in detail in Appendix 3, briefly in Table 3 and in the individual results chapters below. Compared to previous calculations (Karlsson et al 2021; Nilsson et al., 2022; Mattsson et al., 2024), we added two more indicators; 1. Area-based relative production of forest raw materials; 2. Area of production forests with characteristics that are positive for reindeer husbandry.

Table 3. *Sustainability indicators used in the present study.*

Indicator	Unit	Short description
1. Production of wood-based raw materials	Ratio versus site quality, m^3o.b. ha^{-1} yr^{-1}/ m^3o.b. ha^{-1} yr^{-1} *	Area based annual production for the specific period/scenario/county relative to the "site quality" (bonitet) of the same area.
2. Impact on biodiversity	Ratio versus total productive forest area	Calculated as the summed area that fulfil some selected structural characteristics divided by the total area of productive forest of the forest owner
3. Impact on carbon stock change	Ton CO_2 ha^{-1} yr^{-1}, uptake from the atmosphere to the forest ecosystem is calculated with negative values.	Calculated with a methodology compatible to what is used in international reporting within the sector land use, land use change and forestry (LULUCF). Changes are calculated for the carbon stocks living and dead biomass and soil carbon, the latter separated into mineral and organic soils.
4. Impact on fossil emissions	Ton CO_2 ha^{-1} yr^{-1}, emissions to the atmosphere is calculated with positive values.	Calculated based on the extent of various forestry management practices (e.g., harvesting, site preparation, etc.), multiplied by emission factors
5. Impact on recreational values	Ratio versus total productive forest area	Calculated as the summed area that fulfil some selected structural characters divided by the total area of productive forest of the forest owner
6. Impact on forest owner economic net income	SEK ha^{-1} yr^{-1}.	The forest owner's economic revenue is estimated by the Heureka model for each forest stand and 5-year period, based on the estimated income and costs. Mean values are calculated for each 5-year period for all stands within the respective county.
7. Impact on regional job opportunities	Annual work units, AWU	Based on statistics from the Swedish Forest Agency regarding the AWU that is connected with different forestry activities, aggregated for the categories large-scale forestry, small-scale forestry and entrepreneurs
8. Impact on reindeer husbandry	Ratio versus total productive forest area	Intended to reflect forest conditions that are favorable for the growth of abundant ground-based lichens. Summed areas with open Scots pine dominated forests, with standing stock for pine >65% of total standing stock and with a total forest basal area <18 m^2 ha^{-1}.

* o.b., over bark

5 Results

The results of the calculations of the different indicators are described in detail below with diagrams spanning the 20 consecutive 5-year periods. Furthermore, 20-year mean values were calculated representing the beginning (10-30 years) and end (80-100 years) of the 100-year period. The tables for these 20-year mean values can be found in Appendix 4. The reason for not starting the analysis with the first two periods was that initial changes on the forest management practices resulted in some transient changes in the forest stand characteristics.

5.1 Production of forest raw materials

Calculations with the Heureka PlanWise software can provide results for the production of forest raw materials of different qualities, i.e. saw timber and pulpwood, separated for final cut harvests, thinning and cleaning. However, for this study the indicator for the production wood-based raw materials was aggregated across all different qualities of the materials. The area based annual production (m^3o.b. ha^{-1} yr^{-1}) was related to the mean "Site Quality" (m^3o.b. ha^{-1} yr^{-1}) of the same area, as a ratio. The Site Quality is a classification of forest land in terms of the capacity to repeatedly produce industrial wood. This classification is based on the maximum mean annual increment, of natural, well- stocked, even-aged stands of species suitable to the local site (Hägglund & Lundmark 1981). An indicator value >1 thus represents a production that is higher than the estimated Site quality and vice versa. The mean values for the indicator for forest raw materials were estimated separately for each time period and for each county. In this regard, each county was regarded as one large forest owner. Since the production of wood-based raw materials is already calculated in relation to Site quality, no characterization factors were calculated. In the scenario "STOP" there was, of course, no production of forest raw materials. The estimated mean Site quality was for Kronoberg 9.16, for Västernorrland 4.02 and for the scenario "standard forestry" 5.1 m^3o.b. ha^{-1} yr^{-1}.

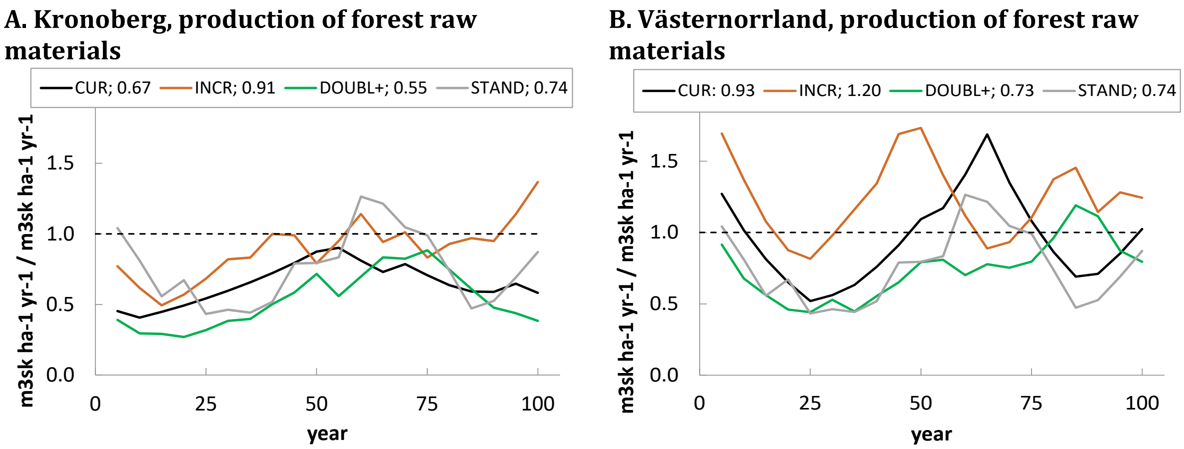

Figure 2. *Indicator for the production of wood-based raw materials. The indicator is calculated over 100 years, divided into 5-year periods, as the area based annual production (m^3o.b. ha^{-1} yr^{-1}) relative to the "Site quality" (m^3o.b. ha^{-1} yr^{-1}) of the same area, as a ratio. A value >1 thus represents a production that is higher than the estimated "Site quality" and vice versa. For the scenario "STOP", the production is zero and not shown. The value when actual production is the same as "Site quality", 1.0, is indicated with a horizontal dashed line. The mean "Site quality" was for Kronoberg 9.16, for Västernorrland 4.02 and for the scenario "standard forestry" 5.1 m^3o.b. ha^{-1} yr^{-1}. In the figure legend, next to each scenario abbreviation, is indicated the mean indicator value for the specific scenario for the period 10-100 years.*

The production of forest raw materials, relative to the "Site Quality", for the scenario "Current forestry" ("CUR") was in general higher in Västernorrland compared to Kronoberg (Figure 2, Appendix 4, Table A4_1). The production in the scenario "CUR" in Kronoberg was slightly lower compared to the production in the scenario the "Standard forestry scenario" ("STAND"). However, it should be noted that the Site Quality for the scenario "STAND" was much lower, compared to the Site Quality used for Kronoberg.

The relative production in the scenario "CUR" in Västernorrland was considerably higher compared to the production in the scenario the "STAND". However, in this case it should be noted that the Site Quality was much higher in the scenario "STAND", compared to the Site Quality used for Västernorrland. The relative production in the different scenarios varied between the different periods. In the scenario "INCR", the production over the entire 100-year period was on average 30-40% higher, compared to "CUR" (Figure 2). In the scenario "DOUBL+", the production was on average 20% lower compared to "CUR".

The relative production was in general higher in Västernorrland compared to Kronoberg. The relative production in the “Standard forestry scenario” was lower compared to Kronoberg but higher compared to Västernorrland.

The production of forest raw materials was, compared to the scenario “CUR”, in the order of 30-40% higher in the scenario “INCR” and approximately 20% lower in the scenario DOUBLE+”.

5.2 Indicators for biodiversity

The indicator for the impacts by forestry on biodiversity is based on the summed area that fulfil some selected structural characteristics that can be considered as positive for biodiversity divided by the total productive forest area of the forest owner. The selected characters were:

> **1. Stands with old trees**. The average tree age in the stand should be above 140 years in northern Sweden and above 120 years in southern Sweden; **2. Stands with dead wood**; There should be more than 20 m^3 of dead wood per hectare, including only dead wood with a diameter greater than 20 cm; **3. Mixed deciduous and coniferous tree species**. The average tree age in the stand should be above 80 years, and more than 3/10 of the basal area should be deciduous tree species; **4. Stands with a continuous forest management plan.**

The application of a continuous forest management plan will transform the structure of the forest gradually over time. For that reason, for the character **Stands with a continuous forest management plan**, a factor was applied that starts with a value 0.1 for period 1 and for Kronoberg it takes the value of 1.0 at period 10 and beyond. For Västernorrland it takes the value of 1.0 at period 20. The factor was introduced to reflect that the application of a forest management plan for continuous forestry will in reality have a gradually increasing impact to reduce final cut harvests, with its full implication when all forest stands have reached the age for potential final cut harvests. In the scenario “STOP” it was assumed that all areas productive forests were managed as continuous forestry.

The absolute values as well as the characterization factors were overall similar between Kronoberg and Västernorrland (Figure 3, Appendix 4, Table A4_2) for all scenarios. The values for the scenario “CUR” increased over time. The indicator absolute values for “STAND” were in the first part of the 100-year period higher compared to “CUR” in both counties but were similar at the end. This was related to low areas with dead wood and old forests during the first 10 period in the scenarios “CUR” for the two counties, compared to “STAND”. The absolute indicator value for the scenario “STOP” exceeded the ratio value 1.0 early in the 100-year time period. This was possible since double accounting of areas that fulfil several of the selected structural characters was allowed. The differences between the scenarios were as expected, with lower values for the scenario “INCR” and progressively higher value for the scenarios “CUR”, DOUBL+” and “STOP” (Figure 3, Table A4_2).

In the scenario “CUR”, the areas with dead wood contributed the most to the biodiversity indicator in both counties. This was followed by the areas with old forests. The areas with continuous forestry contributed the least (data not shown).

Overall, the indicator for impacts on biodiversity increased oven time, except for the scenario “INCR”, and increased progressively more for the scenarios “CUR”, “DOUBL+” and “STOP”.

The choice of reference scenario did not make much difference for the calculation of characterization factors.

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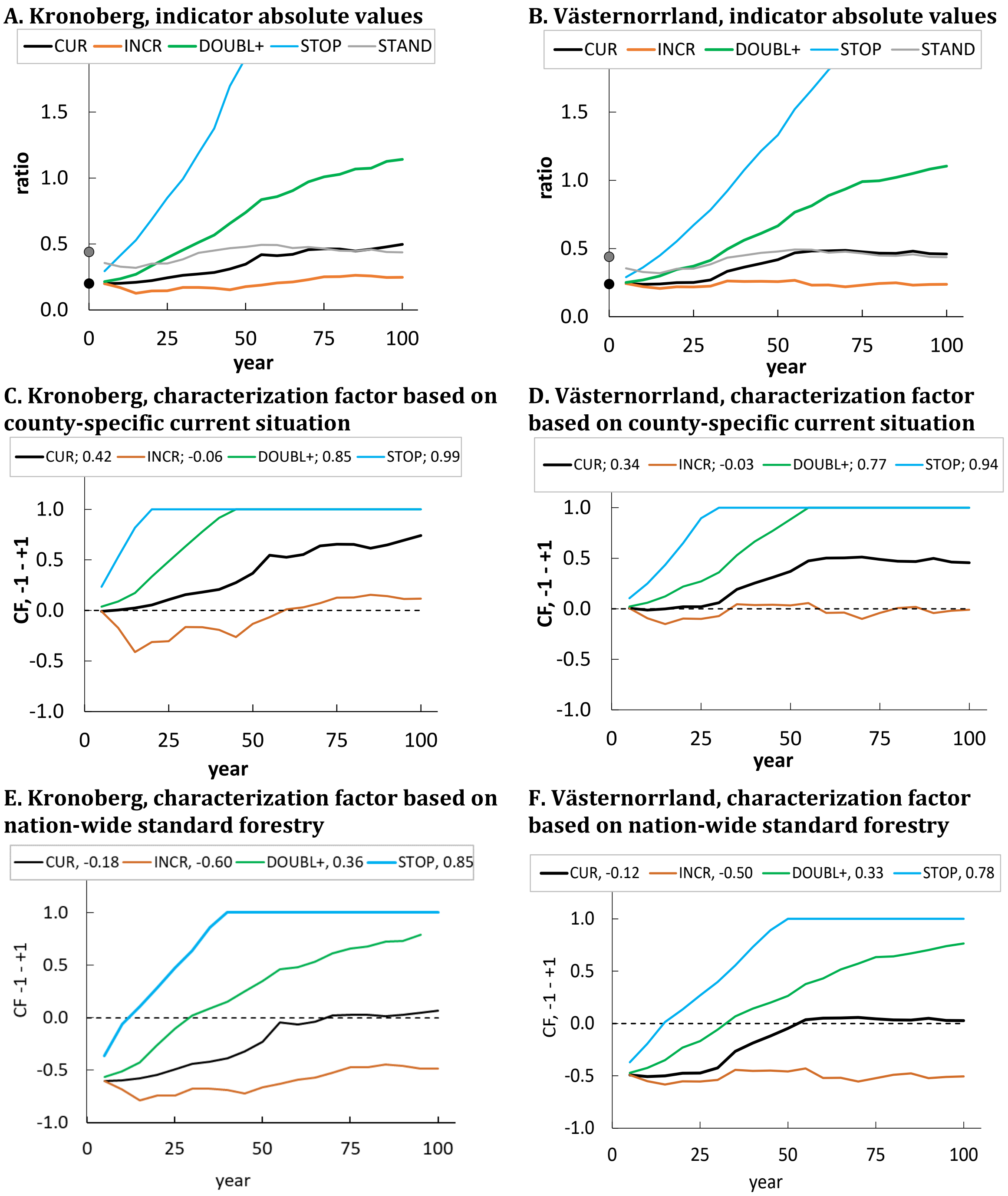

Figure 3. *Indicator for impacts on biodiversity. The indicator is calculated as the summed area that fulfil some selected structural characteristics divided by the total area of productive forest of the forest owner. A,B, indicator values in absolute values; C,D, characterization factors based on the reference scenario for the county-wise current situation; E,F, characterization factors based on the reference scenario for the nation-wide standard forestry. In Figures A and B, the reference values are shown in the y-axis at x=0, such that the circle filled with black shows the county-specific current situation reference values and the circle filled with grey shows that nation-wide standard forestry reference value. In Figures C, D, E and F the mean characterization factor over the time period 10-100 years is shown in the legend for each scenario.*
Scenarios: Current forestry (CUR); Increased growth and harvests (INCR); Doubled conservation areas and additional measures (DOUBL+); Terminated forestry (STOP). Standardized forestry for entire Sweden (STAND). CF, characterization factor, -1 - +1.

5.3 Indicators for changes in forest ecosystem carbon stocks

Indicators for changes in forest ecosystem carbon stocks for the difference scenarios were calculated for the carbon stocks living and dead biomass and soil carbon, the latter separated into mineral and organic carbon stocks. Changes in the soil carbon stocks were estimated based on area-based emission factors, separate for mineral- and organic soils and separate for the two different counties (due to latitude differences). Identical soil emissions factors were used in the different forestry scenarios. The removal of carbon from the atmosphere to the forest ecosystem is shown with a negative sign. However, note that in the case of the characterization factors a positive value represents a removal of carbon from the atmosphere to the forest ecosystems. The fact that absolute values for this indicator can be both positive and negative values complicated the choice of reference values. Values close to zero would be difficult to use for the calculation of the characterization factors. Hence, the choice of reference value was decided as the minimum value (most negative value, i.e. the highest CO_2 uptake to the forest ecosystem) that was present in the scenario "CUR" within the specific county. In the case of "STAND" the 100-year mean value was used. In all cases the preference value was chosen as three times the reference value. The indifference value was chosen to be zero. This means there is no net change in the forest ecosystem carbon stocks.

The results show that the forest ecosystems may shift considerably between being a sink or a source over a period of 100 years in all scenarios except "STOP" (Figure 4). In the scenario "STOP" the forests were always a sink, even though the sink was decreasing towards the end of the 100-year period. There was a net uptake of CO_2 to the forests as an average for both twenty years periods, at the beginning and at the end of the 100-year period, for both counties and for all scenarios, except for the scenario "DOUBL+", 80-100 years in Västernorrland (Table A4_3). The area-based uptake of CO_2 was in general higher in Kronoberg compared to Västernorrland (Appendix 4, Table A4_3, Figure 4). The uptake in the scenario "STAND" was similar to "CUR" in Kronoberg while it was higher compared the scenario "CUR" in Västernorrland.

The CO_2 uptake by forests was highest in the scenario "STOP", followed by "DOUBL+" (Table A4_3, Figure 4). However, in the scenario "DOUBL+" for Västernorrland, 80-100 years, the forest was a strong source of CO_2. The CO_2 uptake was lowest in the scenario "INCR", except for Västernorrland 80-100 years when it was higher in "INCR" compared to "CUR". There was a period in the 100-year period, periods 8-16, when the forest ecosystems in many cases were a source of CO_2 (Figure 4). The performance of the characterization factors was very similar, independent of if they were based on the county-wise current situation or on the nation-wide standard forestry scenario (Figure 4).

Over longer time periods, there was a net uptake of CO_2 at the beginning and at the end of the 100-year period for both counties and for all scenarios, except the scenario "DOUBLE+" at the end of the period.

The CO_2 uptake was highest in the scenario "STOP", followed by "DOUBL+" and the lowest for the scenario "INCR".

The performance of the characterization factors was very similar, independent of if they are based on the county-wise current situation of on the nation-wide standard forestry scenario.

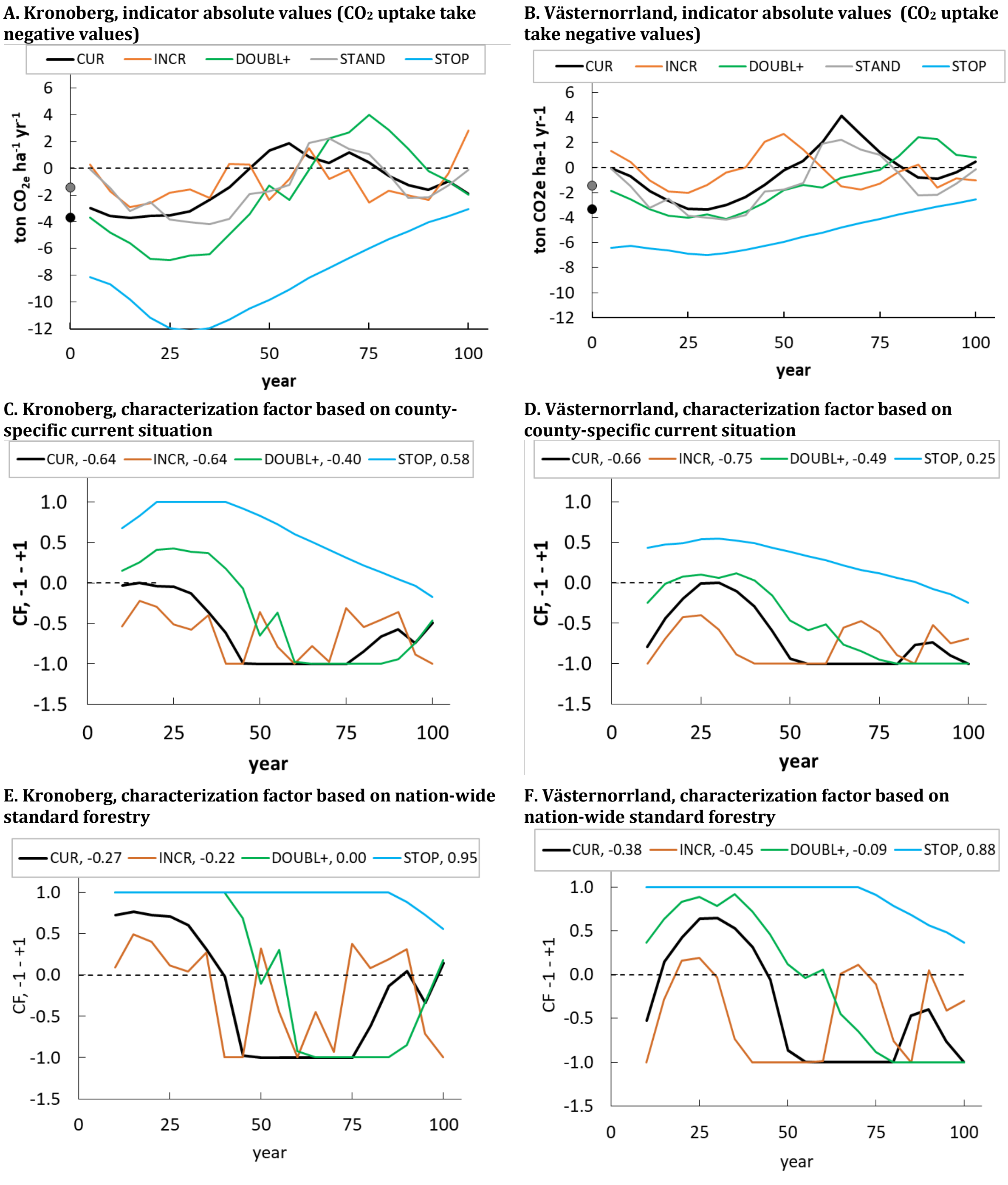

Figure 4. *Indicator for changes in forest ecosystem carbon stocks. The indicator is calculated in line with the methodology used in international reporting within the sector land use, land use change and forestry (LULUCF). A,B, indicator values in absolute values; C,D, characterization factors based on the reference scenario for the county-wise current situation; E,F, characterization factors based on the reference scenario for the nation-wide standard forestry. In Figures A and B, the reference values are shown in the y-axis at x=0, such that the circle filled black shows the county-specific current situation reference values and the circle filled with grey shows that nation-wide standard forestry reference value. In Figures C, D, E and F the mean characterization factor over the time period 10-100 years is shown in the legend for each scenario. Scenarios: Current forestry (CUR); Increased growth and harvests (INCR); Doubled conservation areas and additional measures (DOUBL+); Terminated forestry (STOP). Standardized forestry for entire Sweden (STAND). CF, characterization factor, -1 - +1.*

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5.4 Indicators for fossil emissions

The fossil greenhouse gas emissions from forestry were calculated based on the extent of various forestry management operations (e.g., harvesting, site preparation, etc.), utilizing emission factors developed by the Forestry Research Institute of Sweden (Ågren et al., 2021). These emission factors, applied uniformly across the Nordic region, include only fossil greenhouse gas emissions. Fossil emissions were expressed as ton CO_2e ha^{-1} yr^{-1}. Emission factors were applied for the following forestry activities: Land preparation, Fertilization; Clearing; Thinning; Final felling; Logging, thinning; Logging, final felling; Logging, Extraction of forest fuel branches and tops; Chipping, Extraction of forest fuel branches and tops; Construction of forest roads; Maintenance of harvesters; Maintenance of forwarders,

The fossil emissions were closely coupled to the forest management activity and hence to the area-based harvest rates. The estimated fossil emissions from forestry were generally higher for Kronoberg compared to Västernorrland (Figure 5), mainly due to the longer rotation periods in the latter county. The estimated emissions for the scenario "STAND" were similar to the scenario "CUR" for Västernorrland and lower than for "CUR" in Kronoberg" (Appendix 4, Table A4_4). For both counties, the area-based fossil emissions were highest for the scenario "INCR", followed by the scenarios "CUR" and with less emissions from the scenario "DOUBL+" (Table A4_4). There were no fossil emissions in the scenario "STOP" due to the terminated forestry.

The development of the characterization factors over time were similar when the reference scenarios from today's current forestry or the 100-year mean standard forestry were used (Figure 5). It did not reach the preference or indifference values in any case.

The estimated area-based fossil emissions from forestry were higher for Kronoberg compared to Västernorrland, due to the longer rotation periods in the latter county.

The area-based fossil emissions were highest for the scenario "INCR", followed by the scenario "CUR" and with less emissions from the scenario "DOUBL+". There were no emissions from scenario "STOP".

The development of the characterization factors over time were very similar for both approaches used for the reference scenario.

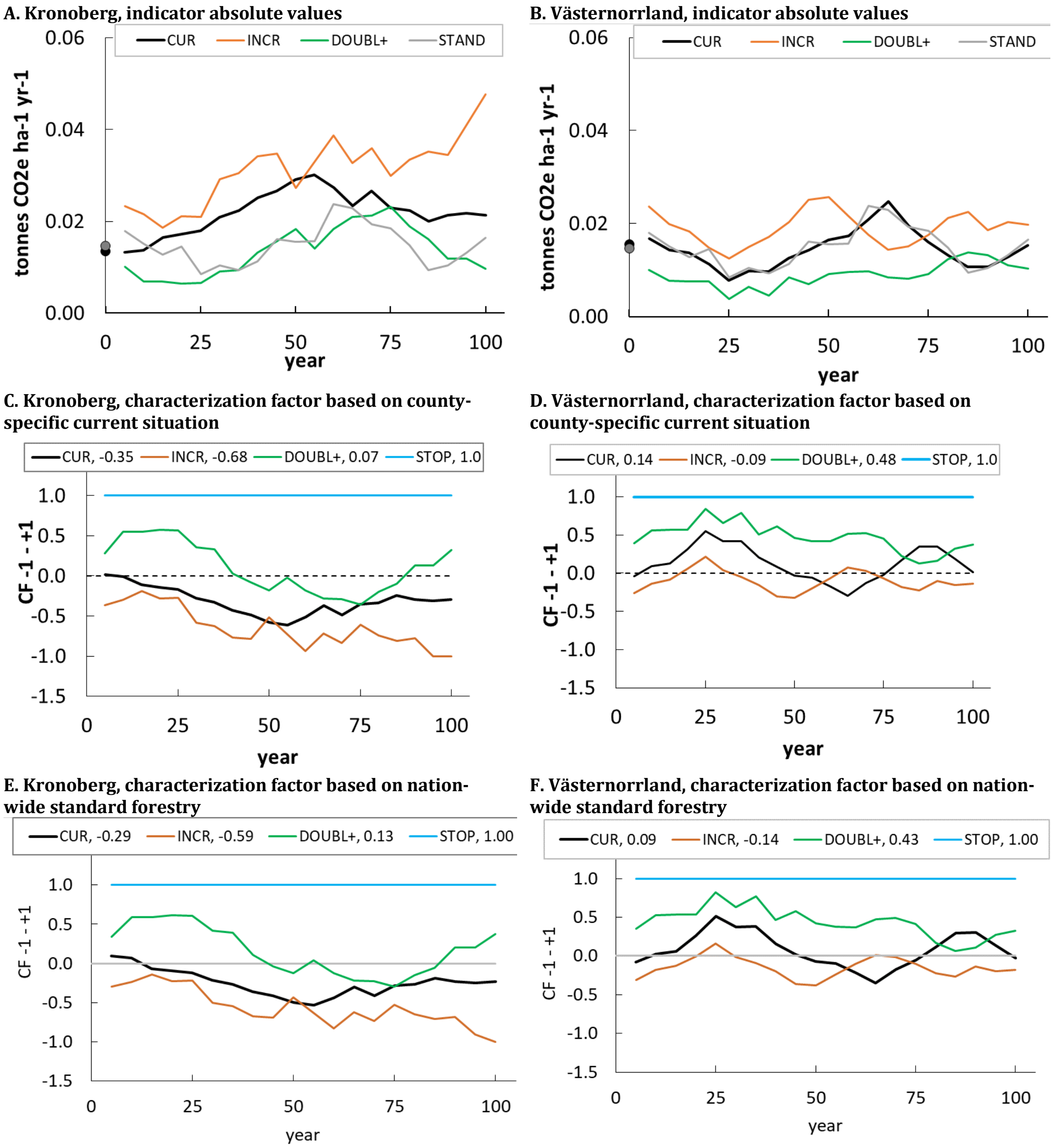

Figure 5. *Indicator for fossil emissions that could be linked to forestry. The indicator is calculated based on forestry operations multiplied with different emission factors. There were no emissions in the scenario "STOP". A,B, indicator values in absolute values; C,D, characterization factors based on the reference scenario for the county-wise current situation; E,F, characterization factors based on the reference scenario for the nation-wide standard forestry. In Figures A and B, the reference values are shown in the y-axis at x=0, such that the circle filled black shows the county-specific current situation reference values and the circle filled with grey shows that nation-wide standard forestry reference value. In Figures C, D, E and F the mean characterization factor over the time period 10-100 years is shown in the legend for each scenario.*
Scenarios: Current forestry (CUR); Increased growth and harvests (INCR); Doubled conservation areas and additional measures (DOUBL+); Terminated forestry (STOP). Standardized forestry for entire Sweden (STAND). CF, characterization factor, -1 - +1.

5.5 Indicators for recreation values

The recreational values of the forests were calculated as the cumulative area of forest land that meets the requirements for:

1. Easily accessible forests with good visibility, meaning sparsely grown, mature productive forests. Sparsely grown forests are calculated as areas with a maximum of 1000 tree stems per hectare and a stand age exceeding 50 years; **2. Forests where the proportion of deciduous trees** exceeds 80%. The proportion of deciduous forest is calculated for stands older than 20 years; **3.** Areas with productive forest stands that are **devoid of final-cut harvests** during the last ten years, were included as the fraction exceeding 80%.

The sum of the areas meeting these criteria was related to the total area of productive forest land as a ratio. However, due to the allowed double accounting, these values could sometimes exceed 1.0.

For most scenarios and periods, the recreation values were higher in Kronoberg, compared to Västernorrland (Figure 6). The values for the scenario ”STAND" were similar to "CUR" in Västernorrland both lower compared to the values for Kronoberg (Appendix 5, Table A4_5). In general, the recreation values were lowest in the scenario "INCR" and then gradually higher in the scenarios "CUR", and "DOUBL+" (Table A4_5), both initially and at the end of the 100-year period. The value for the scenario "STOP" was overall similar to "DOUBL+". However, it can be assumed that the values for the scenario "STOP" were to some extent overestimated since the increased forest stand densities as a result of terminated forestry may not have been fully accounted for.

The order between the scenarios regarding the CF values did not differ much if the reference was based on the county-wise current situation or on the nation-wide standard forestry 100-year mean value (Figure 6).

The recreation values were in most scenarios higher in Kronoberg, compared to Västernorrland

The recreation values were lowest in the scenario "INCR" and then increased gradually in the scenarios "CUR", and "DOUBL+". The values for the scenario "STOP" was overall similar to the scenario "DOUBL+".

The CF value did not differ depending on the choice of reference value.

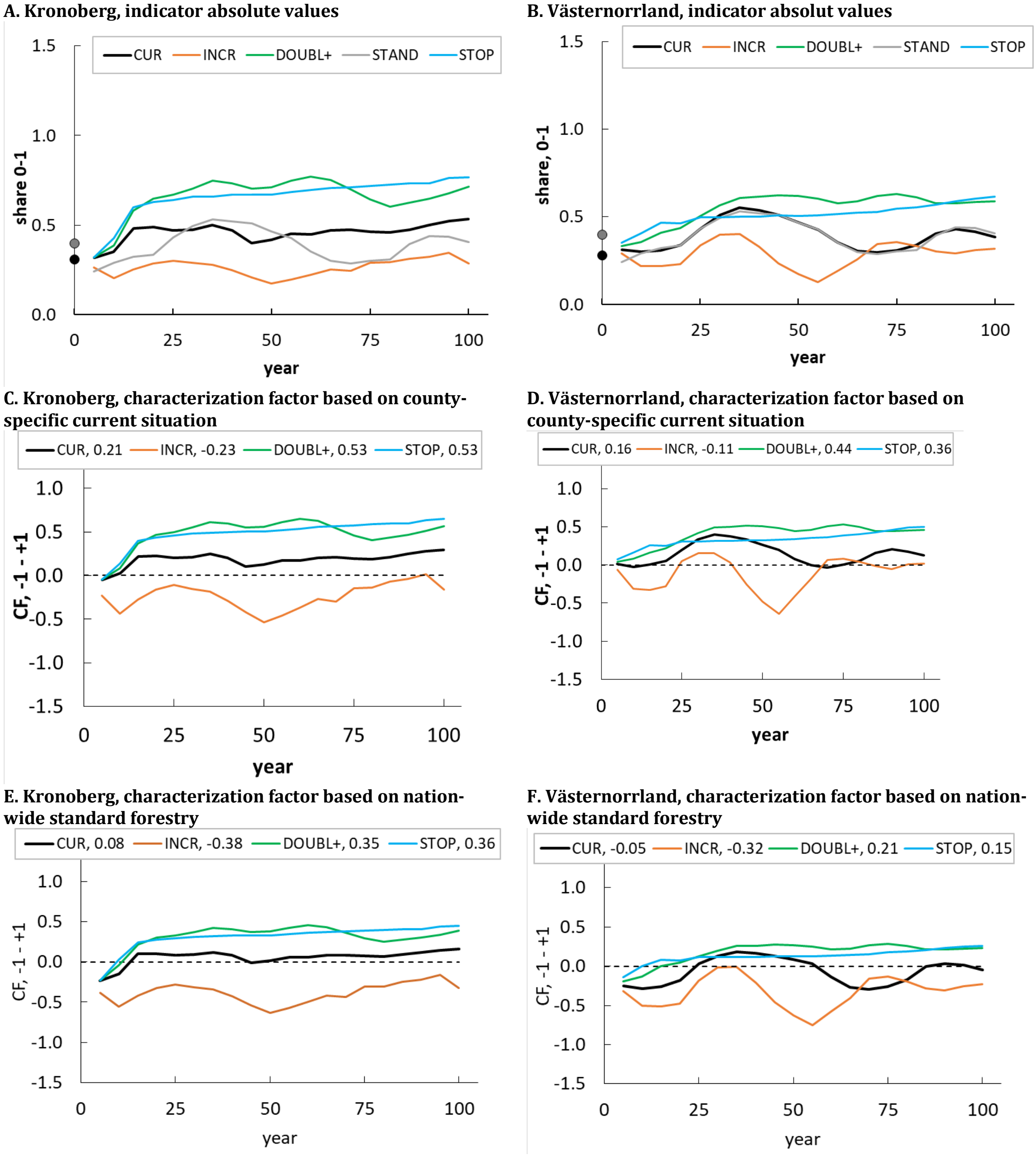

Figure 6. *Indicator for the recreation values of the forests. The indicator is calculated as the cumulative area of forest land that meets certain requirements in relation to the total area of productive forests. A,B, indicator values in absolute values; C,D, characterization factors based on the reference scenario for the county-wise current situation; E,F, characterization factors based on the reference scenario for the nation-wide standard forestry. In Figures A and B, the reference values are shown in the y-axis at x=0, such that the circle filled black shows the county-specific current situation reference value and the circle filled with grey shows that nation-wide standard forestry reference value. In Figures C, D, E and F the mean characterization factor over the time period 10-100 years is shown in the legend for each scenario. Scenarios: Current forestry (CUR); Increased growth and harvests (INCR); Doubled conservation areas and additional measures (DOUBL+); Terminated forestry (STOP). Standardized forestry for entire Sweden (STAND). CF, characterization factor, -1 - +1.*

5.6 Indicators for forest owner's economic revenue

The forest owner's economic revenue was calculated by the Heureka model for each forest stand and 5-year period, based on the estimated income and costs. Mean values for all stands were then calculated for each 5-year period within the respective county. In this respect, the calculations assumed that the county was one large "forest owner". In the scenario "STOP" the forest owner revenue was zero at all times.

The output for this indicator was strongly linked to the annual production of forest raw materials (Figure 2). Hence, the area based economic revenue was considerable higher in Kronoberg, compared to Västernorrland (Figure 7, Appendix 4, Table A4_6). The economic revenue in the scenario "STAND" was similar to scenario "CUR" in Västernorrland. However, it should be noted that the economic income will depend also on the quality of the harvested wood, i.e. sawtimber vs pulpwood, which is not taken into account in this study.

In Kronoberg, the forest owner´s economic revenue remained at a relatively low level for the forest 15 years of the 100-year period (Figure 7), due to the relatively low stand age and harvest rates in the county. Then, the revenue increased as the stand reached the age for final cut harvests. The increase was similar in the scenario "INCR" while it was less in the scenario "DOUBL+". The forest owner revenue in Kronoberg was relatively similar between the scenarios "CUR" and "INCR" for the first 75 years but at the end of the 100-year period the revenue was much higher in the scenario "INCR". The revenue was in the scenario "DOUBL+" approximately half of that in the scenario "CUR" during the years 10-30, while during the years 80-100 the revenue was only 10% lower in "DOUBL+" (Table A4_6).

In Västernorrland the revenue initially decreased due to the overall stand age distribution in the county. The revenue then increased considerably in the scenario "INCR" and later also in the other scenarios except "DOUBL+" (Figure 7). However, in the scenario "DOUBL+" the revenue was high towards the end on the 100-year period, during years 80-100 it was 60% higher compared to the scenario "CUR" (Table A4_6). In the scenario "INCR" the revenue was 50-65% higher compared to "CUR" during the different 20-year periods (Table A4_6).

The development of the CF factors over time was relatively similar in the two counties independently of the choice of reference scenario (Figure 7).

The timing of changes in economic net revenue varied considerably across the different scenarios.

The area-based net economic revenues were during different time periods between 16 and 90 % higher in the scenario "INCR", compared to "CUR". The revenue for the scenario DOUBL+ varied considerably over time, but was mostly lower compared to "CUR".

The development of the CF factors over time was independently of the choice of reference scenario.

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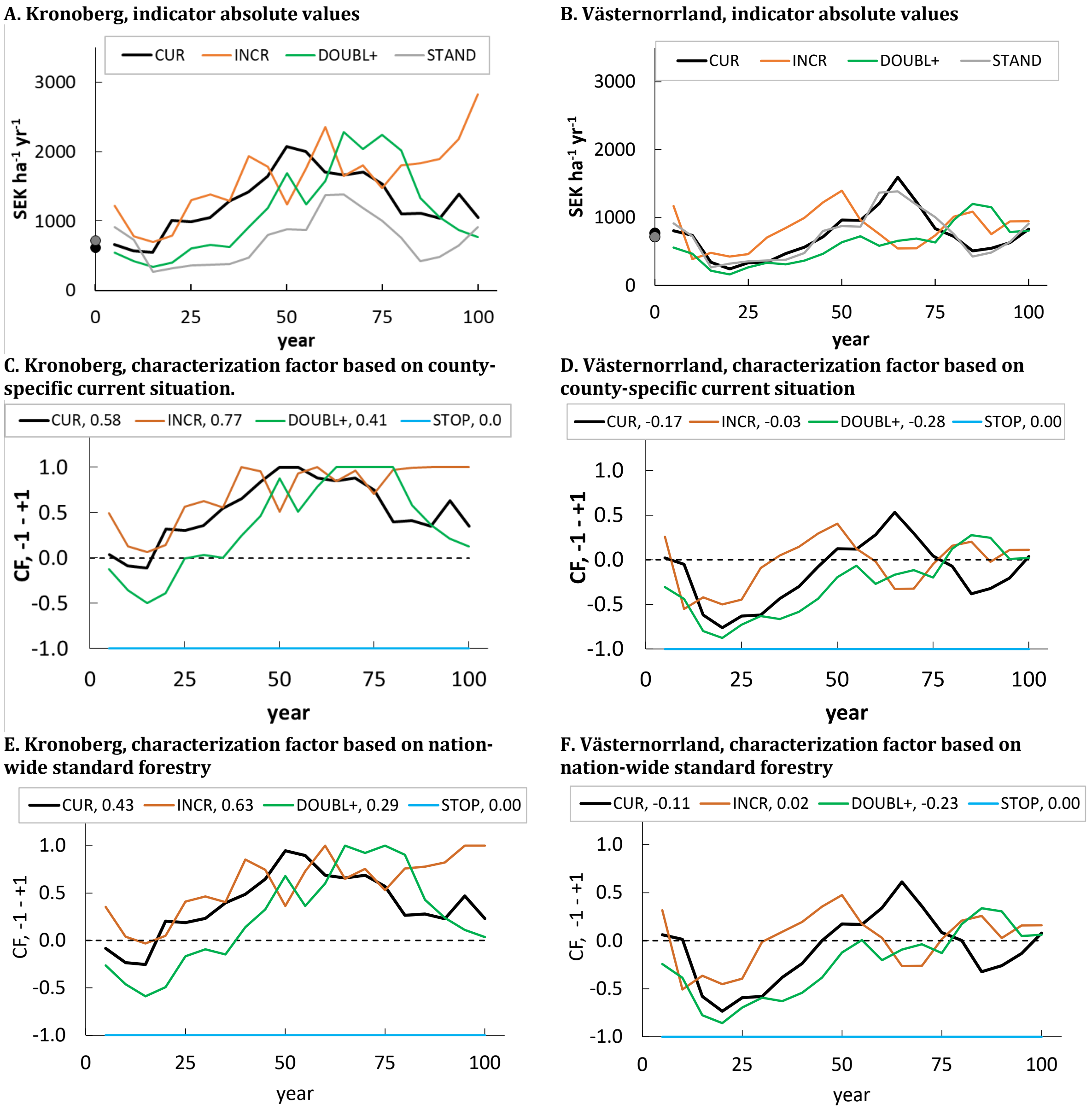


Figure 7. *Indicator for the economic net revenue by the forest owner. The indicator is calculated by the Heureka model, based on income and costs. A,B, indicator values in absolute values; C,D, characterization factors based on the reference scenario for the county-wise current situation; E,F, characterization factors based on the reference scenario for the nation-wide standard forestry. In Figures A and B, the reference values are shown in the y-axis at x=0, such that the circle filled black shows the county-specific current situation reference value and the circle filled with grey shows that nation-wide standard forestry reference value. In Figures C, D, E and F the mean characterization factor over the time period 10-100 years is shown in the legend for each scenario. The economic revenue was zero in the scenario "STOP". Scenarios: Current forestry (CUR); Increased growth and harvests (INCR); Doubled conservation areas and additional measures (DOUBL+); Terminated forestry (STOP). Standardized forestry for entire Sweden (STAND). CF, characterization factor, -1 - +1.*

5.7 Indicators for local job opportunities

The aim of this indicator was to reflect the impact of forestry on the regional/local economic "welfare". The choice was to use the role of forestry in creating regional/local job opportunities. This indicator might be important since there is a future trend towards increased automation in forestry operations (La Hera et al., 2024). However, the availability of statistics for the annual work units (AWU) that can be associated with different forest management practice operations is poor.

The relation between the forestry activity and AWU was based on statistics from the Swedish Forest Agency (SFA). The SFA publishes 3-year mean values for the AWU by county that can be regarded as connected with different forestry activities, divided into the categories large-scale forestry, small-scale forestry and entrepreneurs. In our calculations, the AWU of the different categories were aggregated and for each county divided by the total harvest volumes for the same county and years. These values were then multiplied with the values for the estimated total harvest volumes for each county, scenario and 5-year period. The AWU was expressed per area of total productive forests and the unit was AWU ha^{-1} yr^{-1}. There was no AWU created in the scenario "STOP".

The output for this indicator was also strongly linked to the annual production of forest raw materials (Figure 2). In general, much more area-based AWU was created from forestry in Kronoberg, compared to Västernorrland (Figure 8, Appendix 4, Table A4_7). This may be due to the larger forest stands in Västernorrland that would allow for a more "efficient" forest practice in this county, as well as to longer rotation periods.

As expected, the AWU was highest in the scenario "INCR" and lowest in scenario "DOUBL+" (Table A4_7), except in Västernorrland where "DOUBL+" was slightly higher than "CUR" towards the end of the period.

There were considerably more area-based AWU connected with forestry in Kronoberg, compared to Västernorrland.

The AWU per productive forest area was highest in the scenario "INCR" and least in the scenario "DOUBL+". However, in the scenario "STOP", the AWU was of course zero.

The order of the development of the CF factors over time in the different scenarios was relatively independent of the choice of reference scenario.

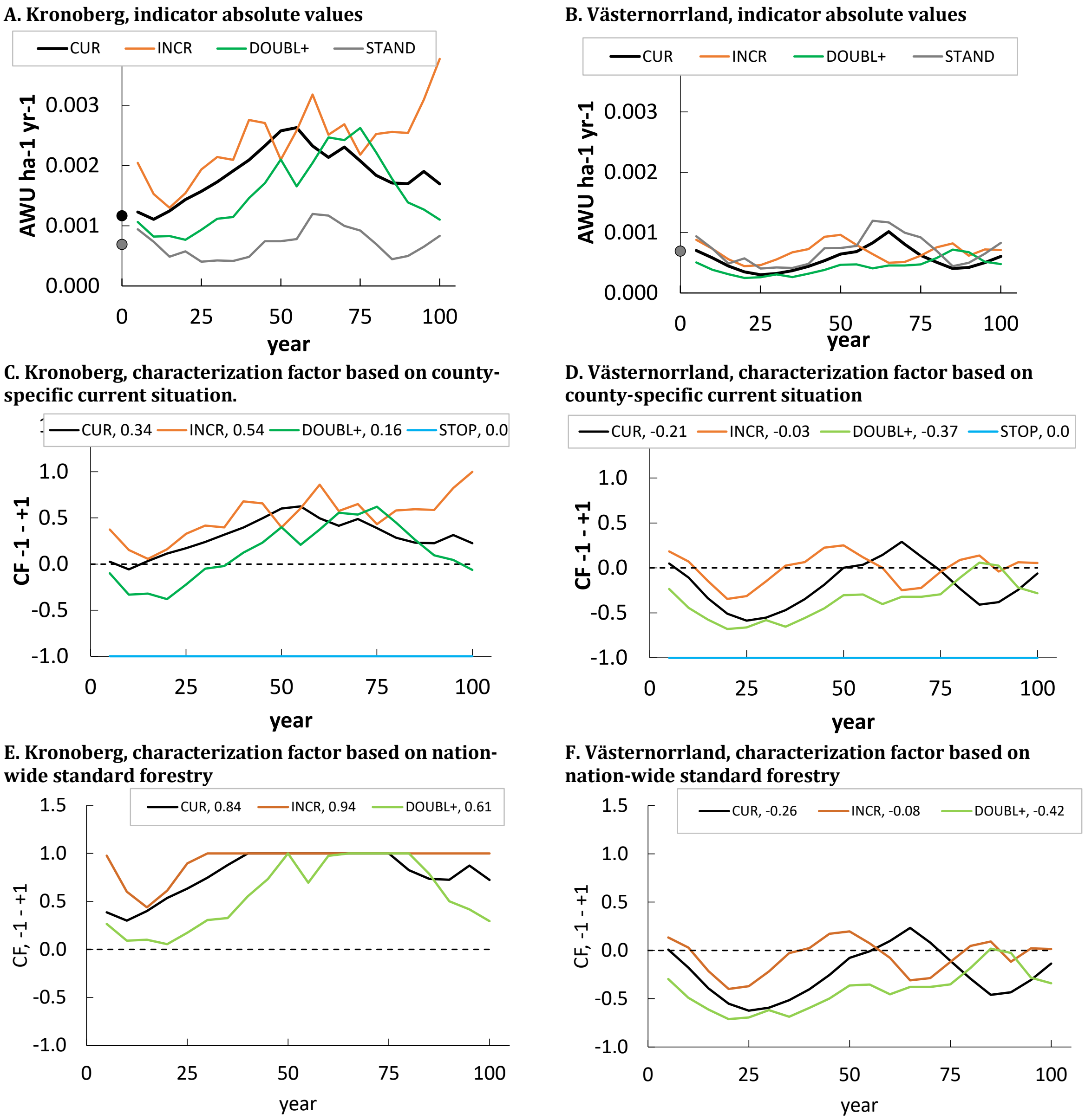


Figure 8. *Indicator for impacts on local job opportunities (Annual Work Units, AWU) that can be linked to local forest management practice. The indicator was calculated based on official statistics provided by the Swedish Forest Agency. We applied a mean value for the most recent years with available information, 2015-2017. A,B, indicator values in absolute values; C,D, characterization factors based on the reference scenario for the county-wise current situation; E,F, characterization factors based on the reference scenario for the nation-wide standard forestry. In Figures A and B, the reference values are shown in the y-axis at x=0, such that the circle filled black shows the county-specific current situation reference value and the circle filled with grey shows that nation-wide standard forestry reference value. In Figures C, D, E and F the mean characterization factor over the time period 10-100 years is shown in the legend for each scenario. AWU is of course zero for the scenario "STOP".*
Scenarios: Current forestry (CUR); Increased growth and harvests (INCR); Doubled conservation areas and additional measured (DOUBL+); Terminated forestry (STOP). Standardized forestry for entire Sweden (STAND). CF, characterization factor, -1 - +1.

5.8 Indicators for reindeer husbandry

The reindeer husbandry system constitutes historical legacy, closely connected to the indigenous Sami people. The Swedish Reindeer Husbandry Act (1971:437) defines the exclusive rights for the Sami people to herd and graze their reindeer on parts of the Swedish land area. For that reason, forestry impacts on reindeer husbandry are included as a separate sustainability indicator.

The indicator for forestry impacts on reindeer husbandry was intended to reflect some aspects of the forest conditions that can be regarded as favorable for the growth of abundant ground-based lichens. Forestry impacts on reindeer husbandry are however complex (Eggers et al., 2023) and the aspects that we include in this study are only a small part of the total forestry impacts on reindeer husbandry.

The criteria used aim to reflect relatively open Scots pine dominated forests, with standing stock for pine >65% of total standing stock and with a total forest basal area <18 m^2 ha^{-1}. The forest stands that fulfilled these criteria were summed up and related to the total area of productive forests in the county, as a ratio. The indicator was only calculated for counties that are included in the part of Sweden where the Sami people have reindeer husbandry rights, which applies to the county Västernorrland but not in Kronoberg. Hence, the reference scenario "STAND" was not relevant here either.

The share of the productive forests in Västernorrland that fulfil the criteria to be favorable for ground-based lichens was generally very small in all scenarios (Figure 9, Appendix 4, Table A4_8), less than 10%. This is consistent with what has been already shown by Sandström et al. (2016).

The indicator values were lowest in the scenarios "DOUBL+" and "STOP", scenarios that otherwise generally have positive values for biodiversity. At the end of the 100-years period, the share became low also in the scenario "INCR" (Figure 9).

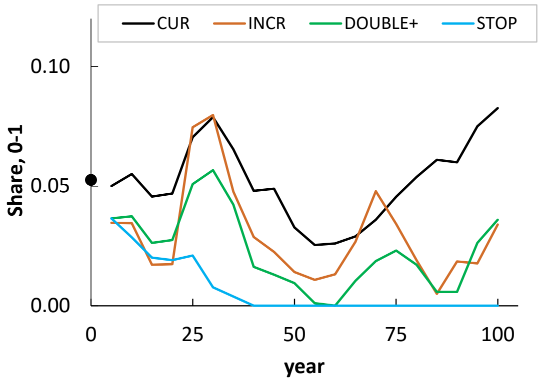
The share of the productive forests that fulfil the criteria to be favorable for ground-based lichens was generally very small in all scenarios.

The share was lowest in the scenarios "DOUBL+" and "STOP" and highest in the scenarios "CUR" and "INCR". Hence, there is a conflict between the impacts on reindeer husbandry and the impacts on biodiversity.

A. Kronoberg, absolute values

Not applicable

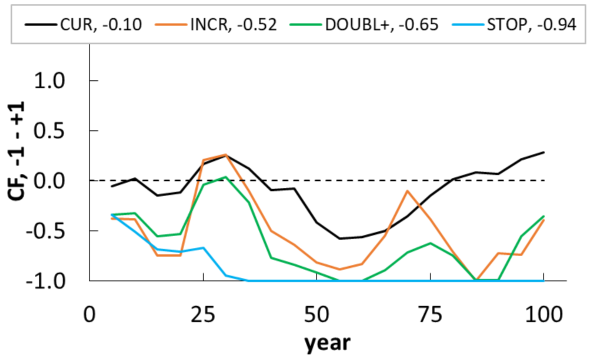
B. Västernorrland, indicator absolute values



C. Kronoberg, characterization factor based on county-specific current situation

Not applicable

D. Västernorrland, characterization factor based on county-specific current situation



E. Kronoberg, karakteriseringsfaktor baserat på standardskogsbruk respektive period

Not applicable

F. Västernorrland, characterization factor based on nation-wide standard forestry

Not applicable

Figure 9. *Indicators for reindeer husbandry. B, indicator values in absolute values; D, characterization factors based on the reference scenario for the county-wise current situation. In Figure B, the reference value is shown in the y-axis at x=0, such that the circle filled black shows the county-specific current situation reference value. In Figure D, the mean characterization factor over the time period 10-100 years is shown in the legend for each scenario.*
Scenarios: Current forestry (CUR); Increased growth and harvests (INCR); Doubled conservation areas and additional measured (DOUBL+); Terminated forestry (STOP). CF, characterization factor, -1 - +1.

5.9. Integrated assessments across all indicators

All indicators described above have been recalculated as characterization factors for each indicator, with a normalized scale between -1 and +1, using reference values together with preference- and indifference values. The results may be visualized with continuous values between -1 and +1 in spider diagrams. Another option would be to show the results as non-continuous values, divided into discrete categories and shown with symbols, e.g., 0, +, ++, -, -- etc, where + indicates a positive value from a sustainability point of view etc.

As shown above, we have tested two different possibilities regarding the reference scenario used for the transfer to the normalized scale, either the county-specific current situation or a 100-year mean value for standardized forestry scenario common for entire Sweden.

The calculated characterization factors are shown as mean values for two different periods during the 100-year period, 10-30 years and 80-100 years. In the main text, we show results for the mean values for the first period, 10-30 years. The complete results for all periods and types of visualizations are shown in Appendix 5.

5.9.1 Results expressed as continuous values with spider diagrams

The mean characterization factors for the period 10-30 years for Kronoberg and Västernorrland counties are shown in Figure 10, based on the two different reference scenarios, county-specific current situation as well as based on a 100 year mean value for a standardized forestry scenario common for all Sweden. The midpoint of the spider diagram represents the indifference value, the middle circle represents the reference value and the outer circle the preference value. **In other words, values that are further out from the midpoint represents "better" values from a sustainability point of view.** For clarity, results are shown only for the three scenarios INCR, DOUBL+ and STOP.

In general, the order between the different scenarios on the scale from the midpoint towards the outer circle was similar, independently for which reference scenario that was used. Regarding the indicators for biodiversity, carbon stock changes, fossil fuel emissions and recreation values, the best values from a sustainability point of view were, as expected, obtained for the scenario STOP followed by DOUBL+ and the worst values were for scenario INCR. Regarding recreation, the values were relatively similar between scenarios STOP and DOUBL+. For the indicators for the owners net economic revenue and for the work opportunities, the order between the scenarios was reversed, which was connected to the amounts of forest raw materials produced in the different scenarios. The indicator for reindeer husbandry could only be applied for Västernorrland and for all scenarios the values were below the reference line, independently of which reference that was used. The worst result was for the scenario STOP. The share of the total productive forests that was suitable for reindeer husbandry was generally very low, but the best situation was in fact when current forestry was applied. Again, the fraction of the forests that were suitable for reindeer husbandry as expressed in this study, was overall very low (see further the discussion).

When the initial state in the CUR scenario was used as reference, the value for the scenarios STOP and DOUBL+ were for the indicators for biodiversity, carbon stock changes, fossil emissions and recreation values above (outside) the reference value, while for the scenario INCR in was generally below the reference value. When the nationwide standard forestry was used as reference the result for Kronoberg was relatively similar, with the exception that for the carbon stock change, the results for all scenarios were well above the reference value. The results for these indicators were relatively similar also for Västernorrland county. For the indicators owners net economic revenue and work opportunities, the results were below the reference level in Västernorrland, independently of choice of reference, while for Kronoberg, the values for the scenario INCR were above the reference and for DOUBL+ close to the reference. For the scenario STOP the impacts on the economic indicators were of course negative since no forest biomass was produced.

Overall, the results were relatively similar, independently of the choice of reference scenario.

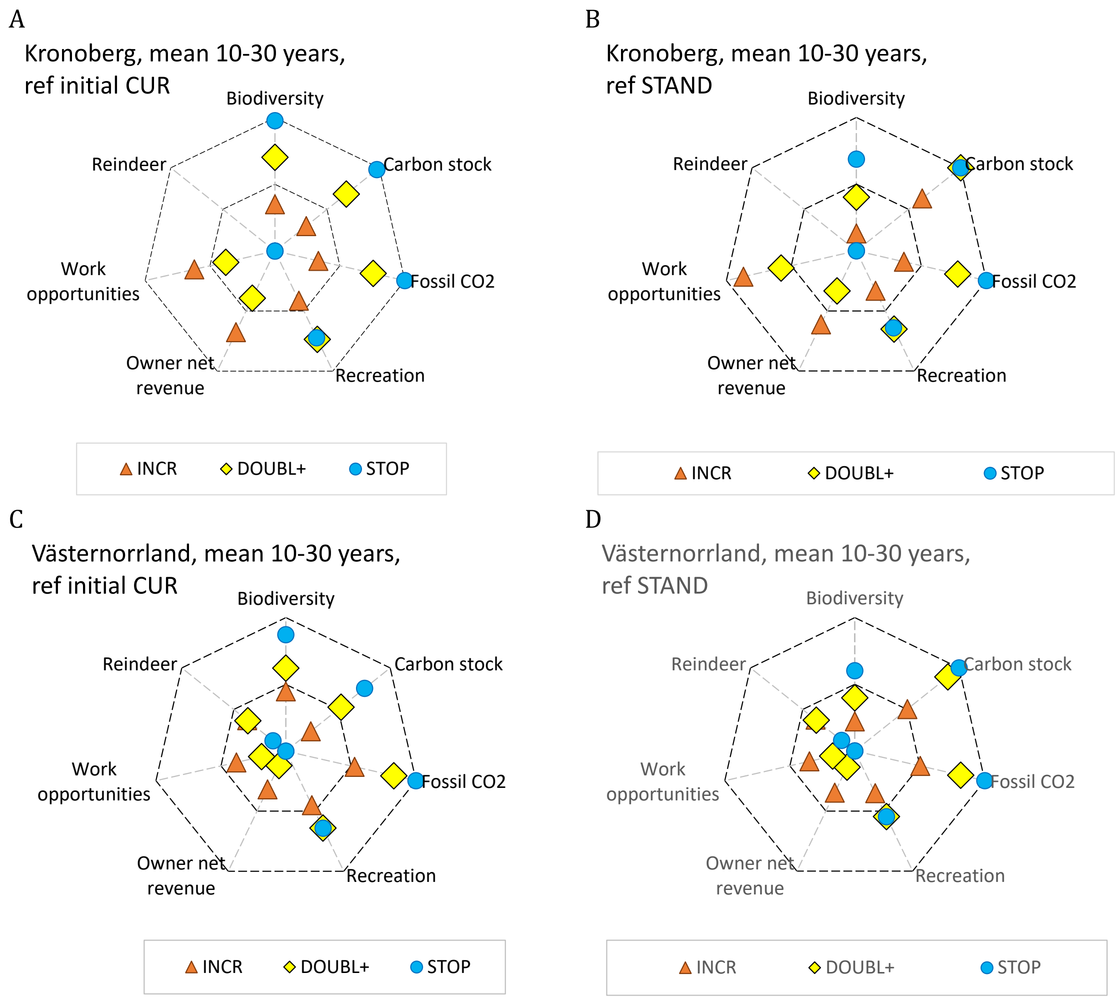


Figure 10. *Spider diagrams illustrating the mean characterization factors for the time period 10-30 years for Kronoberg and Västernorrland counties based on county-specific current situation (initial CUR) as well as based on a 100-year mean value for a standardized forestry scenario common for all Sweden (STAND). The different forestry scenarios were calculated over a 100-year period, starting in 2010. Indicator values for reindeer husbandry were not calculation for Kronoberg.*
Values on the middle circle represent characterization values of zero. The outer circle represents characterization values of +1 and the middle point of the diagram represent characterization values of -1. Hence, values that are further out from the midpoint represents "better" values from a sustainability point of view.
Scenarios: Increased growth and harvests (INCR); Doubled conservation areas and additional measured (DOUBL+); Terminated forestry (STOP).

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5.9.2 Results expressed as non-continuous values with symbols in tables

The choice of limits for the discrete categories that were used to define the different symbols are shown in Table 4. As above, for clarity the results are shown only for the three scenarios “INCR”, “DOUBL+” and “STOP”.

Table 4. *Definitions used for the different symbols (CF, characterization factor):*

Symbol used in table	Definition of CF	Symbol used in table	Definition of CF
0	CF=0	-	CF -0.49 - 0
+	CF 0-0.5	--	CF -0.99 – 0.5
++	CF 0.5-0.99	---	CF <-0.99
+++	CF >0.99		

When the results were visualized as non-continuous values, divided into discrete categories, the order between the different scenarios was, with few exceptions, relatively similar to what was shown with the spider diagrams above. Regarding the indicators for biodiversity, changes in carbon stock, fossil emissions and recreation values, the scenario “STOP” performed best, followed by “DOUBL+” and the worst was scenario “INCR” (Tables 5,6,7 and 8). The reverse was the case for the indicators for the forest owner net economic revenue and the local job opportunities, and reindeer husbandry.

The disadvantages of using symbols based on non- continuous values was the difficulties in assessing the difference in values between the different scenarios.

Table 5. *Characterization factor based on reference value based on county-specific* ***current situation,*** *based on the mean values for the period 10-30 years.*

Kronoberg, 10-30 yr	Biodiversity	Carbon stock	Fossil CO2	Recreation	Owner net revenue	Work opportunities	Reindeer
INCR	-	-	-	-	+	+	
DOUBL+	+	+	++	++	-	-	
STOP	++	++	+++	+	---	---	

Table 6. *Characterization factor based on reference value based* ***nation-wide*** *standard forestry mean values 100 years, based on the mean values for the period 10-30 years.*

Kronoberg, 10-30 yr	Biodiversity	Carbon stock	Fossil CO2	Recreation	Owner net revenue	Work opportunities	Reindeer
INCR	--	++	--	-	+	++	
DOUBL+	-	+++	++	+	-	+	
STOP	+	+++	+++	+	---	---	

Table 7. *Characterization factor based on reference value-based* ***county-specific current*** *situation, based on the mean values for the period 10-30 years.*

Västernorrland 10-30 yr	Biodiversity	Carbon stock	Fossil CO2	Recreation	Owner net revenue	Work opportunities	Reindeer
INCR	-	--	+	-	-	-	-
DOUBL+	+	+	++	+	--	--	-
STOP	++	++	+++	+	---	---	--

Table 8. *Characterization factor based on reference value-based* ***nation-wide*** *standard forestry, based on the mean values for the period 10-30 years.*

Västernorrland, 10-30 yr	Bio-diversity	Carbon stock	Fossil CO2	Recreation	Owner net revenue	Work opportunities	Reindeer
INCR	--	+	-	-	-	-	-
DOUBL+	-	++	++	+	--	--	-
STOP	+	+++	+++	+	---	---	--

6. Discussion

6.1 Evaluation of the overall approach in relation to aims

The main aim of this study was to develop methods that can be used for integrated, overall assessments of to what extent one scenario for future Swedish forest management practices is more or less sustainable compared to another scenario. The study aims to contribute to the development of standardized and transparent sustainability assessments methods that can be used as a common basis for future discussions among different stakeholders. It was not intended to provide an answer to which future scenario that is the most sustainable.

The approach was to apply a wide selection of quantitative sustainability indicators linked to the forest management activities and the forest structure that could be applied for the entire area of production forests under the control of large forest owners or forest owner associations. The absolute values for the different indicators were transferred to a normalized scale, in the case of this study between -1 and +1, based on reference- and target values. This allows the user to transparently assess the performance of one scenario, in comparison with another, from widely different perspectives.

The system boundaries applied in this study for calculating sustainability indicators related to forest management practices were concluded at landings by the roadside. Consequently, aspects for the forest value chains downstream from forestry were not considered. Ultimately, however, the goal is to enable sustainability assessments for different scenarios for entire forest value chains, including transport and industrial processes (Nilsson et al., 2022). First attempts have already been made regarding the total climate impacts across entire value chains based on some of the scenarios used in the present study (Nilsson et al., 2022). This work will continue for other indicators, when possible.

A similar approach to ours has previously been applied in the calculation tool “Tool for Sustainability Impact Assessment” (ToSIA, **http://tosia.efi.int** , Lindner et al., 2010). However, in ToSIA, the sustainability aspects of different options for forest management were not analyzed in great detail. On the other hand, sustainability aspects of different options for forest management were analyzed in great detail within the Landscape simulation and Ecological Assessment (LEcA) tool (Pang et al., 2017a;b). LecA was applied for two different forest management scenarios for the county Kronoberg for the period 2010–2110, and the results for different sustainability indicators were presented with spider diagrams. However, indicator values were not transferred to a common relative scale, resulting in values outside the scale. Simulation of forest management were made with a simplified, GIS-based tool, which was, as far as we could see, not validated. However, the GIS-tool provided the advantage that the aspect of connectivity between forest stands with high biodiversity value could be considered as well as the distance between forests with high recreation value and urban areas.

The results obtained in the present study revealed that the relative values for different indicators varies substantially over time between different forestry scenarios. These variations were influenced by factors such as the age structure of the forest stands at the start of the simulations. Hence, it was important that assessments of different forest management scenarios were integrated over long time periods. In the present study, the forestry practices in the different scenarios and counties were estimated for a 100-year period.

Generally, it may be argued that weighting different aspects of sustainable forestry is necessary, since sustainability encompasses widely different aspects, including the environmental, social, and economic dimensions. By weighting these factors, a more balanced and context-specific sustainability evaluation can be achieved, reflecting the relative importance of each aspect based on the goals, values, and priorities set by different stakeholders. For example, biodiversity conservation might be prioritized in some situations, while in others, economic viability or social equity could be of greater importance. Consequently, weighting these factors allows for a more comprehensive assessment of the sustainability of forestry practices (Karvonen et al. 2017). In the present study, the developed methods were intended to be applied for different future forestry scenarios defined and created by the user. An alternative approach would have been to define indicators that describe certain important basic ecological functions within the forest ecosystems. It would then have been possible to include a "back-casting", optimization function that would describe what kind of forestry scenario that would have been required to optimize these basic ecological functions. As far as the authors are aware, basic ecological functions for northern managed forests have not yet been defined or described. Hence, the weighting of different sustainability indicators is beyond the scope of this study.

6.2 Limitations and advantages of the analytical framework

In general, it may be suggested that the number of indicators used in forestry sustainability assessments should be limited, to avoid too complex and confusing results. On the other hand, relevant and important indicators must be included. Other possible indicators, besides those applied in the present study, include the role of forestry for the acidification, presence of humic substances and methyl mercury in surface waters, the use of chemicals, emissions of volatile organic compound (VOC) from forest stands, which can cause the formation of ground-level ozone and aerosols which affect the climate, as well as possible impacts on cultural heritage from forest management.

Changes in the forest management strategies in the simulations had to be implied rather abruptly, early on in the 100-year period. This may not be entirely realistic, resulting in initial transient impacts on the calculated values for the different indicators.

The evaluation of the performance of the analytical framework, including the sustainability indicators used, depends on the forest management scenarios used for testing. We strongly emphasize that the scenarios we have used should not be regarded as predictions for the future of Swedish forestry. On the other hand, we consider that the scenarios used offer realistic representations of the potential future trajectory of Swedish forestry, except for the scenario “STOP” which was included to illustrate the possible consequences if all forestry operations were suddenly terminated. In this study, for clarity we applied a limited number of forest management scenarios to make a first test of the performance of the indicators. For example, the scenario “DOUBLE+” included several different forest management practices intended to increase sustainability values, such as a doubling of the set-aside areas, longer rotation periods and larger areas for planning for continuous forestry. In future applications, it would be suitable to apply these changes step by step to understand which changes in forest management that are most important.

We applied simulations of forest management for two different counties with large differences in climate as well as other physical conditions for forestry, reflected in different “Site Qualities”. Due to its southern location with a milder climate and an extended growth season, Kronoberg county has higher site quality owing to more productive soils. Both the counties also differed regarding the owner structures for the forests, with smaller, private owned forest properties in Kronoberg and larger company owned forest properties in Västernorrland. The results indicated that the suggested methods could be relatively well applied for both counties.

The flexibility of the input values used for the calculation of the sustainability indicators represents an advantage of the suggested methodology. Input values could be generated with the Heureka PlanWise software. This is a software that is commonly used for forest planning by large forest owners in Sweden and is publicly available on the internet (**https://www.heurekaslu.se/wiki/Download_and_install**). Alternatively, input values can be generated from forest inventories made by the forest owner.

6.3 Evaluation of the indicators in relation to scenarios

As discussed above, the choices and calculation of the indicators as well as forest management scenarios involve simplifications and assumptions. Some of these are discussed below.

6.3.1 Production of forest raw materials

The production of forest raw materials is of great importance for the Swedish forest industry and thus for the Swedish society. Sweden ranks as the fourth-largest global exporter of pulp, paper, and sawn wood products (UNECE, 2020). Production volumes in 2022 reached 11.8 Mt of pulp, 8.5 Mt of paper, and 19 M m^3 of sawn timber (Swedish Forest Industries, 2022). Calculations with the Heureka PlanWise software can provide results for the production of forest raw materials with different qualities, i.e., saw timber and pulpwood, separated for final cut harvests, thinning and cleaning. However, for this study the indicator for the production wood-based raw materials was aggregated across all different qualities of the materials.

To relate to the physical conditions for forestry in each county, the production of forest raw materials was related to the mean estimated Site Quality in the respective county. We name this “relative production”. The Site Quality is a classification of forest land in terms of the capacity to repeatedly produce industrial wood. Market demands for wood of different quality were not accounted for in the simulations. Hence, e.g. market price impacts on harvest rates were not considered.

The relative production was in general higher in Västernorrland compared to Kronoberg. The production of forest raw materials was, compared to the scenario “CUR”, in the order of 30-40% higher in the scenario “INCR” and approximately 20% lower in the scenario DOUBLE+”.

The relative production, i.e. in relation to the Site Quality, was on average 30-40% higher in the scenario "INCR", compared to "CUR" and on average 20% in the scenario "DOUBLE+". There was no production in the scenario "STOP".

6.3.2 Indicators for biodiversity

The indicators for forest biodiversity selected in this study reflect forest stand structures that are regarded as favorable for biodiversity (Cosovic et al., 2020; Gao et al., 2014). The selected structure criteria are used within the Swedish Environmental Objective "Sustainable Forests" and were originally suggested by SLU Swedish Species Information Centre (Artdatabanken, 2011). Such structural indicators are considered useful and cost-effective to use because they are readily visible to non-professionals and can be acquired through forest inventories. Direct biodiversity measures, such as the presence of selected species, can be obtained through, for example, a nature value inventory (NVI) conducted according to Swedish standards. This provides a high-quality mapping and documentation of an area's natural values but is time-consuming and costly to carry out, especially for small forest owners. High-resolution data from airborne laser scanning provides, as in this study, an indirect measure of biodiversity and can potentially offer information about additional forest structures relevant to biodiversity, such as standing and fallen deadwood and trees with high conservation value (Lindberg et al 2015). An alternative approach could involve using the LEcA tool referenced earlier, to assess habitats for selected focal species (Pang et al., 2017b). However, we suggest that this would have been a too narrow approach for this study.

The differences in the indicator values for impacts on biodiversity between the different forestry scenarios were very clear, with the lowest values for the scenario "INCR" and progressively higher values for the scenarios "CUR", "DOUBL+" and "STOP". The preference values, i.e., three times the reference value, were reached early on in the simulation period for the scenario "STOP", independently of reference scenario used. It was reached also for the scenario "DOUBLE+" when the current county-specific reference value was used, but not when the nation-wide reference scenario was used. The preference values were not reached in the scenarios "INCR" or "CUR".

The differences in the estimated values for the indicator for impacts on biodiversity between the forestry scenarios were as expected, with the lowest values for the scenario "INCR" and progressively higher values for the scenarios "CUR", "DOUBL+" and "STOP".

6.3.3 Indicator for changes in forest ecosystem carbon stocks

The calculations of changes in forest ecosystem carbon stocks were made in line with the methods used for Sweden´s international reporting within the LULUCF sector. However, instead of being based on the results from 30 000 observation plots revisited every 5th year, our calculations were based on forest growth and removal dynamics as estimated with Heureka in combination with default IPCC methods regarding "biomass expansion factors" etc.

There are however some major assumptions and uncertainties in these calculations:

- The tree mortality pattern may be outdated, and storms, drought and insect pests are not accounted for. If this is added, mortality increases with stand age might reduce the climate benefit of management actions that leads to increased rotation periods and stand age.
- Different factors for greenhouse gas emissions are used for mineral soils as well as for drained and non-drained peatlands. However, areas with drained peat land as well as the emission factors used were not changed between the different scenarios.

- The possible removals or decay of stumps and major roots are not included in the calculations
- Carbon leakage is not accounted for, i.e., if a drastic reduction in Swedish forest raw material production leads to increased production outside Sweden

As expected, the CO_2 uptake was highest in the scenario “STOP”, followed by “DOUBL+” and the lowest for the scenario “INCR”. The uptake in the scenario “STOP” might, however, have been overestimated due to uncertainties in the tree mortality rates.

6.3.4 Indicator for fossil fuel emissions

The fossil greenhouse gas emissions from forestry are much smaller compared to the much larger potential CO_2 emissions/ uptake due to changes in the forest ecosystem carbon stocks (e.g. Nilsson et al., 2022). However, the fossil fuel emissions from forestry are important since they may have a more permanent character, compared to changes in forest carbon stocks.

The fossil emissions are calculated in a very simplified way, based on the extent of various forestry management operations (e.g., harvesting, site preparation, etc.), utilizing emission factors that were developed uniformly across the Nordic region. The emissions will therefore correlate closely with different forest management operations.

As expected, the area-based fossil emissions were highest for the scenario ”INCR”, followed by the scenario “CUR” and with less emissions from the scenario “DOUBL+”. There were no emissions from scenario ”STOP”.

6.3.5 Indicator for recreation values

The recreational values are calculated as forests that meet certain criteria, such as good visibility, different forest tree species and absence of final-cut harvests. Unfortunately, the methods used did not allow to include the proximity to urban areas or other aspects of the public availability. The presence of forest paths or small roads were not included in the assessment. It might be assumed that the indicator for recreation values would be more important for the more densely populated regions in southern Sweden. The estimated recreation values were indeed higher in the southern county Kronoberg, compared to the northern Västernorrland. Furthermore, it is not scientifically established how well the structural criteria in Heureka for assessing recreational value reflect people's experiences. This is an area that warrants further research.

The recreation values were lowest in the scenario “INCR” and then increased gradually in the scenarios “CUR”, and “DOUBL+”. The values for the scenario “STOP” was overall similar to the scenario “DOUBL+”.

It might be assumed that the values for the scenario “STOP” were to some extent overestimated since the increased forest stand densities, as a result of terminated forestry, might not have been fully accounted for.

6.3.5 Indicator for forest owner’s economic revenue

The forest owner’s economic revenue was calculated by the Heureka model, based on the estimated income and costs. This indicator would, of course, be depending on the overall economic developments and predictions for the future are therefore very uncertain. This indicator should therefore be regarded as an estimate of how future forestry developments might be evaluated with today’s economic conditions. An additional economic value that might have been used is the present and future expected value of the forest land. However, this would have even more uncertain since it would depend strongly on the development of future interest rates.

The area-based net economic revenues were during different time periods between 16 and 90 % higher in the scenario "INCR", compared to "CUR". The revenue for the scenario DOUBL+ varied considerably over time, but was mostly lower compared to "CUR".

6.3.6 Indicator for local job opportunities

This indicator was chosen to reflect impacts of forestry on the regional/local economic "welfare" and might also be important due to the future trend for increased automation in forest management practice operations. An alternative regional economic indicator would have been "Gross value added" from forestry. However, it was regarded that this indicator would have been very similar to the indicator for forest owner's economic revenue described above.

The availability of statistics for the annual work units (AWU) that can be associated with different forest management practice operations is very poor. Therefore, the output for this indicator is at present very uncertain and strongly linked to the annual production of forest raw materials.

As expected, the AWU per productive forest area was highest in the scenario "INCR" and least in the scenario "DOUBL+". In the scenario "STOP", the AWU was of course zero.

6.3.7 Indicator for reindeer husbandry

The exclusive rights for the Sami people to herd and graze their reindeer on parts of the Swedish land area is well founded legally. Therefore, this indicator has a special importance. Forestry impacts on reindeer husbandry are complex and none of the scenarios used in this study are well suited for reindeer husbandry. The indicator for reindeer husbandry had very low values in all scenarios.

Forestry scenarios that are more optimized for reindeer husbandry have been described by Eggers et al., (2023).

Of the scenarios included in the present study the indicator value for reindeer husbandry was lowest in the scenarios "DOUBL+" and "STOP" and highest in the scenarios "CUR" and "STAND". Hence, there was a conflict between the impacts on reindeer husbandry and the impacts on biodiversity.

6.7. The choice of reference, preference and indifference values

In general, the choice of reference scenario did not influence the order for how the analyzed scenarios performed regarding the normalized characterization factors. It had however, strong influence of the characterization values and the number of cases when the preference values were exceeded. A large exceedance of the preference or indifference values will cause confusion for the diagrams with the characterization factors (see for example Figures 4E and F).

Furthermore, a general problem is to interpret the results when the indicators are above or below the nationwide standard forestry reference value.

Preference (target) values can be derived from target levels defined within environmental goal frameworks or climate policy objectives. Alternatively, they can be based on scientific evaluations of acceptable impact levels over the long term (preference) and thresholds beyond which impacts become negligible (indifference). Defining such preference and indifference values is a complex task and lies outside the scope of this study. One key challenge in setting target values for different indicators is that they often operate at varying scales—regional, national, EU, or global—while the timeframes for achieving these targets frequently differ. Additionally, there may be trade-offs between these targets that must be considered. Targets can also vary in nature; some are absolute, while others are more abstract and may intersect with other sectors, as is the case with climate change mitigation goals.

7. Overall conclusions and outlook

For the indicators related to biodiversity, carbon stock changes, fossil fuel emissions and recreational values, the best values from a sustainability point of view were, as expected, obtained for the scenario “STOP” followed by “DOUBL+” and the worst values were for scenario “INCR”. Regarding recreation, the values were relatively similar between scenarios “STOP” and “DOUBL+”. However, the values for the scenario “STOP” could have been overestimated since the increased forest stand densities as a result of terminated forestry might not have been fully accounted for. For the indicators of the forest owners net economic revenue and work opportunities, the order between the scenarios was reversed, which is related to the amounts of forest raw materials produced in the different scenarios.

The indicator for reindeer husbandry could only be applied for Västernorrland and in all scenarios the values were below the reference line, independently of which reference that was used. The worst result was for the scenario STOP. The share of the total productive forests that was suitable for reindeer husbandry was generally very low, but the best situation was in fact when current forestry was applied.

The overall conclusion from this study is that the suggested methodology results in reasonable values for the different sustainability indicators and the forestry scenarios tested. The methods need further development, particularly concerning the choice of reference- and preference values.

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Appendix 1. Input values that are needed within the suggested methods to calculate sustainability indicators

Table A1_1. *In the table below all input values that are needed within the suggested methods to calculate sustainability indicators are described, including units and for which indicator(s) the value is used. Also indicated are the Heureka output names. "Column" refers to which column in the calculation files that the value appears. "TU", treatment unit.*

Column	Heureka output	Specification	Unit	Used for indicator(s)
B	AreaFactor	TU size	ha	Areal TU totalt, ha, used for many indicators
D	Proportion	Share of TU	0-1	Areal TU totalt, ha, used for many indicators
AJ	AlternativeSummaryData Management System		Even-aged/ Uneven-aged/ Unmanaged	Biodiversity
AP	DeadWoodData Dead Standing Trees >=20cm		m3	Biodiversity, Living biomass carbon stock change
AQ	DeadWoodData Downed Deadwood >=20cm		m3	Biodiversity, Living biomass carbon stock change
AD	ForestData Mean Age (excl overstorey)		year	Biodiversity/ recreation value
S	SpeciesData Volume (incl overstorey)_Pine		m3o.b.	Biodiversity/ recreation value/ reindeer
T	SpeciesData Volume (incl overstorey)_Spruce		m3o.b.	Biodiversity/ recreation value/ reindeer
U	SpeciesData Volume (incl overstorey)_Birch		m3o.b.	Biodiversity/ recreation value/ reindeer
V	SpeciesData Volume (incl overstorey)_Aspen		m3o.b.	Biodiversity/ recreation value/ reindeer
W	SpeciesData Volume (incl overstorey)_Oak		m3o.b.	Biodiversity/ recreation value/ reindeer
X	SpeciesData Volume (incl overstorey)_Beech		m3o.b.	Biodiversity/ recreation value/ reindeer
Y	SpeciesData Volume (incl overstorey)_SouthernBroadleaf		m3o.b.	Biodiversity/ recreation value/ reindeer
Z	SpeciesData Volume (incl overstorey)_Contorta		m3o.b.	Biodiversity/ recreation value/ reindeer
AA	SpeciesData Volume (incl overstorey)_OtherBroadleaf		m3o.b.	Biodiversity/ recreation value/ reindeer
AB	SpeciesData Volume (incl overstorey)_Larch		m3o.b.	Biodiversity/ recreation value/ reindeer
CI	GrowthData CAI Gross (All species)	CAI=current annual increment	m3o.b.	Carbon stock change
CM	SiteData Ditch		TRUE/FALSE	Carbon stock change
CN	SiteData Peat		TRUE/FALSE	Carbon stock change
BM	ValueData Pulpwood Volume All Species		m3 u.b./yr	Carbon stock change/ AWU
BM	ValueData Timber Volume All Species		m3 u.b./yr	Carbon stock change/ AWU
AZ	ValueData Harvest Residues Extracted All Species		ton TS/yr	Fossil emissions
CO	TreatmentData Treatment		Forestry practise	Fossil emissions
AR	DeadWoodData Volume Decayclass 0		m3	Carbon stock change
AS	DeadWoodData Volume Decayclass 1		m3	Carbon stock change
AT	DeadWoodData Volume Decayclass 2		m3	Carbon stock change

AU	DeadWoodData Volume Decayclass 3		m3	Carbon stock change
AV	DeadWoodData Volume Decayclass 4		m3	Carbon stock change
BI	ValueData Net Revenue		sek/yr	Owner net revenue
AC	ForestData Dgv		cm	Recreation value/ reindeer husbandry
AE	ForestData Stems		st	Reindeer husbandry
CP	TreatmentData Volume Cut All Species		m3o.b.	Relative production

Appendix 2. The reference-, preference- and indifference values for Kronoberg and Västernorrland based on the reference scenario for a nationwide standard forestry

Table A2_1. *Reference, preference and indifference values used for Kronoberg, (value before the slash) and for Västernorrland (value after the slash) based on the reference scenario for a nationwide standard forestry. Since the reference value is based on a nationwide standard forestry, it will be identical for Kronoberg and Västernorrland. The principles used for the calculation of the values are indicated in the three columns to the right. Note that double accounting of areas that fulfil several of the defined characteristics is permitted. Also note that a reference value based on a nationwide standard forestry is not relevant for the indicator for reindeer husbandry.*

	Unit	**Reference**	**Preferens**	**Indiffe-rens**	**Principle, reference**	**Principle, preferens**	**Principle, indifferens**
Biodiversity	fraction of total productive forest area	0.44/ 0.44	1.31/ 1.31	0.044/ 0.044	Standard forestry, average periods 3-20	3 * reference value	10% of reference value
Change carbon stocks	ton CO_{2e} ha^{-1} yr^{-1} (uptake negative value)	-1.45/ -1.45	-4.36/ -4.36	0.00/ 0.00	Standard forestry, average periods 3-20	3 * reference value	zero (carbon neutral)
Fossil emissions	ton CO_{2e} ha^{-1} yr^{-1}	0.015/ 0.015	0.0015/ 0.0015	0.044/ 0.044	Standard forestry, average periods 3-20	10% av reference value	3 * reference value
Recreation	fraction of total productive forest area	0.40/ 0.40	1.21/ 1.21	0.04/ 0.04	Standard forestry, average periods 3-20	3 * reference value	10% of reference value
Job opportunities	AWU, ha^{-1} yr^{-1}	0.0007/ 0.0007	0.0021/ 0.0021	0.00007/ 0.00007	Standard forestry, average periods 3-20	3 * reference value	10% of reference value
Net economic income	SEK ha^{-1} yr^{-1}	716/ 716	2157/ 2147	72/ 72	Standard forestry, average periods 3-20	3 * reference value	10% of reference value
Reindeer husbandry	fraction of total productive forest area	-/ -	-/ -	-/ -	Standard forestry, average periods 3-20	3 * reference value	10% of reference value

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Appendix 3. Detailed description of revised calculations

Introduction

Eight different sustainability indicators, SI, were implemented: 1. production of wood-based raw materials; 2. impact on biodiversity; 3. impact on carbon stock change; 4. impact on fossil fuel emissions; 5. impact on recreation values; 6. impact on forest owner economic net income; 7. impact on regional work opportunities; 8. impact on reindeer husbandry. The SI were generally calculated based on the total area of productive forests under the control by the forest owner, which enables the comparison of different sized forest owners.

The calculations of SI are based on the characteristics of individual stands (in Heureka named ”Treatment Units”, TU). The conditions in each TU are homogenous.

The absolute values for the eight, widely different SI were transferred to a common, normalized scale with values between -1 and +1, where the value +1 represents the most positive aspects from a sustainability point of view. These normalized values are named “characterization factors”, CF. The absolute values were transferred to normalized values using reference-, preference- and indifference values. The preference (target) value defined the normalized value +1 while the indifference value defined the value -1. The reference value defined the normalized zero value.

The calculations of the CF follow the following general equation:

For SI < indifference (indiff.) then CF = 1; For SI > preferensvärdet preference (target) value (pref.) then CF =-1; F0r indiff. < SI < reference value (ref). then CF = (ref. - SI) / (ref. - indiff.); For ref. < SI < pref. then CF= (ref. - SI) / (pref. - ref.)

The calculations of the CF are not further described here.

Indicator for the production of forest raw materials

The relative production of forest raw materials (P_{rel}, ratio) was calculated as the absolute, area based annual production of forest raw materials in the region for all tree species and material qualities, including final harvests, thinning and claening ($\sum P_{abs}$, m^3o.b. ha^{-1} yr^{-1}) divided by the “Site Quality” (S.Q, m^3o.b. ha^{-1} yr^{-1}) representative for the same region, as a ratio. The S.Q. is a classification of forest land in terms of the capacity to repeatedly produce industrial wood. Site quality was for Kronoberg 9.16, for Västernorrland 4.02 and for the scenario “standard forestry” 5.1 m^3o.b. ha^{-1} yr^{-1}.

$P_{rel} = \sum P_{abs} / S.Q$

$\sum P_{abs} = P_{all} / A_{prod}$

$P_{all,}$ annually harvested volumes, all species, all harvests including final cut, thinning and cleaning, m^3 ob yr^{-1}.

A_{prod}, total area of productive forests in the region, all species, ha

Indicator for impacts on biodiversity

The indicators selected in this study reflect forest stand structures that are regarded as favorable for biodiversity. We suggest using four of the biodiversity indicators that are used in the Swedish Environmental Quality Objective 'Sustainable Forests'. In addition, one indicator was included to describe the application of forestry practice with the absence of final fellings, i.e., continuous cover forestry. We summarize the areas of forest stands that comply with each of the five indicators and relate these summarized areas to the total areas of productive forest under the control of an individual forest owner, as a ratio.

The five assessed biodiversity indicators used were as follows:

(1) Area stands with old trees, A_{ot}. The average tree age in the stand should be above 140 years in northern Sweden and above 120 years in southern Sweden;

(2) Area stands with dead wood, A_{dw}. There should be more than 20 m^3 of dead wood per hectare, including only dead wood with a diameter greater than 20 cm;

(3) Area stands with large trees, A_{lt}. There should be more than 60 trees per hectare with a diameter greater than 45 cm for Norway spruce, Scots pine, and southern broadleaves and a diameter greater than 35 cm for other tree species;

(4) Area stands with mixed deciduous and coniferous tree species, A_{df}. The average tree age in the stand should be above 80 years, and more than 3/10 of the basal area should be deciduous tree species;

(5) Area stands that are managed with continuous cover forestry, A_{ccf}, i.e., with no final fellings.

Double accounting was allowed, hence the ratio can take values >1.0.

In addition, the calculations may in the future include a factor to reflect "connectivity". However, this factor has for the time being set to 1.0.

The indicator for biodiversity, I_{BD}, is calculated as follows:

$I_{BD} = (A_{ot} + A_{dw} + A_{lt} + A_{df} + A_{ccf}) / A_{prod}$, (ha/ha)

A_{ot}, area stands with old trees, ha.

A_{dw}, area stands with dead wood, ha.

A_{lt}, area stands with large trees, ha.

A_{df}, area stands with mixed deciduous and coniferous tree species, ha.

A_{ccf}, area stands that are managed with continuous cover forestry, ha,

A_{prod}, total area of productive forests in the region, all species, ha

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Indicator for changes in forest carbon stocks

The indicator for impacts on annual changes in forest carbon stocks, I_{cs}, is calculated for living and dead biomass as well as the soil carbon, categorized into mineral and organic (peat) soils and expressed as CO_{2e} ha $^{-1}$ yr^{-1}. A negative value is used for the uptake of CO_2 from the atmosphere to the forest ecosystem. It is assumed that no slash is left in the forests after harvesting.

$I_{cs} = [(\Delta CS_L) + (\Delta CS_D) + (\Delta CS_{min}) + (\Delta CS_{org})] / A_{Prod}$

where

ΔCS_L = annual change in the living biomass carbon stocks, above and below ground, in the total area productive forests, ton CO_{2e} yr^{-1}

ΔCS_D = annual change in the dead biomass carbon stocks, in the total area productive forests, excluding litter, ton CO_{2e} yr^{-1}

ΔCS_{min} = annual change in the mineral soil carbon stocks, in the total area productive forests, ton CO_{2e} yr^{-1}

$\Delta CS_{min} = E_{min} * A_{min}$

E_{min} = Emission factor for the yearly change in the mineral soil carbon stocks, ton CO_{2e} ha^{-1} yr^{-1} (Table 1)

A_{min} = area with mineral soils, in the total area productive forests, ha

ΔCS_{org} = annual change in the organic soil carbon stocks, in the total area productive forests, ton CO_{2e} yr^{-1}

$\Delta CS_{org} = E_{org} * A_{org}$

E_{org} = Emission factor for the yearly change in the organic soil carbon stocks, ton CO_{2e} ha^{-1} yr^{-1} (Table 1)

A_{min} = area with organic soils, in the total area productive forests, ha

In the pilot study with Kronoberg and Västernorrland counties is not changes in the carbon stocks for litter and humus layer included. Furthermore, emission factors used are for a 100-year perspective and it was assumed that all wetlands were nutrient rich.

Table A3_1. *Emission factors for the yearly change in the mineral and organic soil carbon stocks, ton CO_{2e} ha^{-1} yr^{-1}, positive value = release to the atmosphere.*[1] *Emission factors are valid for a 100-year perspective.*

Emissions, organic soils	Ditched since long time	Not ditched/ re-wetted
South Sweden, nutrient rich	16	9.8
South Sweden, nutrient poor	4.6	3.2
North Sweden, nutrient rich	5.7	4.4

[1] Skogsstyrelsen, 2021a. Klimatpåverkan från dikad torvtäckt skogsmark – effekter av dikesunderhåll och återvätning. Rapport 2021/7

North Sweden, nutrient poor	0.2	0.3
Emissions, mineral soils		
South Sweden	-0.09	
North Sweden	0.08	

$\Delta CS_L = \Delta SS * F_{CO2e}$

ΔSS = annual change in forest standing stocks, all species and all qualities, m^3 o.b. yr^{-1}.

F_{CO2e} = factors for the conversion from forest standing stocks volumes to living biomass carbon stocks, including above and below biomass (Table 2).

$\Delta SS = GG - REM - HARV$

GG = annual gross growth, all tree species m^3 o.b. yr^{-1}.

REM = annual natural removals, all tree species m^3 o.b. yr^{-1}.

HARV = annual harvests, including final cut harvests, thinning and cleaning, all tree species m^3 o.b. yr^{-1}.

Table A3_2. *Factors for the conversion from forest standing stocks volumes to living biomass carbon stocks, including above and below biomass,* F_{CO2e} *.*[2]

Conversion from m^3 o.b. to ton CO_{2e}.	**Values**
Conversion to fub	0.83
D, density stem (tonnes dry weight m^{-3})	0.5
CF, "carbon fraction", of dry matter (tonnes $tonnes^{-1}$)	0.5
BEF, biomass expansion factor, converts between stem biomass and total living biomass including branches, leaves and roots	1.7
The value of ΔC was then converted to CO_2-eqvivalents (CO_{2e}) by multiplying with 3.67	3.67

$\Delta CS_D = (\Delta DW_0 * F_{DW0}) + (\Delta DW_{1-4} * F_{DW1-4})$, ton CO_{2e} yr^{-1}

ΔDW_0 = annual change in the stocks of dead wood, both standing and downed, decayclass 0, M m^3 ob yr^{-1}. Calculated between two 5-year periods. Can not be calculated for period 1.

F_{DW0} = factors used for densities and carbon contents of dead wood, decayclass 0 (Table 3)

ΔDW_{1-4} = annual change in the stocks of dead wood, both standing and downed, Decayclass 1-4, M m^3 ob yr^{-1}. Calculated between two 5-year periods. Can not be calculated for period 1.

F_{DW1-4} = factors used for densities and carbon contents of dead wood, decayclass 1-4 (Table 3)

[2] von Arnold, K., Hånell, B., Stendahl, J., Klemedtsson, L. 2005. Greenhouse gas fluxes from drained organic forestland in Sweden. Scandinavian Journal of Forest Research, 20, 400 – 411.

Table A3_3. *Factors for the conversion from volumes dead wood to carbon stocks in dead wood, separated for different decay classes. Based on mean values across all tree species. From Ågren et al. , 2021.*[3]

Densities, ton m⁻³				
Decay class according to the Swedish National Forest Inventory	Scots pine	Norway spruce	Birch	mean
Decay class 0	0.40	0.38	0.47	0.42
Decay class 1-4	0.28	0.24	0.24	0.25
Carbon content, fraction				
Decay class according to the Swedish National Forest Inventory	Scots pine	Norway spruce	Birch	mean
Decay class 0	0.50	0.49		0.50
Decay class 1-4	0.51	0.50		0.51

Indicators for fossil emissions from forestry

The impact of fossil greenhouse gas emissions from forestry on climate change is calculated based on the extent of various forestry management practices (e.g., harvesting, site preparation, etc.), utilizing the life-cycle assessment (LCA)-based emission factors developed by the Forestry Research Institute of Sweden (Ågren m. fl., 2021). These emission factors, uniform across the Nordic region, include only fossil greenhouse gas emissions.

For the calculations, it has been assumed that the use of one liter diesel may be causing fossil emissions of 2.54 kg CO_2. It was assumed that 20% of the diesel used would be biodiesel, which was subtracted. Furthermore, it was assumed that the oil used for maintenance of forestry machinery has a similar emission factor as diesel. Fossil emissions connected with production in plant nurseries are not included as well as not the emissions from the transport of the plant material.

The indicator for fossil emissions from forestry, I_{fos}, is calculated as follows (unit ton CO_{2e} ha^{-1} yr^{-1}):

$$I_{fos} = (\sum (FA_1 * E_1), (FA_2 * E_{2, \ldots}) / A_{prod}$$

$FA_{x\ldots}$, different forestry activities

$E_{x, \ldots,}$ different emission factors connected with the specific forestry activity

A_{prod}, total area of productive forests in the region, all species, ha

The different forestry activities and the connected emission factors may be expressed per area forest stand where the specific activity is applied or per harvested volume that is harvested using the specific forestry activity.

[3] Ågren, K., Högbom, L., Johansson, M., och Wilhelmsson, L. 2021. Datainsamling till underlag för livscykelanalyser (LCA) av det svenska skogsbruket. Skogforsk ARBETSRAPPORT 1086–2021. ISSN 1404-305X.

Table A3_4. *Emission factors for yearly fossil emissions that can be connected with different specific forestry activities. Source Ågren m. fl., 2021. Units are provided in the table for each forestry activity.*

Soil preparation, l diesel/ ha harvested area	25
Fertilization, l diesel/ ha avverkad areal	11
Cleaning, l diesel/ ha	9.9
Thinning, l diesel/ harvested m^3ub	1.6
Final cut harvests, l diesel/ harvested m^3ub	0.8
Skotning, gallring, l diesel/ harvested m^3ub	1
Skotning, slutavverkning, l diesel/ harvested m^3ub	0.7
Skotning, GROT, l diesel/ m^3f	1
Flisning, GROT, l diesel/ m^3f	1
Bygga skogsbilvägar, l diesel/ harvested m^3ub	0.24
Underhåll av skördare, l olja/ harvested m^3ub	0.0596
Underhåll av skotare, l olja/ harvested m^3ub	0.0274

Indicator for impact on the forest's recreational value

In this study, the impact on the forest's recreational value serves as an indicator of forestry's influence on social values. This was quantified as the cumulative area of forest land meeting criteria for easily accessible forests with good visibility, characterized by sparsely grown, mature productive forests, and forests where the proportion of deciduous trees exceeds 80%. The sum of the areas meeting these criteria is related to the total area of productive forest land as a fraction from 0 to 1. Due to the possibility of forest areas meeting multiple criteria, double accounting may occur, leading to rare instances where the final recreation index value may exceed 1.0.

The assessed recreation indicators used were as follows:

(1) Area, stands with easily accessible forests with good visibility, A_{af}, is estimated as forest stands with a maximum of 1000 stems ha^{-1} and a stand age >50 years;

(2) Area, stands with a faction of broadleaf trees > 80% and a stand age i>20 years, A_{bl}.;

(3) Area, stands that have not been final-cut harvested during the last ten years, A_{nfc}, as the fraction exceeding 80%.

The indicator for recreation values, I_{REC}, is calculated as follows:

$I_{REC} = (A_{af} + A_{bl} + A_{nfc}) / A_{prod}$, (ha/ha)

A_{af}, stands with easily accessible forests, ha.

A_{bl}, stands with a faction of broadleaf trees, ha.

A_{nfc}, stands that have not been final-cut harvested, ha.

A_{prod}, total area of productive forests in the region, all species, ha

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Definitions above. Double accounting was allowed, hence the ratio can take values >1.0.

Indicator for the forest owner net economic revenue

The forest owner's economic revenue was calculated by the Heureka model for each forest stand and 5-year period, based on the estimated income and costs. Mean values for all stands were then calculated for each 5-year period within the respective county. In this respect, the calculations assumed that the county was one large "forest owner". In the scenario "STOP" the forest owner revenue was zero at all times.

The Heureka output value for "Net Revenue" is used on a yearly basis and divided by the total area of productive forests in the region, all species, A_{prod}, ha. The net economic revenue for the forest owner is expressed as SEK ha^{-1} yr^{-1}. The net economic revenue for the individual forest owner will of course vary between years. However, for a large forest owner or as a mean value for all forest owners in a large region, the estimated values will be relevant.

Indicator for local job opportunities connected with forestry

The Swedish Forest Agency, SFA, publishes 3-year mean values for the annual work units, AWU, by county that can be regarded as connected with different forestry activities, divided into the categories large-scale forestry, small-scale forestry and entrepreneurs. In our calculations, the AWU of the different categories were aggregated and for each county divided by the total harvest volumes for the same county and years, AWU $(m^3o.b.)^{-1}$ yr^{-1}. These values were then multiplied with the values for the estimated total harvest volumes for each county, scenario and 5-year period, m^3o.b. The AWU was expressed per area of total productive forests and the unit was AWU ha^{-1} yr^{-1}. There was no AWU created in the scenario "STOP".

The original statistical values used for the calculations of yearly AWU connected with forestry in the two different counties are shown in Table X.

Table A3_5*. The original statistical values used for the calculations of yearly annual work units, AWU, connected with forestry in the two different counties. Values are 3-year mean values for the categories large-scale forestry, small-scale forestry and entrepreneurs. One yearly AWU is 1 800 work hours. One yearly AWU could represent the workhours from several persons. Source:* **https://www.skogsstyrelsen.se/globalassets/statistik/statistiska-meddelanden/sm-sysselsattning-i-skogsbruket-ke.pdf**

County	Small-scale forestry	Large-scale forestry	Entrepreneurs	Total	m^3o.b. AWU^{-1}
Kronoberg	554	67	484	1105	3205
Västernorrland	518	157	626	1301	6903

Indicator for forestry impacts on reindeer husbandry

The indicator for forestry impacts on reindeer husbandry was intended to reflect some aspects of the forest conditions that can be regarded as favorable for the growth of abundant ground-based lichens. Forestry impacts on reindeer husbandry are however complex and the aspects that we include in this study are only a small part of the total forestry impacts on reindeer husbandry.

The criteria used aim to reflect relatively open Scots pine dominated forests of all stand ages, with standing stock for pine >65% of total standing stock and with a total forest basal area <18 m^2 ha^{-1}. The forest stands that fulfilled these criteria were summed up and related to the total area of productive

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forests in the county, A_{prod}, ha, as a ratio. The indicator was only calculated for counties that are included in the part of Sweden where the Sami people have reindeer husbandry rights, which applies to the county Västernorrland but not in Kronoberg. Hence, the reference scenario “STAND” was not relevant here either.

The following equations were applied for the calculations of the indicators for impacts of forestry on reindeer husbandry, I_{rd} (unit ratio), for each treatment unit and timer period (referring to output data from Heureka PlanWise):

IF $(SS_{pine} / (SS_{pine} + SS_{spruce} + SS_{birch} + SS_{aspen} + SS_{oak} + SS_{beech} + SS_{sbl} + SS_{cont} + SS_{obl} + SS_{larch})) >0.65$

Then

IF$(((S_{dia}/2/100)^2 *3.14* S_{stems}/ A_{prod})<18$

Then A_{TU}, ha

$I_{rd} = (\sum A_{TU})/ A_{prod}$ (ratio)

SS_{pine} = standing stocks, volume (incl overstorey)_Pine, m^3 o.b.

SS_{spruce} = standing stocks, volume (incl overstorey)_Spruce, m^3 o.b.

SS_{birch} = standing stocks, volume (incl overstorey)_Birch, m^3 o.b.

SS_{aspen} = standing stocks, volume (incl overstorey)_Aspen, m^3 o.b.

SS_{oak} = standing stocks, volume (incl overstorey)_Oak, m^3 o.b.

SS_{beech} = standing stocks, volume (incl overstorey)_Beech, m^3 o.b.

SS_{sbl} = standing stocks, volume (incl overstorey)_SouthernBroadleaf, m^3 o.b.

SS_{cont} = standing stocks, volume (incl overstorey)_Contorta, m^3 o.b.

SS_{obl} = standing stocks, volume (incl overstorey)_OtherBroadleaf, m^3 o.b.

SS_{larch} = standing stocks, volume (incl overstorey)_Larch, m^3 o.b.

S_{dia}, Forest basal area weighted mean diameter, “ForestData Dgv”, cm

S_{stems} , Forest basal area weighted number of stems", “ForestData Stems”, number

A_{TU}, area of the treatment unit, ha

A_{prod}, total area of productive forests in the region, all species, ha

Appendix 4. Mean absolute values for the different sustainability indicators based on 20-year mean values from the beginning (10-30 years) and end (80-100 years) of the 100-year period

Table A4_1. *The relative production of forest raw materials. The relative production is calculated as actual production divided by the expected production based on "bonitet", as a share 0-1. Both values are expressed as m^3 sk ha^{-1} yr^{-1}. Mean values are shown for two 20-year periods, 10-30 year and 80-100 year, respectively.*

	Current forestry (CUR)	**Increased growth and harvests (INCR)**	**Doubled conservation areas and additional measured (DOUBL+)**	**Terminated forestry (STOP)**
Kronoberg, 10-30 yr	0.52	0.64	0.32	0.00
Kronoberg, 80-100 yr	0.60	1.11	0.48	0.00
Västernorrland, 10-30 yr	0.64	0.94	0.50	0.00
Västernorrland, 80-100 yr	0.82	1.28	0.99	0.00
Standard forestry (STAND) 10-30 yr	0.53			
Standard forestry, (STAND), 80-100 yr	0.64			

Table A4_2. *Indicator for biodiversity as absolute values. The indicator is calculated as the summed area that fulfil some selected structural characters divided by the total area of productive forest of the forest owner. 20-year mean values are shown for the periods 10-30 year and 80 – 100 year.*

	Current forestry (CUR)	Increased growth and harvests (INCR)	Doubled conservation areas and additional measured (DOUBL+)	Terminated forestry (STOP)
Kronoberg, 10-30 yr	0.23	0.15	0.36	0.76
Kronoberg, 80-100 yr	0.47	0.25	1.10	2.70
Västernorrland, 10-30 yr	0.25	0.22	0.36	0.61
Västernorrland, 80-100 yr	0.47	0.24	1.06	2.39
STAND, 10-30 år	0.35			
STAND, 80-100 år	0.44			

Table A4_3. *Indicator for changes in forest ecosystem carbon stocks. The indicator is calculated according to the methodology used in international reporting witSIn the sector land use, land use change and forestry (LULUCF. Changes are calculated for the carbon stocks living and dead biomass and soil carbon, the latter separated into mineral and organic carbon stocks. A negative values indicaes an uptake from the atmosphere to the forest ecosystem, in the unit ton CO_2 ha^{-1} yr^{-1}. 20-year mean values are shown for the periods 10-30 year and 80 – 100 years.*

	Current forestry (CUR)	Increased growth and harvests (INCR)	Doubled conservation areas and additional measured (DOUBL+)	Terminated forestry (STOP)
Kronoberg, 10-30 yr	-3.50	-2.22	-6.42	-11.26
Kronoberg, 80-100 yr	-1.42	-0.50	-0.44	-3.85
Västernorrland, 10-30 yr	-2.81	-1.59	-3.74	-6.74
Västernorrland, 80-100 yr	-0.38	-0.81	1.64	-2.98
STAND, 10-30 yr	-3.40			
STAND, 80-100 yr	-1.45			

Table A4_4. *Indicator for fossil emissions that could be linked to forestry. Positive values indicate emissions to the atmosphere, in the unit ton CO_2 ha^{-1} yr^{-1}. 20-year mean values are shown for the periods 10-30 year and 80 – 100 years.*

	Current forestry (CUR)	Increased growth and harvests (INCR)	Doubled conservation areas and additional measured (DOUBL+)	Terminated forestry (STOP)
Kronoberg, 10-30 yr	0.018	0.022	0.007	0
Kronoberg, 80-100 yr	0.021	0.040	0.012	0
Västernorrland, 10-30 yr	0.011	0.015	0.006	0
Västernorrland, 80-100 yr	0.012	0.020	0.012	0
STAND 10-30 år	0.012			
STAND 80-100 år	0.012			

Table A4_5. *Indicator for the recreation values of the forests. The indicator is calculated as the summed area of forest land that meets certain requirements expressed as absolute values in relation to the total area of productive forests. 20-year mean values are shown for the periods 10-30 year and 80 – 100 years. Unit: share 0-1.*

	Current forestry (CUR)	Increased growth and harvests (INCR)	Doubled conservation areas and additional measured (DOUBL+)	Terminated forestry (STOP)
Kronoberg, 10-30 yr	0.48	0.28	0.65	0.63
Kronoberg, 80-100 yr	0.51	0.32	0.67	0.75
Västernorrland, 10-30 yr	0.40	0.30	0.48	0.48
Västernorrland, 80-100 yr	0.41	0.31	0.58	0.59
STAND 10-30 yr	0.40			
STAND 80-100 yr	0.42			

Table A4_6. *Indicator for the economic net revenue by the forest owner in absolute values. The indicator is calculated by the Heureka model, based on income and costs. Unit SEK ha^{-1} yr^{-1}. 20-year mean values are shown for the periods 10-30 year and 80 – 100 years*

	Current forestry (CUR)	**Increased growth and harvests (INCR)**	**Doubled conservation areas and additional measured (DOUBL+)**	**Terminated forestry (STOP)**
Kronoberg, 10-30 yr	899	1042	500	0
Kronoberg, 80-100 yr	1148	2182	1007	0
Västernorrland, 10-30 yr	315	519	245	0
Västernorrland, 80-100 yr	629	933	986	0
STAND 10-30 yr	328			
STAND 80-100 yr	616			

Table A4_7. *Indicator for local job opportunities (Annual Work Units, AWU) that can be linked to local forest management practice. Unit AWU ha^{-1} yr^{-1}. 20-year mean values are shown for the periods 10-30 year and 80 – 100 years.*

	Current forestry (CUR)	**Increased growth and harvests (INCR)**	**Doubled conservation areas and additional measured (DOUBL+)**	**Terminated forestry (STOP)**
Kronoberg, 10-30 yr	0.0015	0.0017	0.0009	0
Kronoberg, 80-100 yr	0.0018	0.0030	0.0014	0
Västernorrland, 10-30 yr	0.00036	0.00051	0.00028	0
Västernorrland, 80-100 yr	0.00048	0.00072	0.00060	0
STAND 10-30 yr	0.00047			
STAND 80-100 yr	0.00061			

Tabell A4_8*. Indicators for reindeer husbandry. The indicator is calculated as the share of summed area with with standing stock for pine >65% of total standing stock and with a total forest basal area < 18 m^2 ha^{-1}.* Unit, share 0-1. *20-year mean values are shown for the periods 10-30 year and 80 – 100 years.*

	Current forestry (CUR)	**Increased growth and harvests (INCR)**	**Doubled conservation areas and additional measured (DOUBL+)**	**Terminated forestry (STOP)**
Kronoberg, 10-30 yr	-	-	-	-
Kronoberg, 80-100 yr	-	-	-	-
Västernorrland, 10-30 yr	0.060	0.047	0.040	0.017
Västernorrland, 80-100 yr	0.066	0.019	0.018	0.000
STAND 10-30 år	-	-	-	-
STAND 80-100 år	-	-	-	-

Appendix 5. Integrated assessments across all indicators

A5.1 Results expressed as continuous values with spider diagrams

In Figure xx is shown the characterization factors for Kronoberg county based on the two different reference scenarios, county-specific current situation as well as based on a 100 year mean value for a standardized forestry scenario common for all Sweden. The midpoint of the spider diagram represents the indifference value, the middle circle represents the reference value and the outer circle the preference value. In other words, values that are further out from the midpoint represents "better" values from a sustainability point of view.

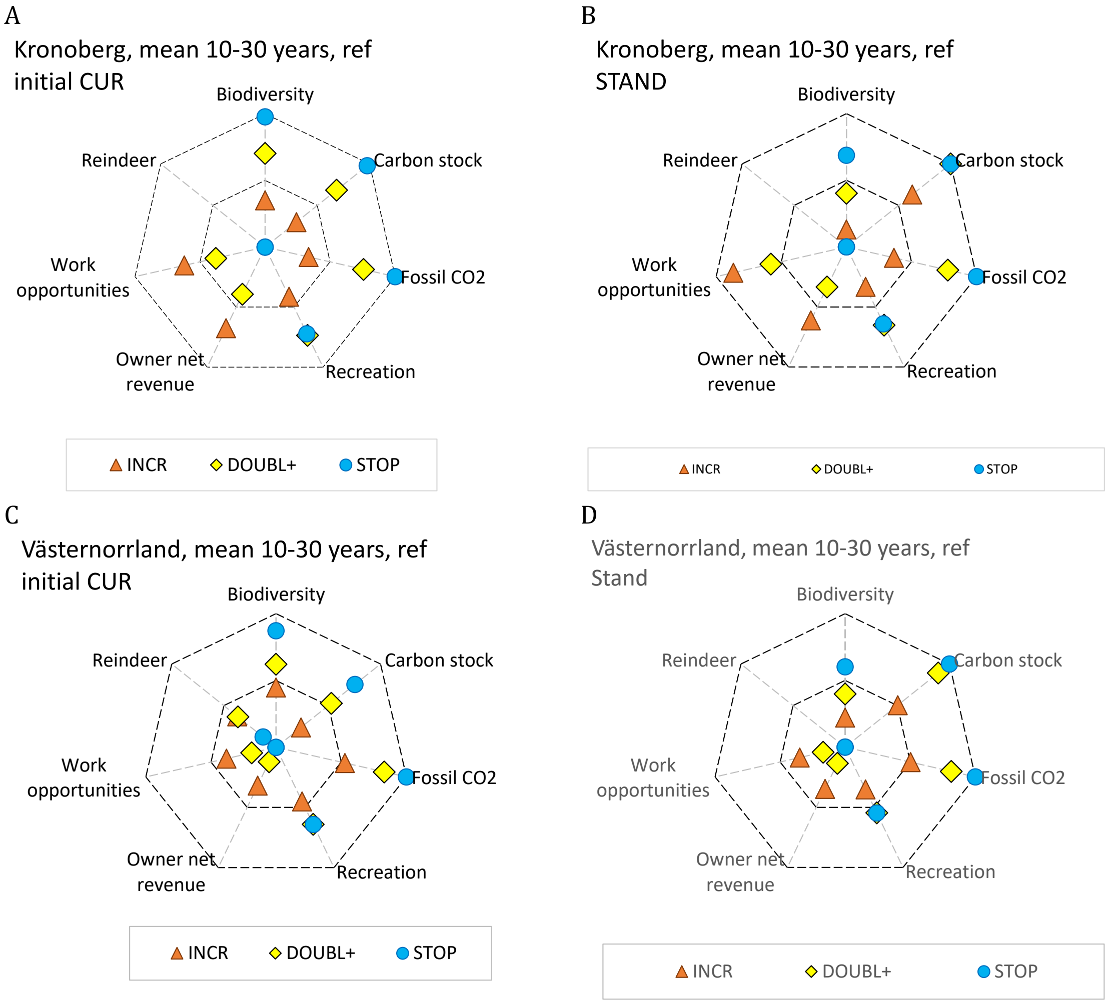

Figure A5_1. *Spider diagrams illustrating the mean characterization factors for the time period 10-30 years for Kronoberg and Västernorrland counties based on county-specific current situation (initial CUR) as well as based on a 100-year mean value for a standardized forestry scenario common for all Sweden (STAND). The different forestry scenarios were calculated over a 100-year period, starting in 2010. Values on the middle circle represent characterization values of zero. The outer circle represents characterization values of +1 and the middle point of the diagram represent characterization values of -1. Hence, values that are further out from the midpoint represents "better" values from a sustainability point of view.*
Scenarios: Increased growth and harvests (INCR); Doubled conservation areas and additional measured (DOUBL+); Terminated forestry (STOP).

A

B

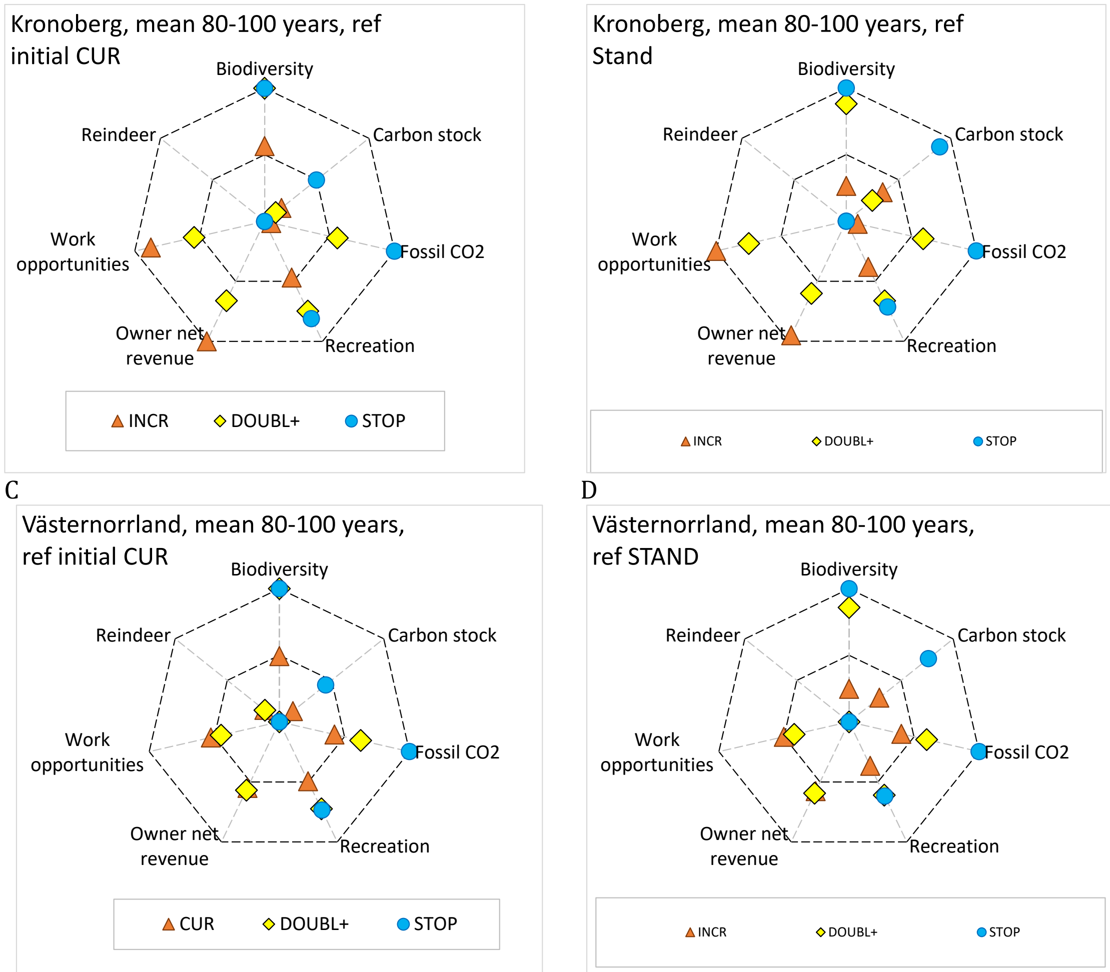

Figure A5_2. *Spider diagrams illustrating the mean characterization factors for the time period 80-100 years for Kronoberg and Västernorrland counties based on county-specific current situation (initial CUR) as well as based on a 100-year mean value for a standardized forestry scenario common for all Sweden (STAND). The different forestry scenarios were calculated over a 100-year period, starting in 2010. Values on the middle circle represent characterization values of zero. The outer circle represents characterization values of +1 and the middle point of the diagram represent characterization values of -1. Hence, values that are further out from the midpoint represents "better" values from a sustainability point of view.*
Scenarios: Increased growth and harvests (INCR); Doubled conservation areas and additional measured (DOUBL+); Terminated forestry (STOP).

A5.2 Results expressed as continuous values with symbols in tables

Table A5_1. *Definitions used for the different symbols (CF, characterization factor):*

Mistra
Digital Forest

Symbol used in table	Definition of CF	Symbol used in table	Definition of CF
0	CF=0	-	CF -0.49 - 0
+	CF 0-0.5	--	CF -0.99 – 0.5
++	CF 0.5-0.99	---	CF <-0.99
+++	CF >0.99		

Table A5_2. *Kronoberg. Characterization factor based on reference value based on county-specific* ***current situation,*** *based on the mean values for the period 80-100 years.*

Kronoberg, 80-100 yr	Biodiversity	Carbon stock	Fossil CO2	Recreation	Owner net revenue	Work opportunities	Reindeer
INCR	+	--	--	-	+++	++	
DOUBL+	+++	--	+	++	+	+	
STOP	+++	-	+++	++	---	---	

Table A5_3. *Kronoberg. Characterization factor based on reference value based* ***nation-wide*** *standard forestry mean, based on the mean values for the period 80-100 years.*

Kronoberg, 80-100 yr	Biodiversity	Carbon stock	Fossil CO2	Recreation	Owner net revenue	Work opportunities	Reindeer
INCR	-	-	--	-	++	+++	
DOUBL+	++	--	+	+	+	++	
STOP	+++	++	+++	+	---	---	

Table A5_4. *Västernorrland. Characterization factor based on reference value-based* ***county-specific current*** *situation, based on the mean values for the period 80-100 years.*

Västernorrland 80-100 yr	Biodiversity	Carbon stock	Fossil CO2	Recreation	Owner net revenue	Work opportunities	Reindeer
INCR	-	--	-	-	+	+	--
DOUBL+	+++	---	+	+	+	-	--
STOP	+++	-	+++	+	---	---	---

Table A5_5. *Västernorrland. Characterization factor based on reference value-based* ***nation-wide*** *standard forestry, based on the mean values for the period 80-100 years.*

Västernorrland, 80-100 yr	Bio-diversity	Carbon stock	Fossil CO2	Recreation	Owner net revenue	Work opportunities	Reindeer
INCR	+	--	+	-	-	-	+
DOUBL+	--	-	-	-	+	+	--
STOP	++	---	+	+	+	-	--

Appendix 6. Members of the scientific advisory board

Table 6_1. *Members of the external scientific advisory board. As to participation during 2024. The members are listed in no particular order.*

	Namn	Tillhörighet	Expertis
1	Jeannette Eggers	SLU, Umeå	Forskare inom skoglig planering. Programchef för "Forest Sustainability Analysis". Forskar kring hållbart skogsbruk för multipla ekosystemtjänster och biodiversitet.
2	Sten Nilsson		Professor. Debattör. Gästprofessor vid "International Institute for Systems Analysis (IIASA), Österrike", och vd Forest Sector Insights AB
3	Torbjörn Skytt	Mitt-universitetet	Tekn dr Ekoteknik/Miljövetenskap. Klimatrelaterad forskning: samhälleliga kol- och energiflöden, simulering skogsscenarion.
4	Johnny de Jong	SLU, Centrum för Biologisk Mångfald	Docent i naturvårdsbiologi. Arbetar med forskning och uppdrag, med koppling till skogsbruk, energi, infrastruktur och naturvård.
5	Per Sandström	SLU, Umeå	Docent. Biology/ ekolog med inriktning på viltfrågor på landskapsnivå. Markanvändning och planering med inriktning på rennäringen.
6	Peter Fredman	Mitt-universitetet	Professor i Naturturism. Kunskap och lösningar för ökad hållbarhet inom idrotten och friluftslivet.
7	Giuliana Zanchi	Skogs-styrelsen	Klimatexpert. Skogsbrukets påverkan på skogens kolsänkor.
8	Line Djupström	Skogforsk	Programchef skötselprogram. Fil. Dr. Forskare inom naturvårdsbiologi. Kunskap om miljöhänsyn och biologisk mångfald i det brukade skogslandskapet.
9	Robert Lundmark	Luleå tekn univ.	Professor i ekonomi. Tillämpad ekonomiforskning kring skogsbruk, energi och miljöekonomi. Har varit verksam inom "International Institute for Applied Systems Analysis (IIASA)".
10	Bengt-Gunnar Jonsson	Mitt-universitetet	Professor. Biologisk mångfald och naturvård med fokus på skog.
11	Mattias Lundblad	SLU	Department of Soil and environment. Estimation of carbon budgets and greenhouse gas balances for different land use categories. Emissions and removals from the LULUCF-sector for the annual reporting to UNFCCC and EU.
12	Göran Englund	Umeå Univ	Institutionen för ekologi, miljö och geovetenskap.
13	Camilla Sandström	Umeå Univ	Statsvetenskapliga institutionen.