Modelling the effects of management intensification on multiple forest services: a Swedish case study

Zanchi, Giuliana; Belyazid, Salim; Akselsson, Cecilia; Yu, Lin

Published in:
Ecological Modelling

DOI:
10.1016/j.ecolmodel.2014.04.006

2014

Citation for published version (APA):
Zanchi, G., Belyazid, S., Akselsson, C., & Yu, L. (2014). Modelling the effects of management intensification on multiple forest services: a Swedish case study. *Ecological Modelling*, *284*, 48-59. https://doi.org/10.1016/j.ecolmodel.2014.04.006

Total number of authors:
4

Title: MODELLING THE EFFECTS OF MANAGEMENT INTENSIFICATION ON MULTIPLE FOREST SERVICES: A SWEDISH CASE STUDY

Authors:
Zanchi, Giuliana[a,*]
Salim Belyazid[b]
Cecilia Akselsson[a]
Lin Yu[b]

[a] Department of Physical Geography and Ecosystem Science, Lund University, Sölvegatan 12, SE-223 62 Lund, Sweden.
[b] Centre for Environmental and Climate Research, Lund University, Sölvegatan 37, 22362 Lund, Sweden.

*Corresponding author: e-mail: giuliana.zanchi@nateko.lu.se, phone: + 046-222 37 49
Other authors: cecilia.akselsson@nateko.lu.se, salim@belyazid.com, lin.yu@cec.lu.se

ABSTRACT

The study presents a method to evaluate the response of forest ecosystems to increased biomass extraction based on the integrated ecosystem model ForSAFE. It evaluates the effects of residue removal, intensification of thinnings and a shorter rotation period on a forest site in Southern Sweden. The evaluation includes multiple ecosystem indicators for productivity, carbon storage, wood production, water use and water quality. Such integrated assessments can contribute to identify negative or positive impacts affecting ecosystem services provided by forests. Results show that increased biomass extraction reduces the carbon stored in the forests, but at the same time reduces the loss of nitrogen and carbon through leaching. Within one rotation, residue removal affects the carbon stock in the soil, but it does not affect forest productivity and therefore tree carbon stock. Contrarily, the intensification of thinnings and shorter rotation periods reduce carbon stored in trees. In all cases, the amount of wood available for products increases, but the additional harvest from increased thinnings and earlier clear cutting does not compensate for the loss of carbon in trees. A positive consequence of removing the decomposing material from the site is the reduced amount of nutrients lost with runoff. Both leached nitrogen and dissolved organic carbon decrease with intensification. In addition, a positive effect of increased thinnings and a shorter rotation period is a reduced evapotranspiration, i.e. reduced water use. The effect on acidification differed depending on the time frame considered and the applied management scenario, due to different dominating processes regulating acidity. To avoid acidification, management intensification should include measures to prevent loss of base cations in the soil. Overall, under the studied conditions, the risk for negative effects seems to be smaller for residue extraction than for management changes including additional tree harvest.

Keywords: integrated assessment, dynamic model, forest management, ecosystem service, long-term measurement

1. INTRODUCTION

Societies face today the challenge to minimize negative environmental impacts produced by human activities. To respond to this need, environmental policies that aim to prevent or reduce such negative effects are promoted from the regional to the international level. These policy measures are usually the result of a process that includes interactions between, monitoring, research, assessment and policy-making (Millenium Ecosystem Assessment, 2005).

Forest management is one of the activities that can produce significant positive or negative effects on environmental resources. For this reason, forestry is expected to contribute to achieve multiple environmental objectives set by policies by providing services such as timber production, biodiversity conservation, carbon storage, supply of bioenergy and water resource protection (COM, 2005; Rayner et al., 2010). However, each management strategy has often impacts on the provision of several services which can conflict with each other (Wang and Fu, 2013). Trade-offs have been identified, for example, between wood production and biodiversity or carbon storage and bioenergy (Parrotta et al., 2012; Vanhala et al., 2013).

Due to the conflicts or synergies between different services, there is an increasing need to evaluate the effects of forestry activities in an integrated perspective and therefore support management strategies that could help countries to comply with multiple environmental objectives. Research studies that perform quantitative assessments of the impact of forestry on multiple forest services are just emerging and are still quite limited (Başkent et al., 2011; Duncker et al., 2012; Gamfeldt et al., 2013; Schwenk et al., 2012).

This study presents a method to evaluate the response of abiotic properties of forest ecosystems to environmental changes, based on an integrated ecosystem model. We focused on the effects of management intensification on indicators of site productivity, carbon storage, wood production, water use and water quality at forest site level. The response of these indicators to management changes can provide information for the identification of trade-offs between different forest ecosystem services and therefore increase knowledge on optimal management strategies. The method has been applied to a forest site, which is part of a long-term monitoring network in Swedish forests. After validating the model results against measured data, we simulated ecosystem responses under different management scenarios in an integrated manner.

2. DATA and METHODS

2.1. The biogeochemical model ForSAFE

ForSAFE is a mechanistic model of the dynamics of forest ecosystems. The model is a mechanical aggregation of interacting but mutually independent processes that constitute the building blocks of the model. Each independent process - chemical, physical or physiological- is based on empirical evidence (Belyazid et al., 2006; Wallman et al., 2005). It was designed for the purpose of simulating the dynamic responses of forest ecosystems to environmental changes. ForSAFE combines the engines of four established models: the tree growth model PnET (Aber and Federer, 1992), the soil chemistry model SAFE (Alveteg, 1998), the decomposition model Decomp (Wallman et al., 2006; Walse et al., 1998), and the hydrology model PULSE (Lindström and Gardelin, 1992). Merging these components brings together the three basic material and energy cycles in a single integrated model: the biological cycle representing the processes involved in tree growth; the biochemical cycle including uptake, litter decomposition and soil nutrient dynamics; and the geochemical cycle including atmospheric deposition and weathering processes (Figure 1).

[Figure 1]

2.2. Datasets

In this study, the model ForSAFE was used to simulate the effects of management changes on a forest site in Southern Sweden, Västra Torup (13.51E, 56.14N). The site is located on a flat area with annual average temperature of about 8°C and average annual precipitation of about 900 mm. The site is a spruce dominated managed forest on a brown podzolic soil with a mean net annual increment of about 6 m^3 ha^{-1} $year^{-1}$ over the rotation period. The site is part of the Swedish

Throughfall Monitoring Network (SWETHRO) (Pihl Karlsson et al., 2011). In the SWETHRO sites, several parameters are measured, including throughfall deposition and soil water chemistry inside forest stands and measurements of air concentrations of sulphur dioxide, nitrogen oxides and ammonia and bulk deposition in nearby open areas. The first sites were initiated in the end of the 1980's.

Västra Torup is also part of the ICP FOREST LEVEL II monitoring programme (International Co-operative Program on Assessment and Monitoring of Air Pollution Effects on Forests, http://www.icp-forests.org). Historical data are available on tree biomass (1996-2010 on a 5 year interval), soil chemistry (from 1995 on a yearly basis) and other parameters such as foliage chemistry and defoliation (1995-2010).

Complementary data on soil chemistry and tree biomass were collected in 2010. Soil samples from five distinguished soil horizons were analysed for soil C, N, pH and exchangeable cations, soil texture and total element contents. The total element contents were used as inputs to the program A2M to estimate the normative mineralogical composition of the different layers (Posch and Kurz, 2007). The soil data used as inputs to the model are reported in the Appendix (Table A.1).

The atmospheric deposition scenario used for the simulations is the Current Legislation (CLE) scenario and the Gothenburg protocol of the UN Convention on Long-Range Transboundary Air Pollution provided by the European Monitoring and Evaluation Programme (EMEP) on a 50x50 km grid. The EMEP scenario includes data series for sulphur (SO_4), nitrate (NO_3) and ammonia (NH_4) deposition from 1900 to 2100. The original EMEP data set was downscaled according to measurements collected at the site in 1988-2009 (http://krondroppsnatet.ivl.se/). The downscaling is based on the ratio between the average measured deposition and the average modelled deposition over the same period. Deposition of calcium (Ca), magnesium (Mg), potassium (K), chlorine (Cl) and sodium (Na) was assumed constant over the simulation period (1900-2100) and is equal to the average measured deposition for each element. Modelled deposition data were replaced with measured deposition data when available.

The climate scenario in the period 1900-2100 is based on data from the Global Climate Model ECHAM and follows the SRESA2 emission story line of the IPCC. The model data have been calibrated over the historical climate. Historical data are derived from the SMHI weather station data using-spatial interpolation and from the NCEP/NCAR Reanalysis project for solar radiation (1961-2008) (David Ryner, 2010 , personal communication).

2.3. Model initialization, calibration and validation

The amount of organically bound carbon and nutrients in the soil affects the forest stand's status. The mineralisation of organically bound nutrients can be the most important source satisfying tree uptake requirements, while the decomposition of carbon directly dictates microbial activity and soil acidity. To make sure the current size of the organic pools of carbon and nutrients in the soil are correct, the initial state of the site has to be calibrated. The initial conditions are set through an iterative process that involves the calibration of simulated values of soil organic carbon against a measured value at present. A fundamental part of the information needed to initialize the model is the past land management that strongly influence the accumulation of nutrients in the soil. Information on the past management in Västra Torup was obtained from forest management plans and interviews to the forest manager.

The calibration of the model included the adjustment of some parameters regulating part of the vegetation processes. Some of the default tree species parameters used in the photosynthetic module of ForSAFE, Pn-ET, appeared to be inappropriate for Swedish conditions. These values determined a significant underestimation of biomass growth and stock. Therefore, some of the parameters regulating biomass production were adjusted to better represent site conditions (see Appendix, A.2). The calibration phase included the collection of additional information to regulate the uptake and storage of base cations (Bc) in spruce from literature and available databases. In ForSAFE, the uptake is driven by a minimum nutrient content in foliage and an average content in wood and fine roots. If there is no nutrient limitation, the nutrients allocated to foliage are set higher than the minimum nutrient demand, a phenomenon known as luxury uptake (Tamm, 1975). We used data of nutrient concentrations in spruce foliage from the ICP network to calculate minimum and maximum nutrient contents. The variability of concentration observed in the data supports the theory that tree uptake is larger than the minimum required for tissue formation when there is no nutrient limitation. For example, calcium concentration in spruce foliage can be 5 times the minimum concentration. These values were used to calculate the range of variation over the minimum nutrient requirement and therefore regulate luxury uptake in ForSAFE (Table 1).

[Table 1]

The model results were validated against the measured values from the Västra Torup site. Measured data on tree diameter were used to calculate tree biomass (Marklund, 1988). Biomass data and measurements of soil water chemistry collected in 1996-2011 (pH, NO_3, SO_4, Cl, Na, Bc, total Al) were compared to model results.

2.4. Integrated assessment of indicators in response to management changes

The ecosystem response to different management scenarios has been evaluated by analysing a group of ecosystem indicators: net primary production (NPP, g m^{-2} of carbon), carbon stock in woody biomass (Tree C, g m^{-2} of carbon), soil organic carbon (SOC, g m^{-2} of carbon), amount of harvested wood available for wood products and bioenergy (HV, g m^{-2} of dry matter, d.m.), actual evapotranspiration (AET, l m^{-2}), acid neutralizing capacity (ANC, μeq l^{-1}), nitrogen leaching (Nleach, g m^{-2} of nitrogen) and dissolved organic carbon (DOC, g m^{-2} of DOC). These indicators provide a quantification of ecosystem processes that regulate the provision of some ecosystem services to human societies (Table 2). Therefore, the analysis of the response of these indicators can help understanding how ecosystem service provision from forests could be affected under intensified management.

Several indicators were calculated as cumulative values to highlight the difference over time between different management scenarios.

[Table 2]

Scenarios representing the current (BAS) and three intensified management practices (INT1,INT2 and INT3) have been included in the analysis. The BAS scenario is based on historical data from Västra Torup and the INT scenarios are based on three hypothetical strategies to increase extraction of biomass from forest sites: residue extraction (INT1), increased number of thinnings (INT2) and a shorter rotation period (INT3). The management is equal for all scenarios until 2010. The forest was clear cut in 2010 at the age of about 70 years and was thinned two times before that. The site was marginally affected by the storm Gudrun in 2005. Starting from 2010, the amount of wood extracted in the INT scenarios was increased (Table 3). The INT1 has been simulated to isolate the effect of residue removal from the site. Residue removal is included also in scenarios INT2 and INT3. It is also assumed that 60% of the foliage is removed with the branches in all INT scenarios (Swedish Forest Agency, 2008). This assumption is based on current technical constraints that do not enable residues extraction without foliage.

[Table 3]

As a first step, we simulated each indicator under each management scenario and evaluated the difference between INT and BAS scenarios over time.

As a second step, the response of all indicators was evaluated simultaneously to produce an integrated assessment of the effects of management changes. For this purpose, the values attributed to each indicator have been normalized in order to avoid different units and scales. The following expression has been used to normalize model results:

$$\Delta I = \frac{I_{INT}(t) - I_{BAS}(t)}{\left| I_{BAS}(t) \right|} \times 100$$

Where ΔI is the normalized change of a certain indicator I (e.g. NPP) in percentage and I_{INT} and I_{BAS} are the values of the indicator under the intensified and baseline management scenarios, respectively, at a certain point in time, t.

The conclusions on the effect of management changes are influenced by the time-frame that is chosen to assess ΔI. In this study, we chose to consider the values of I_{INT} and I_{BAS} at two different points in time:

A. 35 years after the first clear cut (in 2045)
B. At the end of the rotation period (in 2079 in BAS, INT1 and INT2 and 2069 in INT3)

Option A focuses on the effects of management changes after a clear cut and on a shorter time frame that can be relevant for policy making. Option B describes a longer time-frame response of the ecosystem, when all the management activities in a rotation period are considered.

In the case of ANC, we chose to consider the average Δ*I* over a time interval (*t2-t1*) rather than the value at a single point in time to avoid biases linked to the high inter-annual variability of this indicator:

$$\overline{\Delta I} = \frac{\sum_{i=t1}^{t2} \Delta I_i}{(t2 - t1)}$$

All the other indicators are cumulative values and therefore they incorporate any inter-annual variability, if present. However, ANC as an indicator of acidification has a meaning only when expressed in terms of concentrations and a cumulative value of a concentration is not applicable. For ANC, the normalized difference between two scenarios is assessed as the average over 10 years (2035-2044 in option A and 2070-2079 or 2060-2069 in option B).

After estimating Δ*I* for all the indicators, the changes are interpreted as a system improvement or worsening. For some indicators (NPP, C stock, ANC and HV), there is an ecosystem improvement when the indicator increases, while for others (AET, Nleach and DOC) there is a positive effect when the indicator decreases. In order to simplify the interpretation of results, the response of this second group of indicators is changed of sign (-Δ*I*). After this correction, a positive Δ*I* corresponds to an ecosystem improvement for all indicators.

Finally, the overall effect of the management change is depicted with the help of spider charts (Figure 2). Spider charts are a graphic tool that has been used to assess the performance of multifunctional systems (Hermann et al., 2013; Paracchini et al., 2011). In this paper, each indicator is represented by a radium in the spider chart. The effect of the management intensification (INT) is represented as a relative change to the baseline (BAS) in percentage and it is equal to ΔI.

[Figure 2]

3. RESULTS

3.1. Model validation

The model validation shows a good agreement between modelled results and measurements (Figure 3). We observed some discrepancies mainly on the modelling of SO4 and Na in the soil solution.

According to the model, SO_4 in the soil solution steadily decrease after the decrease of sulphur deposition in the 1980s'. However, measured data show that sulphate in the soil solution decreases less rapidly than expected. As a consequence, modelled sulphate in the soil solution (SO_4) is underestimated compared to the measurements. We attribute the discrepancy between measured and modelled data to the fact that sulphate adsorption, which slows down the release of SO4 in the soil solution (Eriksson et al.1992, Martinson et al. 2003), was not included in the model runs.

On the opposite, the model overestimates the amount of sodium in the soil solution. We attribute this discrepancy to the Na deposition data used as an input to the model, which are based on observations during a limited period of time (1998-2009). These data could be not fully representative for previous periods of time and therefore cause uncertainties in the estimation. However, the presence of both SO_4 and Na in the soil solution in Southern Sweden is strongly dependent on atmospheric deposition and tree growth has very limited effect on their mobilization. Therefore, it is likely that forest management changes will not strongly affect the amount of SO_4 and Na in the soil solution. For this reason, we believe that the discrepancy between modelled and measured SO_4 and Na should not affect the conclusions in this paper on the effect of management intensification.

[Figure 3]

3.2. Model scenarios

The analysis of the intensified management scenarios shows that management intensification mostly affects forest carbon stock, wood production and nitrogen and carbon leaching. Intensified management limited to the extraction of harvest residues (INT1) does not affect biomass production, the carbon stored in trees and the amount of water used by trees when compared to the baseline (BAS) (Figure 4). However, it produces very soon a permanent decrease of soil organic carbon (SOC). In addition, residue removal increases the acidity of the soil solution in the first half of the rotation period, i.e. the ANC is lower than in the BAS scenario. However, an opposite effect on acidification is simulated in the long term. Over the entire rotation period, the extraction of residues has some positive effects, such as increased wood production and a reduced export of nitrogen and DOC after cutting due to the lower amount of decomposing material in the forest.

[Figure 4]

Compared to residue extraction, the intensification of thinning regime (scenario INT2) produces a further negative effect on the carbon stored in the forest (Figure 5). In addition to the decrease of SOC, there is a permanent decrease of carbon stock in trees and a slight decrease of productivity of the stand, NPP, over the rotation period. Positive effects are still the increase of wood production and the reduced nitrogen and DOC export. In addition there is a slight decrease of water consumption through evapotranspiration, caused by the reduction of tree biomass and consequent reduced water uptake.

[Figure 5]

The adoption of a shorter rotation period (INT3) emphasises most of the effects produced by additional thinnings: lower forest carbon stock and primary productivity counterbalanced by lower evapotranspiration and nitrogen and DOC export (Figure 6). However, an earlier final felling prevents the recovery of ANC observed in scenarios INT1 and INT2 compared to BAS before the clear-cut and therefore the soil solution results more acidified.

[Figure 6]

3.3. Integrated assessment

The integrated assessment of all the indicators confirms that negative effects on the ecosystem are expected to be less when intensification entails only forest residue extraction.

Within 35 years after the change of management, residue removals substantially increase the amount of wood that can be extracted while nitrogen and DOC leaching is reduced and tree biomass and productivity is preserved. The only simulated negative changes are a decrease of SOC and a slight increase of acidification (Figure 7).

An additional negative effect produced by the intensified thinnings and the shorter rotation period is a significant loss of tree carbon stock. This is caused by the inclusion of one additional thinning in both scenarios over the first 35 years. In terms of carbon balance, the amount of additional harvest extracted in INT2 and INT3 does not compensate for the additional loss of carbon in the forest.

[Figure 7]

The different effects in different scenarios become more evident when the integrated assessment is done for the entire rotation period (Figure 8).

Compared to the shorter time-frame analysis, the export of nutrients is further reduced, especially in terms of nitrogen leaching. This positive effect is greater in more intensive management scenarios.

As in the shorter time-frame, all intensified managements result in a loss of soil organic carbon.

In addition, intensified thinnings and the shorter rotation negatively affect the carbon stored in trees. This further decrease of forest carbon stock is not compensated by an equally significant increase of harvest. In the case of a shorter rotation period, the total increase of harvest is even less than the increase produced by residue extraction.

The effect on acidification differs among scenarios. The soil solution is less acidified in the case of residue extraction and additional thinnings, while the shorter rotation period slightly increases acidification.

The shorter rotation period results also in a decreased evapotranspiration, i.e. a lower water consumption, but also in a reduced primary productivity.

For transparency, the absolute values of the indicators, the absolute and normalized changes between scenarios are reported in the Appendix (A.3).

[Figure 8]

4. DISCUSSION AND CONCLUSIONS

In the initialization and calibration phase, we found that past land management has a very strong influence on model results. In several European countries forest area is recovering after the large-scale deforestation that occurred in pre-industrial and industrial times (Forest Europe et al., 2012; Gold, 2003; Kaplan et al., 2009). Many forest sites in Southern Sweden, such as Västra Torup, were previously pasture or cropland. The consideration of past land-use in the model simulations substantially changed the results, mainly due to the higher amount of soil organic carbon and nutrients accumulated under forests. In addition, results were also influenced by the type of management implemented in the 1900s. It is often challenging to retrieve accurate historical information and therefore it is important to have long-term measurements to validate model results against. The combination of measurements and models can increase our understanding of ecosystem processes and responses and at the same time improve our predictive power on future impacts due to environmental changes.

Another factor that influences the response of ForSAFE is atmospheric deposition and some uncertainty in the model outputs is connected to the deposition data used as inputs. In this study, we tried to improve the reliability of deposition input data by correcting them against measurements. This correction strongly improved the agreement of ForSAFE simulations with measurements of soil water chemistry in the validation phase. The uncertainty is higher for base cations (Bc), Cl and Na deposition which we believe causes the overestimation of sodium in the soil solution. In this paper, we adopted for these elements a constant deposition based on averaged values at present time, due to the lack of modelled deposition series. However, series of measurements show that Bc deposition, for instance, is following a declining trend and it might have been higher in the past (Hedin et al., 1994). Therefore, the robustness of simulations at the forest ecosystem level is partially dependent on the reliability of data produced by atmospheric deposition modelling. Similar observations can be applied also to climate input data.

Previous studies showed that the environmental effects of additional biomass extraction vary according to the feedstock, time scale and investigated environmental indicator (Lamers et al., 2013).

According to our results, management intensification has always a negative effect on the soil organic stock which is mainly affected at the final clear-cut. Previous studies show that residue removal can reduce soil organic matter and the probability for this effect to occur is lower after thinnings than clear-cutting (Wall, 2008). The magnitude of the SOC change varies among studies, but it is generally estimated around 5-15% less compared to stem-only harvesting (Kaarakka et al.2014, Johnson et al 2001, Wall, 2012), which is in agreement with our assessment of a 7% decrease.

The tree carbon stock is not always affected by management intensification. On one hand, a significant long term decrease of growing stock and thereby of biomass carbon stock occur when more trees are cut with intensified thinnings or a shorter rotation period. On the other hand, residue extraction does not affect the growing stock and the biomass carbon in our study. However, in time frames longer than a rotation period, the depletion of organic matter in the soil could result in a loss of fertility and eventually affect tree growth. Moreover, nutrient limitations that affect tree growth could emerge within shorter time-frames in nutrient poor sites. Another possible negative impact of residue extraction is the reduced amount of deadwood in the forest. Deadwood is considered a key indicator of biodiversity (Lassauce et al., 2011; Rondeux and Sanchez, 2010) and a permanent increase of biomass extraction could result in loss of biodiversity in forests (Verkerk et al., 2011).

All intensification scenarios increase the amount of harvest and therefore they can potentially increase the carbon stock in wood products. However, this increase of carbon in harvest wood products should be compared to the loss of carbon stock in the forest, in soils and trees. Our results show that, while wood products from residue extraction more than compensate for soil carbon losses, the increase of carbon in wood products from more frequent cuttings can be offset by a significant loss of carbon in trees. These results can change if the effect of natural disturbances is taken into account. More intensive management scenarios can prevent volume losses produced by natural damage (Jönsson et al., 2014) and therefore maintain or even increase the carbon stock in living trees.

Our results also suggest that residue extraction could be a better long-term strategy in terms of harvest, because the intensification of thinnings and shorter rotation periods can reduce growing stock and primary productivity and therefore can result in lower wood production in the long run.

The effect on acidification differed depending on the time frame considered. In the first half of the forest rotation, harvesting of residues led to reduced ANC due to the loss of base cations removed with residues. In the end of the rotation period, however, ANC was higher in the INT scenarios than in the BAS scenario. This can be explained by the lower amounts of N in the soils after intensified management, causing less nitrification and, since nitrification is an acidifying process, less acidification. The lower nitrification in the INT scenarios is shown in the results by the lower N leaching. The results are in agreement with the nitrogen saturation concept which postulates that under continued elevated N input, such as deposition, the system cannot retain it all and leaching occurs (Aber et al., 1989). The Västra Torup site lies in the highest deposition area in Sweden (Pihl Karlsson et al., 2011) where several of the monitored forest sites are continuously leaching nitrate, not only after final felling (Akselsson et al., 2010). Therefore, the high nitrogen inputs in Västra Torup could result in the future in extensive nitrogen leaching under the current management. The results on ANC also highlight that when the soils are capable of retaining nitrogen, i.e. nitrogen is not leached, the acidification process is dominated by base cation depletion due to biomass removal from the site. However, when soils are nitrogen saturated, nitrification is the dominating acidification process. Therefore, to prevent acidification, management intensification should include measures that prevent a loss of base cations, such as fertilisation with ashes.

The method applied in this study proved to be a valid tool for integrated assessment in forest ecosystems. However, only when this or a similar approach will be applied to different conditions it will be possible to draw general conclusions on management effects. Larger scale studies are needed to be able to draw conclusions that are relevant for management plans and policy (Gamfeldt et al., 2013). Some of the factors that could change the outcomes of this study are low fertility, water scarcity and risk for natural disturbances. In sites affected by lower fertility, residue extraction could be enough to reduce nutrient availability and limit tree growth (Palosuo et al., 2008). In area in which water is scarce, reduced rotation periods could have a significant positive effect on water availability because of reduced evapotranspiration. Finally, in areas with high risk for natural disturbances, such as fire and wind throws, lowering the growing stock with more frequent cuttings might be a solution to reduce damage (Jönsson et al. 2014).

As shown in the results, the time-frame chosen for the analysis affects the conclusions drawn. For this reason, it is recommended to consider different time options to avoid time-scale induced biases. Such an overview will also allow decision makers to select appropriate results, according to the goals that society wants to achieve.

The translation of model results into recommendations for policy makers requires a further step to determine if a change of an indicator is relevant or not. With ‘relevant’ we mean an effect that produces negative or positive impacts for the ecosystem and human societies. In this study, we investigated the effects of management changes on the ecosystem. The translation into positive or negative impacts and in policy recommendations would require a comparison of model results with critical values that determine when ecosystem functioning and service provision is affected. We conclude that forest ecosystem modelling coupled with long-term measurements is a powerful tool to move towards integrated environmental assessments. Such assessments are needed to understand the effect of environmental changes on services provided by forest ecosystems. Based on this knowledge, societies could support activities that minimize negative impacts and help complying with multiple environmental objectives.

APPENDIX A

A.1 Soil input data

[Table A.1]

A.2 Model parameterization

The model initialization was limited to a period of 50 years to avoid an excessive accumulation of organic matter in the soil. We made this choice to represent the historical conditions at the site which was a pasture until the 1940s' and not a natural or managed forest.

Most of the tree species parameters were derived from earlier parameterization of the PnET model (Aber and Federer, 1992; Aber et al., 1997; 1995). Some of the parameters were adjusted to better represent biomass accumulation in Sweden (Table A.2). This choice was driven by an initial mismatch between measured and modelled tree biomass.

[Table A.2]

A.3 Indicator values

[Table A.3]

ACKNOWLEDGEMENTS

The authors wish to thank for the financial support granted by the projects “Multistressors on the Baltic Sea”, “ForWater” and “Nitrogen retention in forest soils” funded by FORMAS. We also thank the regional air quality protection associations, county administrative boards and the

Swedish Environmental Protection Agency funding SWETHRO and the Swedish Forest Agency (Skogsstyrelsen) for the data provided. In addition, we thank Dr. Anna Maria Jönsson for her valuable advice on forest management strategies in Sweden.

REFERENCES

Aber, JD, Federer, CA, 1992. A generalized, lumped-parameter model of photosynthesis, evapotranspiration and net primary production in temperate and boreal forest ecosystems. Oecologia 92, 463-474.

Aber, JD, Nadelhoffer, KJ, Steudler, P, Melillo, JM, 1989. Nitrogen Saturation in Northern Forest Ecosystems. Bioscience 39, 378-386.

Aber, JD, Ollinger, SV, Driscoll, CT, 1997. Modelling nitrogen saturation in forest ecosystems in response to land use and atmospheric deposition. Ecol Model 101, 61-78.

Aber, JD, Ollinger, SV, Federer, CA, Reich, PB, Goulden, ML, Kicklighter, DW, Melillo, JM, Lathrop, RG, 1995. Predicting the effects of climate change on water yield and forest production on the Northeastern United States. Clim Res 5, 207-222.

Ågren, GI, Hyvönen, R, Nilsson, T, 2008. Are Swedish forest soils sinks or sources for CO_2 - model analyses based on forest inventory data. Biogeochemistry 89, 139- 149.

Akselsson, C, Belyazid, S, Hellsten, S, Klarqvist, M, Pihl-Karlsson, G, Karlsson, P-E, Lundin, L, 2010. Assessing the risk of N leaching from forest soils across a steep N deposition gradient in Sweden. Environ Pollut 158, 3588-3595.

Alveteg, M, 1998. Dynamics of forest soil chemistry., Department of Chemical Engineering II. Lund University, Lund, Sweden.

Balland, V, Pollacco, JAP, Arp, PA, 2008. Modeling soil hydraulic properties for a wide range of soil conditions. Ecol Model 219, 300-316.

Başkent, E, Keleş, S, Kadıoğulları, A, Bingöl, Ö, 2011. Quantifying the Effects of Forest Management Strategies on the Production of Forest Values: Timber, Carbon, Oxygen, Water, and Soil. Environ Model Assess 16, 145-152.

Belyazid, S, Westling, O, Sverdrup, H, 2006. Modelling changes in forest soil chemistry at 16 Swedish coniferous forest sites following deposition reduction. Environ Pollut 144, 596-609.

COM, 2005. Communication from the Commission to Council and the European Parliament - Reporting on the implementation of the EU Forestry Strategy, Brussels.

Duncker, PS, Raulund-Rasmussen, K, Gundersen, P, Katzensteiner, K, De Jong, J, Ravn, HP, Smith, M, Eckmüllner, O, Spiecker, H, 2012. How Forest Management affects Ecosystem Services, including Timber Production and Economic Return: Synergies and Trade-Offs. Ecol Soc 17.

Eriksson, E, Karltun, E, Lundmark, JE, 1992. Acidification of forest soils in Sweden. Ambio 21, 150-154.

Forest Europe, UNECE, FAO, 2012. State of Europe's forests 2011. Oslo, Norway.

Gamfeldt, L, Snall, T, Bagchi, R, Jonsson, M, Gustafsson, L, Kjellander, P, Ruiz-Jaen, MC, Froberg, M, Stendahl, J, Philipson, CD, Mikusinski, G, Andersson, E, Westerlund, B, Andren, H, Moberg, F, Moen, J, Bengtsson, J, 2013. Higher levels of multiple ecosystem services are found in forests with more tree species. Nat Commun 4, 1340.

Gold, S, 2003. The Development of European Forest rtesources, 1950 to 2000: a better information base, Geneva, Switzerland, 98 pp.

Hedin, LO, Granat, L, Likens, GE, Adri Buishand, T, Galloway, JN, Butler, TJ, Rodhe, H, 1994. Steep declines in atmospheric base cations in regions of Europe and North America. Nature 367, 351-354.

Hermann, A, Kuttner, M, Hainz-Renetzeder, C, Konkoly-Gyuró, É, Tirászi, Á, Brandenburg, C, Allex, B, Ziener, K, Wrbka, T, 2013. Assessment framework for landscape services in European cultural landscapes: An Austrian Hungarian case study. Ecol Indicators, in press.

Kaplan, JO, Krumhardt, KM, Zimmermann, N, 2009. The prehistoric and preindustrial deforestation of Europe. Quaternary Science Reviews 28, 3016-3034.

Jönsson, A, Lagergren, F, Smith, B, 2013. Forest management facing climate change - an ecosystem model analysis of adaptation strategies. Mitig Adapt Strateg Glob Change, 1-20.

Lamers, P, Thiffault, E, Paré, D, Junginger, M, 2013. Feedstock specific environmental risk levels related to biomass extraction for energy from boreal and temperate forests. Biomass Bioenergy 55, 212-226.

Lassauce, A, Paillet, Y, Jactel, H, Bouget, C, 2011. Deadwood as a surrogate for forest biodiversity: Meta-analysis of correlations between deadwood volume and species richness of saproxylic organisms. Ecol Indicators 11, 1027-1039.

Lindström, G, Gardelin, M, 1992. Modelling groundwater response to acidification, Report from the Swedish integrated groundwater acidification project.

Marklund, LG, 1988. Biomassafunktioner för tall, gran och björk i Sverige.

Martinson, L, Alveteg, M, Warfvinge, P, 2003. Parameterization and evaluation of sulfate adsorption in a dynamic soil chemistry model. Environ Pollut 124, 119-125.

Millenium Ecosystem Assessment (ed.) 2005. Ecosystems and Human Well-being: Policy Responses. Island Press, Washington, US, 620 (?) pp.

Palosuo, T, Peltoniemi, M, Mikhailov, A, Komarov, A, Faubert, P, Thürig, E, Lindner, M, 2008. Projecting effects of intensified biomass extraction with alternative modelling approaches. For Ecol Manage 255, 1423-1433.

Paracchini, ML, Pacini, C, Jones, MLM, Pérez-Soba, M, 2011. An aggregation framework to link indicators associated with multifunctional land use to the stakeholder evaluation of policy options. Ecol Indicators 11, 71-80.

Parrotta, J, Wildburger, C, Mansourian, S, 2012. Understanding Relationships between Biodiversity, Carbon, Forests and People: The Key to Achieving REDD+ Objectives. A Global Assessment Report. Vienna.

Pihl Karlsson, G, Akselsson, C, Hellsten, S, Karlsson, PE, 2011. Reduced European emissions of S and N – Effects on air concentrations, deposition and soil water chemistry in Swedish forests. Environ Pollut 159, 3571-3582.

Posch, M, Kurz, D, 2007. A2M—A program to compute all possible mineral modes from geochemical analyses. Computers and Geosciences 33, 563-572.

Rayner, J, Buck, A, Katila, P, (eds.), 2010. Embracing complexity: Meeting the challenges of international forest governance. A global assessment report., IUFRO World Series. IUFRO, Vienna, p. 172.

Reid, I, 1973. The choice of assumed particle density in soil tests. Area 5, 10-12.

Repo, A, Tuomi, M, Liski, J, 2011. Indirect carbon dioxide emissions from producing bioenergy from forest harvest residues. GCB Bioenergy 3, 107-115.

Rondeux, J, Sanchez, C, 2010. Review of indicators and field methods for monitoring biodiversity within national forest inventories. Core variable: Deadwood. Environ Monit Assess 164, 617-630.

Rothpfeffer, C, Karltun, E, 2007. Inorganic elements in tree compartments of Picea abies—Concentrations versus stem diameter in wood and bark and concentrations in needles and branches. Biomass Bioenergy 31, 717-725.

Schwenk, WS, Donovan, TM, Keeton, WS, Nunery, JS, 2012. Carbon storage, timber production, and biodiversity: comparing ecosystem services with multi-criteria decision analysis. Ecol Appl 22, 1612-1627.

Swedish Forest Agency, 2008. Skogliga konsekvensanalyser 2008 – SKA-VB 08. Rapport 25. Jönköping

Tamm, CO, 1975. Plant nutrients as limiting factors in ecosystem dynamics, Productivity of world ecosystems. National Academy of Sciences, Washington D.C., pp. 123-132.

Vanhala, P, Repo, A, Liski, J, 2013. Forest bioenergy at the cost of carbon sequestration? Current Opinion in Environmental Sustainability, in press.

Verkerk, PJ, Lindner, M, Zanchi, G, Zudin, S, 2011. Assessing impacts of intensified biomass removal on deadwood in European forests. Ecol Indicators 11, 27-35.

Wallman, P, Belyazid, S, Svensson, MGE, Sverdrup, H, 2006. DECOMP – a semi-mechanistic model of litter decomposition. Environ Model Software 21, 33-44.

Wallman, P, Svensson, MGE, Sverdrup, H, Belyazid, S, 2005. ForSAFE—an integrated process-oriented forest model for long-term sustainability assessments. For Ecol Manage 207, 19-36.

Walse, C, Berg, B, Sverdrup, H, 1998. Review and synthesis of experimental data on organic matter decomposition with respect to the effect of temperature, moisture, and acidity. Environ Rev 6, 25-40.

Wang, S, Fu, B, 2013. Trade-offs between forest ecosystem services. Forest Policy and Economics 26, 145-146.

Warfvinge, P, Sverdrup, H, 1995. Critical loads of acidity to Swedish forest soils,. Lund, Sweden.

TABLES

Table 1 – Range of nutrient concentrations in tree tissues used to regulate nutrient uptake in ForSAFE

Parameter	N	Mg	Ca	K	Source
Min concentration in leaves (g kg^{-1})	8.5	0.5	1.5	2.3	Calculated based on ICP network data
Fraction of luxury uptake	1.3	3.1	5	1.9	Calculated based on ICP network data
Average concentration in wood (g kg^{-1})	0.75	0.13	0.65	0.40	Rothpfeffer and Karltun (2007) Braun Sabine (2012), personal communication
Average concentration in roots (g kg^{-1})	1.9	0.24	1.8	1.0	Braun Sabine (2012), personal communication

Table 2 – Ecosystem processes and services connected to the investigated indicators

Indicator	Acronym	Process	Service
Net primary production (cumulative)	NPP	Biomass growth	Primary production
Harvested biomass (cumulative)	HV	Extraction of biomass	Production of raw materials
Carbon stock in tree wood	Tree C	Storage of carbon	Climate regulation
Soil organic carbon	SOC	Storage of carbon and other nutrients	Climate regulation, maintenance of soil fertility
Acid neutralizing capacity	ANC	Acidification	Nutrient cycling, water quality control
Nitrogen leaching (cumulative)	Nleach	Nutrient loss, eutrophication	Nutrient cycling, water quality control
Dissolved organic carbon (cumulative)	DOC	Brownification	Nutrient cycling, water quality control
Actual Evapotranspiration (cumulative)	AET	Water use by plants	Water supply

Table 3 – Management scenarios. CC: clear-cut, TH: thinning. The fraction of biomass removed from the site can include stems (S), aboveground wood residues (AgR), foliage (FL). In brackets: for each treatment, the fraction of biomass cut; for removals, the fraction of biomass taken away from the site.

Year	BAS		INT1		INT2		INT3	
	Treatment	Removed	Treatment	Removed	Treatment	Removed	Treatment	Removed
1940	Plantation							
1965	TH (0.25)	S (0.5)						
1985	TH (0.25)	S (1)						
2005	Storm (0.05)	S (0.5)						
2010	CC (0.95)	S (1)	CC (0.95)	S (1), AgR (1), FL (0.6)	CC (0.95)	S (1), AgR (1), FL (0.6)	CC (0.95)	S (1), AgR (1), FL (0.6)
2030					TH (0.3)	S (1), AgR (1), FL (0.6)	TH (0.3)	S (1), AgR (1), FL (0.6)
2035	TH (0.25)	S (0.5)	TH (0.25)	S (1), AgR (1), FL (0.6)				
2045					TH (0.3)	S (1), AgR (1),	TH (0.3)	S (1), AgR (1),

						FL (0.6)		FL (0.6)
2055	TH (0.25)	S(1)	TH (0.25)	S (1), AgR (1), FL (0.6)				
2065					TH (0.3)	S (1), AgR (1), FL (0.6)		
2070							CC (0.95)	S (1), AgR (1), FL (0.6)
2080	CC (0.95)	S (1)	CC (0.95)	S (1), AgR (1), FL (0.6)	CC (0.95)	S (1), AgR (1), FL (0.6)		

Table A.1 – Soil input data from Västra Torup.

Parameter	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5
Thickness (cm)	5	6	20	20	4
Bulk density (g cm^{-3})	0.181	0.959	1.062	1.279	1.446
Particle density (g cm^{-3}) [a]	1.776	2.587	2.596	2.609	2.626
Total carbon (g kg^{-1})	543	34	25	18	8
Total nitrogen (g kg^{-1})	20.9	2.0	1.7	1.3	0.6
Organic matter (g g^{-1} of total soil)	0.87	0.06	0.05	0.04	0.02
Clay (g g^{-1} of mineral soil)		0.05	0.55	0.03	0
Silt (g g^{-1} of mineral soil)		0.27	0.31	0.21	0.17
Sand (g g^{-1} of mineral soil)		0.68	0.64	0.76	0.83
Stoniness (cm^3 cm^{-3})	0.2	0.2	0.2	0.2	0.2
Exposed mineral surface area (10^6 m^2)[b]	214161	1131959	1334007	1167398	909226
CO_2 partial pressure [b]	10	20	20	20	20
Aluminium solubility [b]	6.5	7.6	8.6	9.2	9.2
Cation exchange capacity, CEC (eq kg^{-1})	0.2115	0.0523	0.0360	0.0180	0.0189
Base saturation (CEC fraction)	0.43	0.05	0.06	0.07	0.05
Mineralogy (g g^{-1})					
Apatite $Ca_{10}(PO_4)_6(OH)_2$	0.43	0.14	0.21	0.28	0.33
Chlorite1 $Na_2Ca_3Mg_{107}Fe_{124}TiAl_{124}Si_{138}O_{540}(OH)_{442}$	0.20	0.30	0.49	0.59	0.70
Chlorite2 $Mg_{103}Fe_{58}TiAl_{100}Si_{87}O_{365}(OH)_{302}$	0.13	0.21	0.33	0.40	0.48

Epidote $Ca_{80}Fe_{30}Al_{96}Si_{124}O_{495}(OH)_{44}$	0.01	1.88	2.07	2.16	2.32
Hornblende $K_{18}Na_{54}Ca_{166}Mg_{210}Fe_{180}Ti_{11}Al_{216}Si_{606}O_{2146}(OH)_{188}$	0.02	0.36	0.58	0.70	0.82
Illite1 $K_{0.6}\,Al_2(Al_{0.6}Si_{3.4}O_{10})(OH)_2$	0.32	1.80	3.24	3.12	2.59
K-Feldspar100 $KAlSi_3O_8$	1.15	15.38	12.88	13.93	15.65
Muscovite $K_{44}Na_2Mg_8Fe_{12}Ti_2Al_{96}Si_{120}O_{390}(OH)_{94}$	0.73	3.44	6.19	5.95	4.89
Albite $NaAlSi_3O_8$	1.58	17.93	18.31	19.23	20.00
Anorthite $CaAl_2Si_2O_8$	0.01	2.10	2.31	2.42	2.60
Vermiculite1 $Ca_{20}Mg_{103}Fe_{182}Al_{162}Si_{293}O_{832}(OH)_{804}$	0.11	0.51	0.81	0.99	1.18
Vermiculite2 $Ca_{10}Mg_{103}Fe_{22}Al_{68}Si_{123}O_{249}(OH)_{490}$	0.12	0.20	0.32	0.39	0.46
Quartz SiO_2	4.58	47.77	43.69	43.58	43.85
Water H_2O	89.66	6.12	5.80	3.95	2.16
Hematite Fe_2O_3	0.18	2.08	2.92	1.94	2.11
Rutile	0.05	0.67	0.68	0.55	0.65

TiO_2					
Hydrological parameters (cm^3 cm^{-3})[c]					
Field saturation	0.90	0.63	0.59	0.51	0.45
Field capacity	0.31	0.46	0.40	0.27	0.18
Permanent wilting point	0.11	0.06	0.07	0.06	0.03

[a] Particle density estimated according to Reid (1973): $D_P = 2.65*(1-0.01*\%OM)$

[b] Estimated according to Warfvinge and Sverdrup (1995)

[c] Estimated according to Balland et al. (2008)

Table A.2 – Modified tree species parameters in the tree model component of ForSAFE

Parameter	Definition (units)	Original value	Used value	Notes
FolReten	Foliage retention time (yr)	5	7	The used value reflects the longer retention time at higher latitudes. It was estimated according to the equation reported by Ågren et al., (2008) for spruce (1/FolRet= 0.489 - 0.0063 * Latitude)
FolRelGrowMax	Maximum relative growth rate for foliage (% yr^{-1})	0.3	1	The parameter was introduced in the PnET model to regulate foliage growth few years after a disturbance event. We observed that during longer simulations periods the factor strongly limited the overall growth of the trees. By setting the parameter equal to 1, the maximum growth of foliage is only dependent on light and nutrient availability.
WoodTurnover	Fractional mortality of live wood (yr^{-1})	0.025	0.01	Forest management reduces tree mortality. The value was calibrated to better represent conditions in managed forests

Table A.3 – Indicator values under the four management scenarios (BAS, INT1, INT2, INT3), the absolute difference (INT1-BAS, INT2-BAS, INT3-BAS) and the normalized difference (ΔI_{INT1}, ΔI_{INT2}, ΔI_{INT3}) between intensified scenarios and current management. Option A: values 35 years after the change of management (in 2045); option B: values at the end of the rotation period (in 2080 in BAS, INT1 and INT2 and 2070 in INT3).

Option	Indicator (unit)	BAS	INT1	INT1-BAS	ΔI_{INT1} (%)	INT2	INT2-BAS	ΔI_{INT2} (%)	INT3	INT3-BAS	ΔI_{INT3} (%)
A	Tree C (g m^{-2})	6812	6654	-158	-2.3	4684	-2128	-31.2	4684	-2128	-31.2
	Harv (g m^{-2} of C.)	19572	22781	3209	16.4	24297	4726	24.1	24297	4726	24.1
	NPP (g m^{-2} of C)	120927	120556	-371	-0.3	119983	-944	-0.8	119983	-944	-0.8
	SOC (g m^{-2} of C)	5531	5118	-413	-7.5	5130	-401	-7.3	5130	-401	-7.3
	ANC (μeq l^{-1})	92.2	85.8	-6.4	-7.1	84.0	-8.1	-9.1	84.0	-8.1	-9.1
	N leach (g m^{-2} of N)	15.4	13.4	-1.9	12.7	13.4	-1.9	12.7	13.4	-1.9	12.7
	DOC (g m^{-2} of DOC)	1681	1611	-69	4.1	1608	-73	4.3	1608	-73	4.3
	AET (l m^{-2})	22760	22679	-81	0.4	22606	-154	0.7	22606	-154	0.7
B	Tree C (g m^{-2})	15859	15358	-501	-3.2	12407	-3452	-21.8	12487	-3372	-21.3
	Harv (g m^{-2} of C)	21132	24742	3610	17.1	26867	5735	27.1	24297	3165	15.0

	NPP (g m^{-2} of C)	158720	157343	-1377	-0.9	154711	-4009	-2.5	144386	-14334	-9.0
	SOC (g m^{-2} of C)	5964	5541	-423	-7.1	5542	-422	-7.1	5340	-624	-10.5
	ANC (μeq l^{-1})	103.4	105.5	2.1	2.5	107.2	3.8	4.5	94.8	-8.5	-4.6
	N leach (g m^{-2} of N)	18.1	13.4	-4.6	25.6	14.2	-3.9	21.6	13.4	-4.6	25.7
	DOC (g m^{-2} of DOC)	1901	1820	-80	4.2	1813	-88	4.6	1746	-155	8.1
	AET (l m^{-2})	30417	30183	-234	0.8	29807	-610	2.0	27505	-2912	9.6

FIGURES

Figure 1 - The ForSAFE model. Climate input parameters (temperature and radiation) drive the potential vegetation growth. Nutrient and water availability constrain the potential growth to actual biomass growth and accumulation.

Figure 2 - Example of a spider chart. Each radius represents an indicator and the difference between two scenarios, ΔI is the value reported for each indicator (grey line). When $\Delta I > 0$ the management change produces a positive effect on that indicator (i.e. an ecosystem improvement), while a negative effect is assessed if $\Delta I < 0$. On the black line $\Delta I = 0$, i.e. there is no difference between the two scenarios.

Figure 3 - Comparison of modelled data to measured data in Västra Torup. For each element there are two types of graphs. In the first type, monthly modelled results (grey line) and the moving average on a yearly basis (black line) are compared to measured data (points) over the years. In the second type of graph, the annual means of modelled and measured data in 1996-2011 are plotted against each other. The dotted line and its slope reported in the equation ($y = \mathrm{a}x$) are an indication of the discrepancy between modelled and measured data.

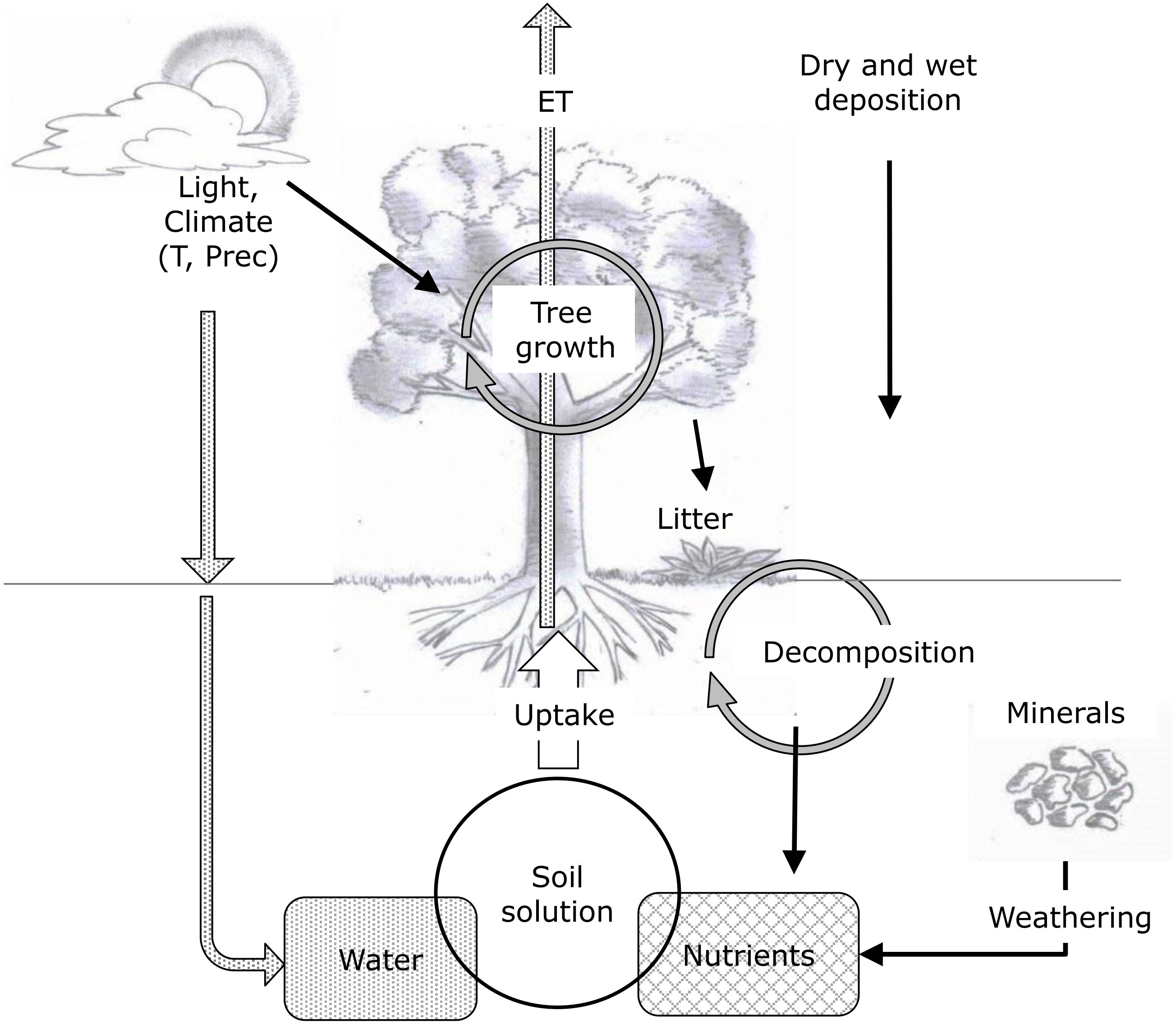
Figure 4 – Effect of aboveground residue extraction on the forest ecosystem (baseline scenario, BAS: black line, residue extraction scenario, INT1: grey line). Cum: cumulative values.

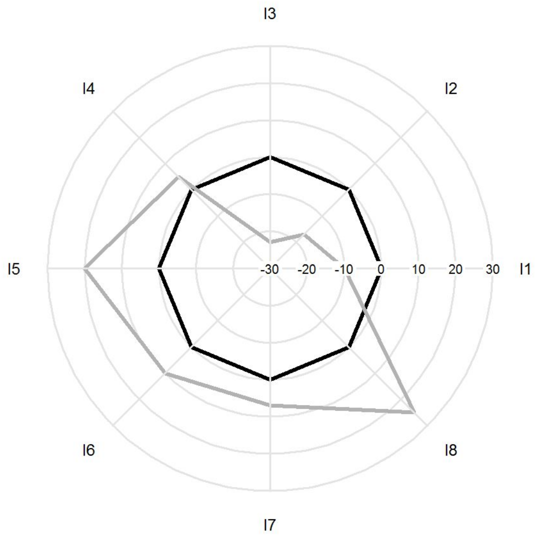
Figure 5 – Effect of intensified thinning regime and residue extraction (baseline scenario, BAS: black line, intensified thinning scenario, INT2: grey line). Cum: cumulative values.

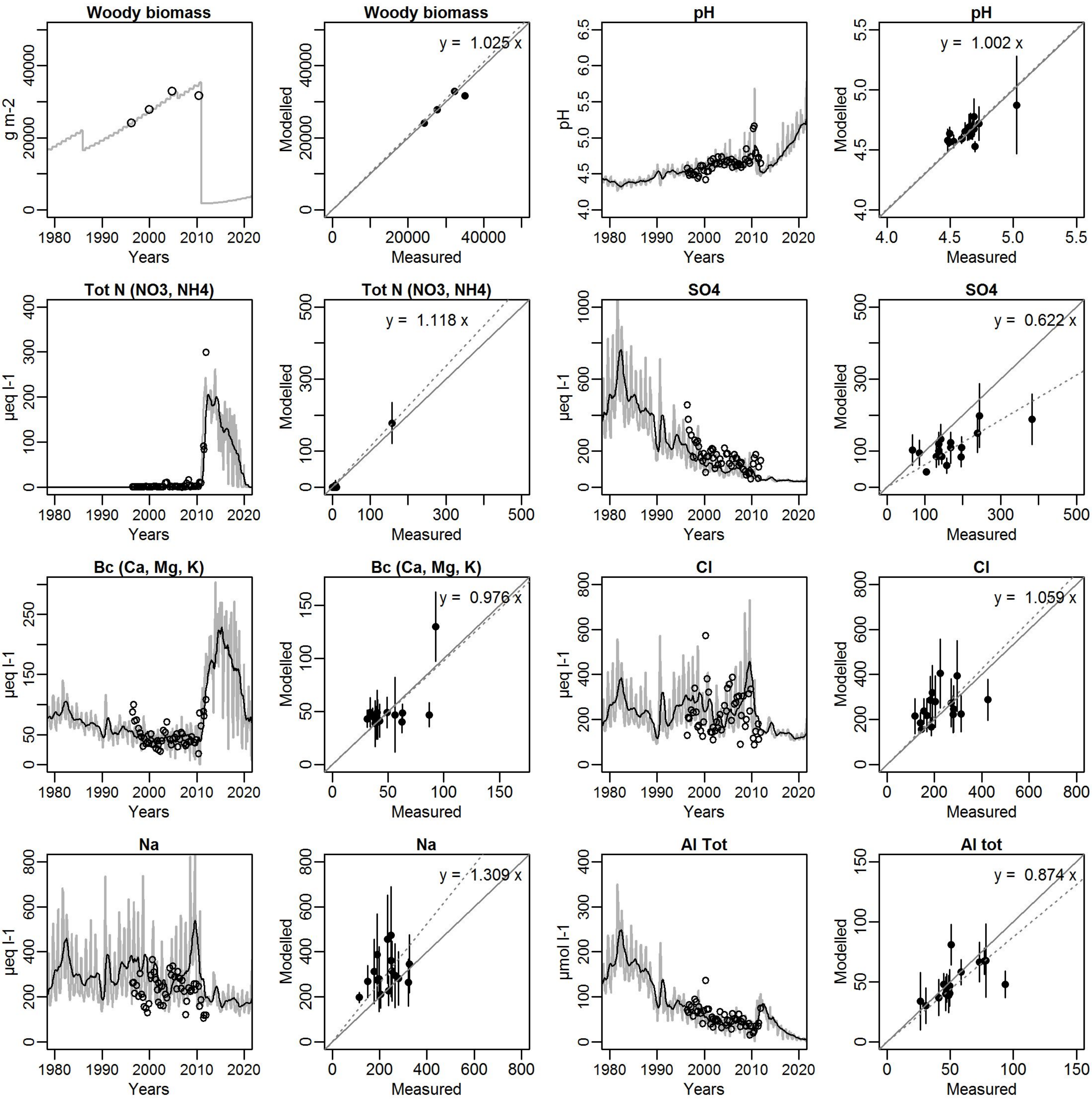
Figure 6 – Effect of intensified thinning regime and residue extraction (baseline scenario, BAS: black line, shorter rotation period, INT3: grey line). Cum: cumulative values

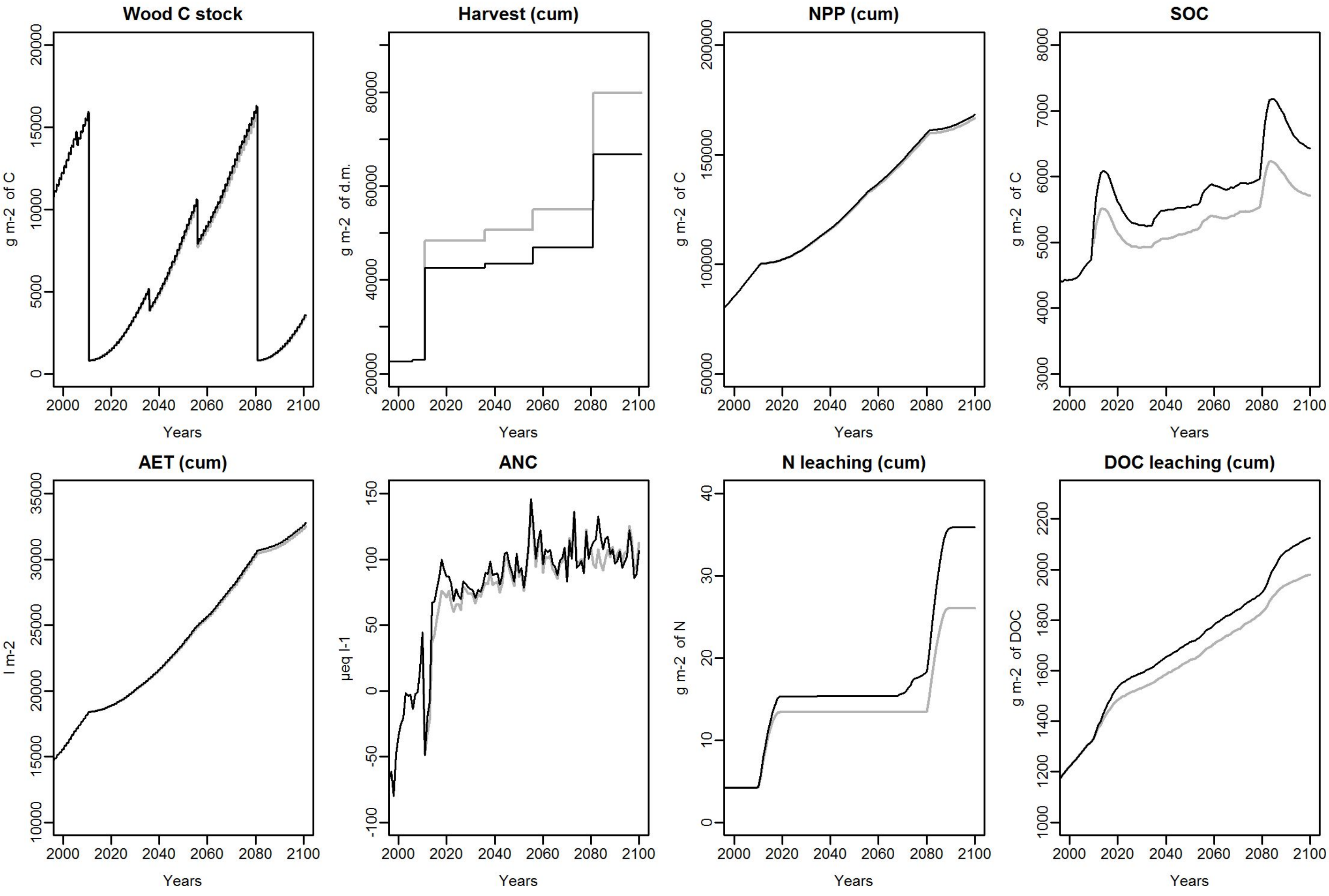
Figure 7 – The green lines represent the relative change of the indicators, ΔI (%), in the INT scenarios compared to the BAS scenario after 35 years from the start of management changes (option A). Solid green line: INT1 (only residues); green dashed line: INT2 (residues and additional thinnings); dark green dot-dash line: INT3 (residues and shorter rotation). $\Delta I>0$ is a positive effect on the ecosystem, $\Delta I<0$ a negative effect.

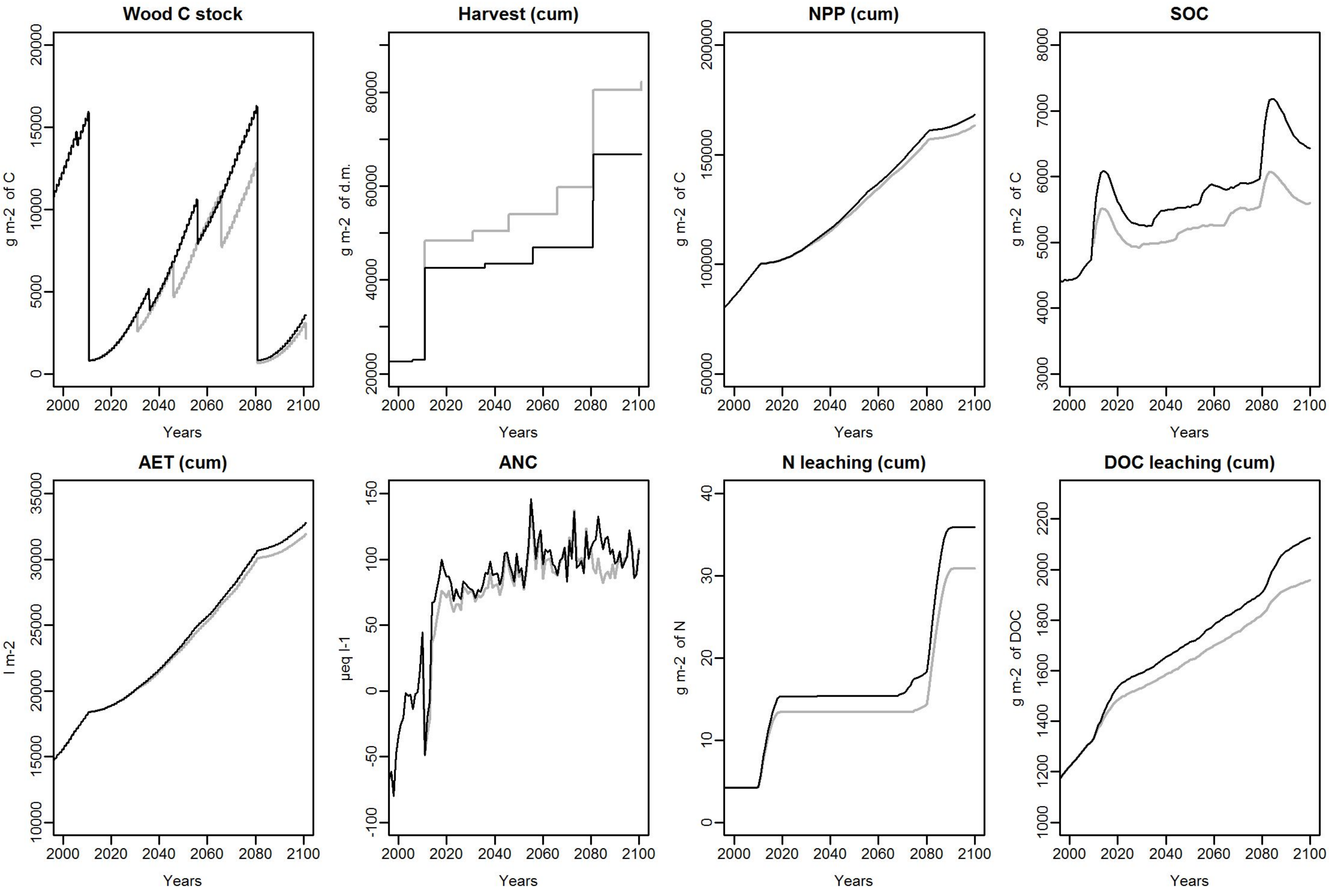
Figure 8 – The grey lines represent the relative change of the indicators, ΔI (%), in the INT scenarios compared to the BAS scenario at the end of the rotation period (option B). Solid green line: INT1 (only residues); green dashed line: INT2 (residues and additional thinnings); dark green dot-dash line: INT3 (residues and shorter rotation).

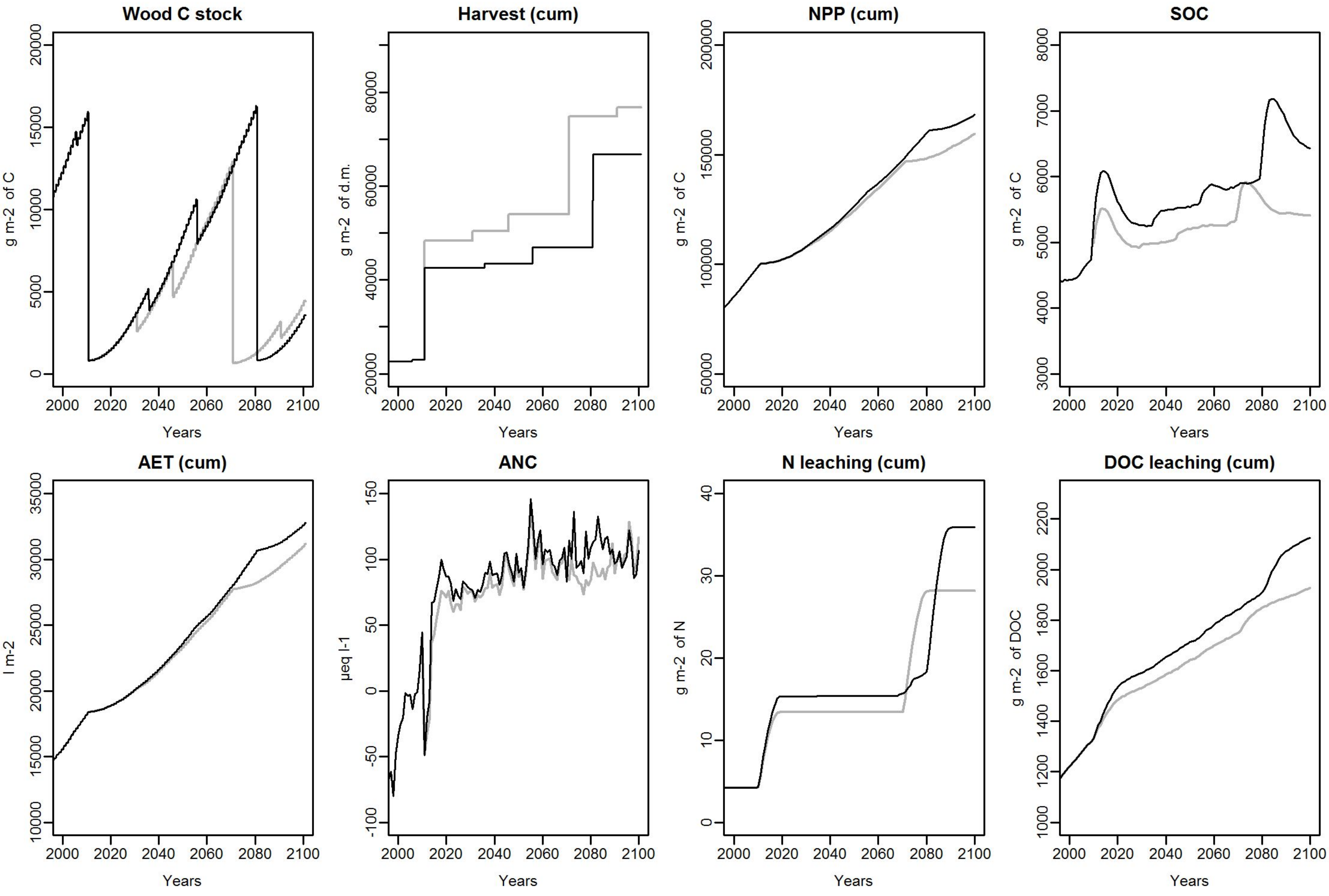

ET
Dry and wet deposition
Light, Climate (T, Prec)
Tree growth
Litter
Decomposition
Uptake
Minerals
Soil solution
Weathering
Water
Nutrients


I3
I2
I4
I5
I1
-30
-20
-10
0
10
20
30
I6
I8
I7

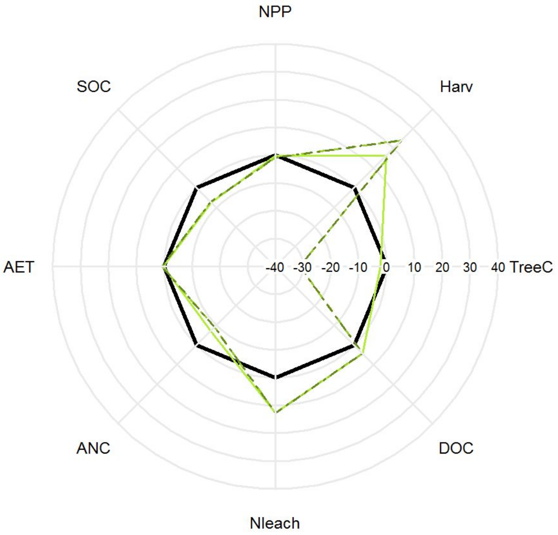

Woody biomass
g m-2
Years
Woody biomass
y = 1.025 x
Modelled
Measured
pH
y = 1.002 x
Tot N (NO3, NH4)
µeq l-1
y = 1.118 x
SO4
y = 0.622 x
Bc (Ca, Mg, K)
y = 0.976 x
Cl
y = 1.059 x
Na
y = 1.309 x
Al Tot
µmol l-1
Al tot
y = 0.874 x

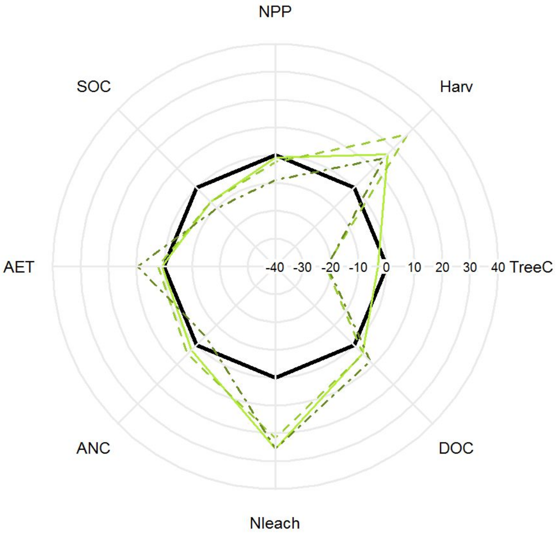

Wood C stock
g m-2 of C
0
5000
10000
15000
20000
Harvest (cum)
g m-2 of d.m.
20000
40000
60000
80000
NPP (cum)
g m-2 of C
50000
100000
150000
200000
SOC
g m-2 of C
3000
4000
5000
6000
7000
8000
AET (cum)
l m-2
10000
15000
20000
25000
30000
35000
ANC
µeq l-1
-100
-50
0
50
100
150
N leaching (cum)
g m-2 of N
0
10
20
30
40
DOC leaching (cum)
g m-2 of DOC
1000
1200
1400
1600
1800
2000
2200
2000
2020
2040
2060
2080
2100
Years


Wood C stock
g m-2 of C
0
5000
10000
15000
20000
Harvest (cum)
g m-2 of d.m.
20000
40000
60000
80000
NPP (cum)
g m-2 of C
50000
100000
150000
200000
SOC
g m-2 of C
3000
4000
5000
6000
7000
8000
AET (cum)
l m-2
10000
15000
20000
25000
30000
35000
ANC
µeq l-1
-100
-50
0
50
100
150
N leaching (cum)
g m-2 of N
0
10
20
30
40
DOC leaching (cum)
g m-2 of DOC
1000
1200
1400
1600
1800
2000
2200
2000
2020
2040
2060
2080
2100
Years



Wood C stock
g m-2 of C
0
5000
10000
15000
20000
Harvest (cum)
g m-2 of d.m.
20000
40000
60000
80000
NPP (cum)
g m-2 of C
50000
100000
150000
200000
SOC
g m-2 of C
3000
4000
5000
6000
7000
8000
AET (cum)
l m-2
10000
15000
20000
25000
30000
35000
ANC
µeq l-1
-100
-50
0
50
100
150
N leaching (cum)
g m-2 of N
0
10
20
30
40
DOC leaching (cum)
g m-2 of DOC
1000
1200
1400
1600
1800
2000
2200
2000
2020
2040
2060
2080
2100
Years


NPP
Harv
TreeC
DOC
Nleach
ANC
AET
SOC
-40
-30
-20
-10
0
10
20
30
40


NPP
Harv
TreeC
DOC
Nleach
ANC
AET
SOC
-40
-30
-20
-10
0
10
20
30
40