Simulating the effect of thinning treatments on soil carbon stocks in Norway spruce in southern Sweden

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Master Thesis no. 217
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Summary

Soil organic carbon (SOC) stocks and the effect of thinning on SOC were simulated by using the Yasso07 model in Norway spruce stands at eight sites in southern Sweden. Five thinning treatments (A, B, C, D and I) with different intensity and frequency were under consideration. The model requires litter input to soil and climate data. Biomass of Norway spruce stands was estimated using tree height and tree diameter with Marklund biomass equations. Litter production was calculated by multiplying the compartment specific turnover rates with biomass. Climate data on temperature and precipitation were taken from closest weather points. The model was run for the total thinning period and at least six years later for each site with yearly litter input and climate data. The sensitivity of the model was checked by increasing and decreasing the temperature and precipitation by 20 %. Simulated mean values of SOC were used to assess the results. Total average and per year average difference in SOC between first and last year of simulations were calculated. General linear model was applied for statistical analysis. Simulated SOC stocks varied from 101 Mg ha^{-1} to 161 Mg ha^{-1} at eight sites. There was a tendency towards higher SOC at high site index locations. No clear trend was observed with respect to latitude of sites, stand age and basal area. Overall, thinning treatments had significant effect on SOC *($p \leq 0.000$).* All thinning treatments negatively affected the SOC, except no thinning treatment (control, I), which had positive affect. One very heavy thinning treatment (C, 70% basal area removal) had highest negative rate of change in SOC. This treatment was significantly different from all other treatments. Treatment A, B and D were normal to heavy in their intensity. These treatments also had negative rate of change in SOC, but were statistically similar. The model was sensitive to both climate parameters (temperature and precipitation) but largest deviation was observed with actual temperature and a 20 % decrease in precipitation.

Keywords: Norway spruce, thinning treatments, soil organic carbon, litter input, climate, modeling, southern Sweden

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List of Abbreviations

A: Acid hydrolysable

cm: Centimeter

CO_2: Carbon dioxide

°C- Degree Celsius

E: Ethanol soluble

Ha: Hectare

H: Humus

$Height_{dom}$: Dominant height

IPCC: Intergovernmental panel on climate change

K: Kelvin

LSD: Least significant difference

Mg: Mega gram

mm: Millimeter

m: Meter

m^2 : Square meter

N: Non-soluble

s: Second

SOM: Soil organic matter

SOC: Soil organic carbon

Std. Dev.: Standard deviation

W: Water soluble

Yr: Year

1. Introduction

1.1. Interest in soil carbon

Increasing concentration of atmospheric carbon dioxide (CO_2), followed by rising global atmospheric temperature has started an intense debate among politicians and policy makers (Peltzer et al., 2010). This concern has also drawn the attention of scientists to clearly understand and predict terrestrial Carbon pools (White et al., 2009). Terrestrial ecosystems are considered as the major sink of atmospheric CO_2 (Schimel et al., 2001) with soil carbon pools being 2-3 times larger than vegetative pools (Raich and Schlesinger, 1992). Soil carbon pools are determined by balance between input flux as organic matter and output as a result of decomposition (Ostle et al., 2009) and leaching of dissolved organic carbon, but estimates of soil carbon sink are still uncertain (Houghton, 2003, Swift, 2001).

Forests have a significant role in the global carbon cycle and can act as a source or sink of CO_2 in response to anthropogenic activities. For example, tropical forests have been found to be a carbon source due to large scale deforestation activities (Masera et al., 2003). Forests are, however, generally categorized as carbon sink, even the quantification of size of this carbon sink is still a challenge due to high degree of uncertainty involved in existing estimation methods (Grace, 2004). Mature forests have been assumed to act as carbon stock where net exchange is nil (Lehtonen, 2005). Therefore, small management changes in forest could have significant impact on global carbon cycle and atmospheric CO_2 level. CO_2 level in atmosphere has been raised up from 352 ppm to 367 ppm during the 1990s and this could have easily reached up to 382 ppm if terrestrial and oceanic carbon sinks had been absent (IPCC, 2001). Almost half of this carbon sink is from the earth‘s land ecosystems, with the major part being located within forests in the northern hemispheres.

Climate change has motivated international agreements e.g. Climate convention, Rio and Kyoto Protocol are aiming to stabilize greenhouse gases concentration in atmosphere. Efficient quantification of carbon flux in forest ecosystems is also vital for proper implementation of Kyoto protocol. Climate convention and Kyoto protocol signatory countries must make national greenhouse gas inventories. Forest carbon flux reporting includes carbon pools from living biomass (above- and belowground), dead organic matter (dead wood and litter), and soil (IPCC, 2003). Countries are improving their national greenhouse gas inventories under new guidelines of Intergovernmental panel on climate change and different methodological issues and developments are under consideration. Nevertheless, interest in SOC and improved knowledge about soil carbon dynamics is worldwide.

1.2. Quantification of forest soil carbon

Forest litter and soil organic matter (SOM) are major carbon pools and most of the emissions comes from soil during deforestation (Feller and Bernoux, 2008). Forest soils are a dynamic component of the terrestrial ecosystem. Although, forests store carbon both in tree biomass and in soil, soil organic carbon has an important role in long term carbon sequestration due to its high stability (Jandl et al., 2007). Reliable monitoring and estimation of forest soil carbon pool is necessary to accomplish carbon sequestration goals (Bou Kheir et al., 2010). Complex and heterogenetic nature of soil makes soil carbon quantification very uncertain. Furthermore, interrelated components and mechanisms in forest ecosystems e.g. clear cutting, litter decomposition, heterotrophic respiration and complex soil processes make the soil carbon quantification process more complicated (Liski et al., 2002). Detection of changes in soil carbon pools on spatial scales is cumbersome and expensive owing to heterogenetic nature of forest soils (Johnson et al., 2010, Yanai et al., 2003) Conversely, temporal changes in total SOC can be spotted by rigorous sampling or chronosequence studies (Lindner and Karjalainen, 2007).

Soil sampling during national forest inventories is a traditional way of monitoring soil carbon as in Sweden and Netherland but monitoring should be long term because changes over short period of time are difficult to detect. Recently, forest carbon budgets are estimated by remote sensing, CO_2 flux measurements by eddy covariance technique, and modeling (Grace, 2004), However; the limitations e.g. high sampling cost, more time consumption, limited availability of data and high uncertainty makes such estimates less reliable. Remote sensing is also combined with process based models but requirement of numerous field samples and inability to estimate understory & belowground biomass are drawbacks (Lehtonen, 2005). Several process base models are used to assess carbon changes by including quantifiable processes and fluxes (Post et al., 2001) However, uncertainties in source data and processes, difficulties to predict night fluxes and strict site specificity are major shortcomings of these models (Kramer et al., 2002). Despite of these facts, countries are working on modeling techniques to monitor forest carbon fluxes, considering them an attractive option in this sense (Schmid et al., 2006). Prediction of future soil carbon fluctuations under changing climate is major benefit of this technique which could be helpful for better allocation of forest management practices. Q (Rolff and Ågren, 1999), DocMod (Currie and Aber, 1997) and ROMUL (Chertov et al., 2001) are famous models for forest soil carbon but require comprehensive soil information which is difficult to find from national forest inventories. Conversely, the model used in this study "*Yasso07*" needs less information and is based on advanced mathematical assumptions (Tuomi et al., 2011b).

1.3. Factors affecting soil organic carbon

Soil carbon accumulation is affected by several factors including input rates and litter decomposition. Liu and Greaver (2010) reported that increased nitrogen deposition causes increased SOM accumulation because of higher leaf/needle biomass and reduced decomposition of organic matter. Climate (temperature and precipitation) also indirectly affects carbon accumulation in forest soils by changing litter-fall amount and litter quality (Hansen et al., 2009). Accumulation of SOC in forests is closely linked to climate and soil type (Vesterdal and Raulund-Rasmussen, 1998) tree species (Paul et al., 2002) soil fertility, moisture and temperature (Ladegaard-Pedersen et al., 2005) initial SOC content, stand growth rates, site productivity and stand age (Amichev et al., 2008). Forest Harvest regimes also affect carbon stock by disturbing physical, chemical and biological processes (Gundersen et al., 2006). Most of these factors are closely related with and affected by forest management in one or the other way.

1.4. Harvesting regimes and Soil organic carbon

Forest management practices e.g. planting fast growing species and afforestation are well known to sequester carbon but are difficult to apply in Europe due to political and environmental restrictions (Jandl et al., 2007). Managing existing forests in different ways could also affect SOC. Harvest of bioenergy which will result in increased biomass extraction may have significant effect on SOC (Melin et al., 2010). Similarly, effect of current thinning and harvesting practices on SOC is unclear and needs more attention. Final harvesting and thinning could affect SOC in different ways. Biomass extraction by thinning and clear-cutting not only reduces litter-fall, but also affects decomposition rate of SOM by affecting microclimate. Thinning could also release trees and microorganisms from competition for moisture and nutrients, ultimately affecting mineralization. Consequently, studies of the effect of different harvesting regimes on SOC are important for the understanding of soil carbon accumulation.

Despite of tremendous importance of forests for global carbon cycles, impacts of management practices and especially of thinning on SOC at stand level are little studied. Also very few studies are done on permanent thinning experiments and existing studies show contrasting results. Hoover (2011) studied the effect of light thinning, heavy thinning and clear-cutting on forest floor and SOC pools but overall results were non-significant and trends were absent. However, Vesterdal et al. (1995) and Jonard et al. (2006) showed significant reduction in SOC content in thinned Norway spruce stands. Jandl et al. (2007) reviewed the effect of forest management on SOC and concluded that export of carbon during harvests may have a negative effect on soil carbon accumulation. Meta-analysis studies by Nave et al. (2010) supported the negative relation between harvesting and SOC while Johnson and Curtis (2001) reported no or very little effect. In another study, Olsson et al. (1996) final harvesting treatments (conventional stem harvest, harvest of aboveground tree parts except needles and above ground whole tree harvest) did not show any pronounced long term effect on SOC.

2. Aim and Objectives

The aim of this work was to study the effect of thinning treatments on SOC. In order to do this SOC stocks in Norway spruce stands in southern Sweden were also simulated using Yasso07 model.

The specific objectives were as follows.

- Compiling the input data for model which includes total biomass, litter production and climate data on temperature and precipitation
- Comparing the effect of thinning treatments on SOC
- Comparing the Norway spruce sites for simulated initial SOC
- To perform sensitivity test by running the Yasso07 under varied climate parameters.

3. Material and Methods

3.1. Study site

Eight sites in southern Sweden were selected from a nationwide thinning experiment (Fig 1) (Nilsson et al., 2010) . Selected sites have pure Norway spruce stands planted in 1930s to 1950s. Although sites were spread from latitude 56° to 59°, climatic and edaphic conditions of this region are favorable for Norway spruce. The soil texture varied between coarse sand to silt and the soil moisture-class was mesic. Annual temperature varied between 6.5-8.0 °C and precipitation varied between 790-941 mm year^{-1} (Table 1).

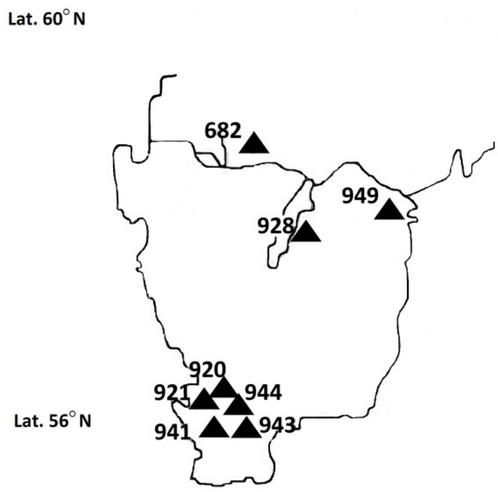


Figure 1: Study sites in southern Sweden

Table 1: Site characteristics

Site No.	Latitude	Longitude	Precipitation (mm year^{-1})	Temperature (°C)	Amplitude (°C)	Soil texture
682	59° 29´	14° 13´	797	6.5	9.8	Silt
920	56° 43´	13° 49´	941	7.5	8.5	Fine sand
921	56° 21´	13° 04´	888	7.7	8.0	Very fine sand
928	58° 52´	14° 41´	834	7.1	9.4	Very fine sand
941	56° 05´	13° 13´	902	7.8	8.0	Coarse sand
943	56° 10´	13° 34´	908	8.0	8.0	Medium sand
944	56° 12´	13° 14´	892	7.8	8.0	Fine sand
949	58° 49´	16° 56´	790	6.5	9.7	Silt

3.2. Treatments

Five thinning treatments were included in this study (Table 3). These treatments were replicated on each site by randomized blocking (Nilsson et al., 2010). Stand characteristics within blocks (sites) were fairly homogeneous for all treatments but slightly different among sites (Table 2). Stands at all sites had undergone at least four thinnings and five measurements. Five measurements were completed in different period of times but average measurement period for all sites was thirty years. Data on several parameters including diameter at breast height, dominant height and natural mortality were available from measurements at each thinning and at least five years after the last thinning (Nilsson et al., 2010).

Table 2: Stand characteristics at the start of thinning experiment

Site No.	Age (years)	Site index (m)	Basal area (m^2 ha^{-1})	No. of stems (ha^{-1})	$Height_{dom}$ (m)
682	30	31	28	4116	13
920	37	31	40	3247	16
921	30	34	40	3977	15
928	23	38	30	2629	13
941	31	30	35	4966	13
943	37	28	34	4173	14
944	31	33	36	3654	15
949	28	33	35	3213	13
Average	31	32	35	3747	14
Std.Dev.	4.6	3.0	4.2	722	1.2

Table 3: Description of thinning treatments

Treatment	No. of thinnings	Thinning form	Basal area after thinning (m^2 ha^{-1})	Thinning grade[1] (%)
A	4-6	Below	28	20-25
B	2-3	Below	23	40-43
C	1	Below	12	63-70
D	4-6	Below	20	40-50
I	0 (Control)	Below		

1. Percent of basal area removed of basal area before thinning

3.3. Yasso07 Model

3.3.1. Introduction

Yasso07 is dynamic soil carbon model and new version of old Yasso (Tuomi et al., 2011b). Both versions can simulate SOC down to one meter depth in mineral upland soils (Liski et al., 2005). The model is constructed on the basis of wide range of data sets on decomposition of non woody and woody litter from Europe, North and Central America (Tuomi et al., 2009). Woody litter, branches and stems up to 60 cm in diameter were included and mass loss was followed up to 70 years (Tuomi et al., 2011a).

Yasso07 model structure and decomposition process are based on three assumptions. Firstly, the model divides the non-woody litter into four chemically differentiable fractions each having unique decomposition rate, which are independent of litter origin. These fractions are acid hydrolysable (A), water soluble (W), ethanol soluble (E) and non-soluble (N). Secondly, decomposition rate of these fractions mainly depends on climate, which is represented by temperature and precipitation; and thirdly decomposition in these compartments results in mass loss and mass flows between the compartments (Fig. 2). This mass loss also results in more stable fraction; Humus (H). Decomposition rate of woody litter additionally depends on physical size of litter (Tuomi et al., 2011a). For detailed model structure and mathematical formulae see Tuomi et al. (2009). Model parameters are shown in Appendix 1 where Tuomi et al. (2011b) gives additional values for woody litter physical size as compared to that in Tuomi et al. (2009)

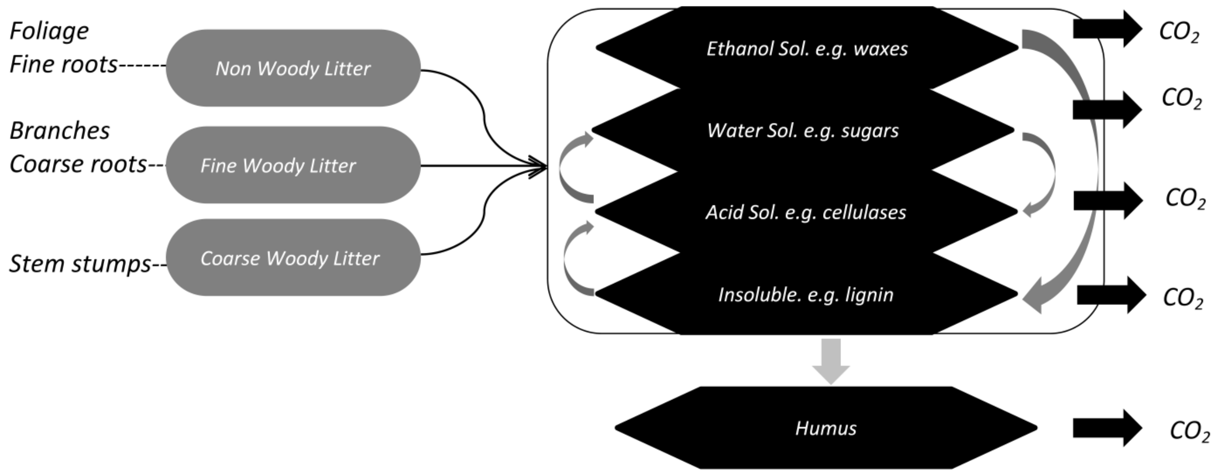


Figure 2: Flow chart Yasso07 (modified from Liski et al. (2005).

Model user interface has three display windows. In the first window, input data is provided and the data required for certain simulations are entered in the second window. The last page display results (Appendix 2, 3, 4).

3.3.2. Input and output

Yasso07 needs simple and easily accessible data on following variables. Litter input to soil, yearly constant average or variable yearly time series, litter physical size class distribution and litter chemical composition (Relative proportions of substrate distributed to A, W, E and N compartments and total summing up to 100). Climate data on temperature (°C), temperature amplitude (°C) and Precipitation either constant yearly/monthly or variable yearly time series are also needed. The model also needs initial stocks of organic carbon in soil and its chemical quality in A, W, E, and N proportions. This initial state is possible to estimate by giving a constant average litter input to the model and assuming that soil carbon input is equal to output (Tuomi et al., 2011b).

The model displays simulated results as numbers and plotted figures. Results also include mean, median, mode, and 95 % confidence limits. Carbon loss by heterotrophic respiration, total SOC, distribution of organic matter to woody, non woody and A, W, E, N compartments are also shown in results.

3.3.3. Uncertainty calculation

Modeling studies involves certain uncertainties which are important to quantify for reliable results. Simulating SOC by Yasso07 may involve three types of uncertainties. (1) Model parameter uncertainties. (2) Uncertainties in input data; and (3) Uncertainties in litter chemical composition. In the model user interface it is possible to study these uncertainties by a built in Markov chain Monte Carlo method (Tuomi et al., 2011b). It is also possible to enter the uncertainty in input data as standard deviation.

3.4. Data compilation

Input data on litter-fall was not available for the selected sites. Litter input was calculated using stand data, biomass equations and compartment specific turnover rates from literature. Species specific biomass equations need stand data on diameter and tree height. Five repetitions of stand data on diameter at breast height (130 cm from ground) and tree height were available from the thinning experiment (Nilsson et al., 2010). Litter fall is calculated by multiplying the compartment specific turnover rates with estimated biomass.

3.4.1. Biomass

Biomass of needles, branches, stem including bark, stumps including bark and roots was calculated using Marklund (1998) biomass equations for Norway spruce. Each of these tree compartments has separate equations. Marklund´s biomass equations are considered as most relevant for Scandinavia in general and for Sweden in particular. These equations are based on large number of samples taken from the whole Sweden and under a variety of management conditions (Marklund, 1998). Equations were applied at individual tree level and biomass was calculated in tons per hectare using the R statistical package. Per hectare biomass of alive, thinned and dead trees was calculated in separate groups.

Marklund´s biomass equations estimate belowground biomass in three (stumps, roots ≥ 5cm, roots ≤ 5 cm) parts. Due to limitations in data, Marklund´s functions do not cover biomass of very small and fine roots. Although, Marklund's biomass equations are unique, they slightly underestimate the below ground biomass (Petersson and Ståhl, 2006). Therefore, belowground biomass estimated with Marklund equations was adjusted using the constants derived by Petersson and Ståhl (2006).

Since the study was done in dense Norway spruce plantations, under story woody vegetation was absent. Biomass of ground vegetation was also assumed to zero, which is normally the case for Norway spruce, especially for dense stands older than 30 years (Hansen et al., 2009). As we had five measurements of stand data, it was possible to calculate the biomass only for five occasions for each site. Biomass in the middle of the growth periods was calculated by taking the average of two consecutive calculated values.

3.4.2. Litter production

Litter input to soil consists of three proportions. (1) Litter from living vegetation (only trees in this case). (2) Litter from trees dead due to natural causes; and (3) litter from harvest residues. First flux was calculated by multiplying estimated biomass with species and compartment specific biomass turnover rates (Table 4). Litter from dying trees was considered equal to the biomass of dead trees. Except from stems, biomass of thinned trees was considered as residue and litter input to soil. Sum of all these fluxes resulted in total litter input to soil (Fig 3).

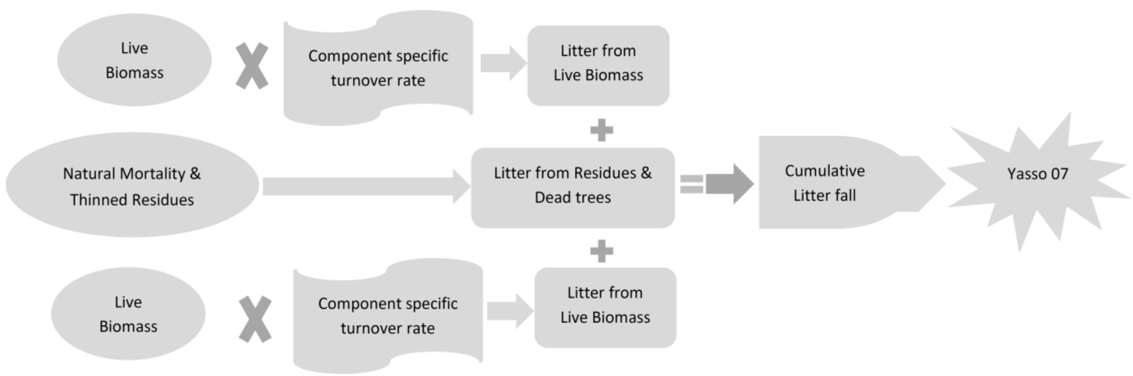


Figure 3: Conceptual diagram of litter production calculation

Table 4: Biomass turnover rates for yearly litter production

Tree component	Turnover rate ($year^{-1}$)	Reference
Needles	0.1100	(Ågren et al., 2007)
Branches	0.0125	(Muukkonen and Lehtonen, 2004)
Stem	0.0043	(Matthews, 1997)
Stumps	0.0043	(Matthews, 1997)
Fine roots	0.8110	(Persson and Stadenberg, 2009)
Coarse roots	0.0125	(Muukkonen and Lehtonen, 2004)

Litter from living trees was included on yearly basis. Harvest residues as litter were included in the year of thinning. Biomass of dead trees, calculated for five measurements was added up and divided by total measurement period for each site. The resulting value was included as yearly litter input to soil from dead trees. By doing this, litter from dead trees was spread over the period of measurements.

3.4.3. Litter size classes

According to model assumptions, the rate of litter decomposition also depends on physical size of woody litter therefore litter has to be divided into size classes. Stand age was different at some of the sites and so does the diameter and size of tree compartments, that's why we assumed different litter size classes (Table 5). Litter from different tree compartments was added up on the basis of litter size class; for instance, litter from branches and coarse roots were under fine woody litter size class.

Table 5: Litter size classification

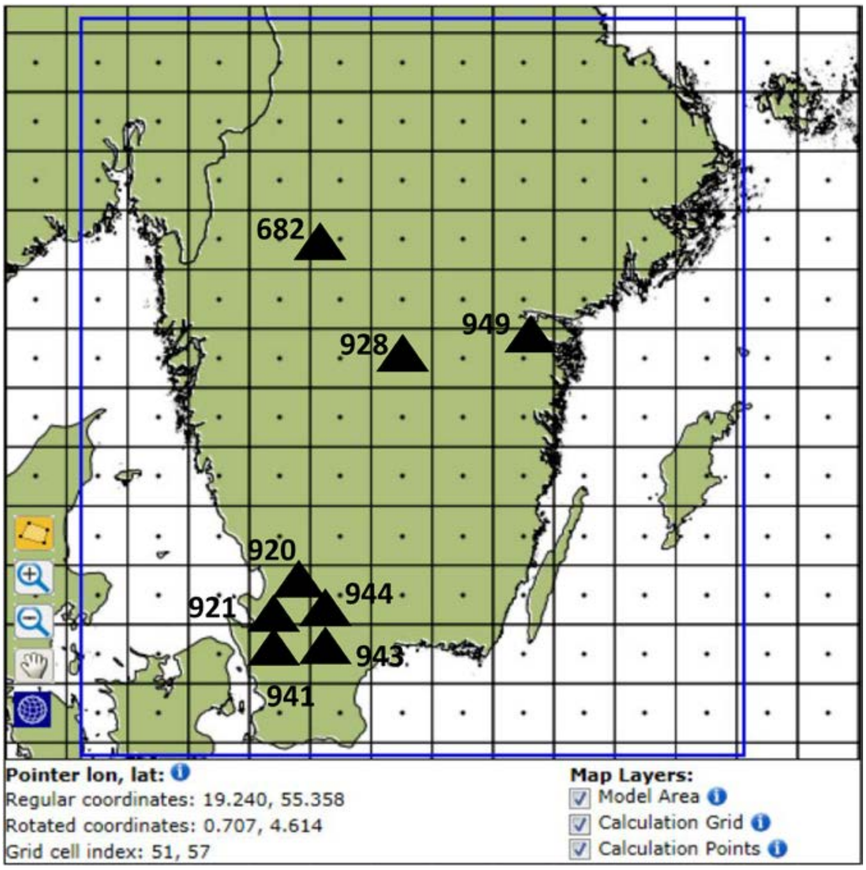
Site No.	Stand age at Start (years)	Litter size classes		
		Class 1 Non woody (needle & fine roots) (cm)	Class 2 Fine woody (branches and coarse roots) (cm)	Class 3 Coarse woody (stem & stumps) (cm)
682	30	0	2.0	10
920	37	0	2.5	12
921	30	0	2.0	10
928	23	0	1.5	08
941	31	0	2.0	10
943	37	0	2.5	12
944	31	0	2.0	10
949	28	0	2.0	10

3.4.4. Litter chemical composition

Litter chemical composition in terms of relative proportion to AWEN fractions also has to be provided for simulations. Usually litter chemical composition does not vary significantly within a species (Tuomi et al., 2009); therefore, chemical composition for each tree compartment was taken from Yasso07 user interface manual by Liski et al. (2009) (Appendix 8).

3.4.5. Climate data

Climate data on temperature and precipitation were taken from the Rossby center, Swedish meteorological and hydrological institute. Data were taken from closest weather point for each site (Fig 4). Units of data were changed according to model requirements (Appendix 5-6). Temperature variation amplitude was calculated using temperature of warmest and coldest months. For simulations, yearly data series of mean precipitation, temperature and temperature amplitude were used.



(http://www.smhi.se/en)

Figure 4: Weather points are denoted by dots and site locations with black triangles

3.5. Simulation

Data as yearly time series on litter (including litter size classes and litter chemical composition) and climate (precipitation, temperature and temperature amplitude) were arranged and entered into the model. Initial state of soil in terms of carbon stocks has to be decided before model run. It could be zero, non-zero and steady state. Non-zero initial state option needs measured values of soil carbon stock, which were not available in our case. Steady state in terms of carbon stocks is calculated assuming that sites are permanent forest localities and carbon stock is in steady state. The model needs data on litter input, its size class distribution and chemical composition to calculate steady state carbon stocks. As we were also aiming to estimate SOC stocks in selected sites, we chose steady state initialization option. It was assumed that sites are permanent forest lands and soil carbon is in steady state. The required litter input was calculated using mean litter input for whole measurement period for each site (Appendix 7). Although, some studies have used average yearly litter input calculated for whole rotation, Liski et al. (2006) calculated average yearly litter input only from fourteen years for steady state initialization.

The model was run for each site and treatment for total measurement period, using one year time step length. A sample size of 100 was selected for uncertainty estimation by built in Markov chain Monte Carlo method.

3.5.1. Data output and statistical analysis

Output data on soil carbon stocks were downloaded in numbers format. Simulated mean values of SOC stock for initial state were used to compare sites. In order to check the treatment effects, difference in SOC stocks of first and last year of measurement period was calculated. Total average and per year average difference for all sites was used to compare treatments. General linear model was applied for statistical analysis. Treatments were compared using LSD mean separation tests at 5 % probability level.

3.5.2. Sensitivity analysis

The model´s sensitivity to climate was checked. Model was run with 20 % increase and decrease in temperature and precipitation for one treatment at one site. We did not use any climate scenario for sensitivity analysis because our simulations were not for the future.

4. Results

4.1. Simulated initial soil carbon stocks

Simulated SOC mean values before first thinning for all selected sites are shown in Fig. 5. Soil carbon stocks varied between 101 Mg ha^{-1} to 161 Mg ha^{-1}. No clear trend was observed with respect to latitude; however, carbon stocks at southernmost sites were between 115 $Mgha^{-1}$ and 135 $Mgha^{-1}$. There was a positive correlation between SOC and site index (Fig 6).

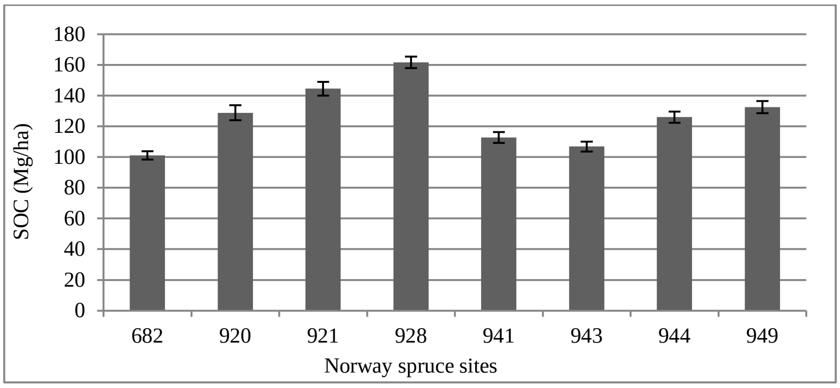


Figure 5: Simulated initial SOC at selected sites. Site numbers and 95 % confidence limits are given

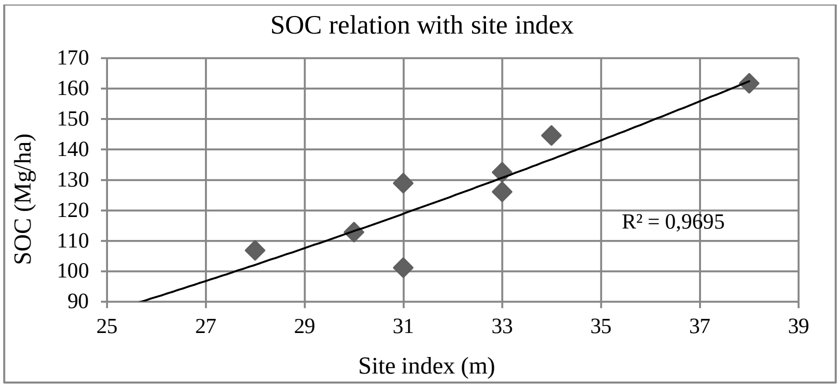


Figure 6: Correlation between simulated SOC and site index

4.2. Simulated soil carbon during thinnings

Simulated time series mean values of soil carbon stocks are shown in Fig 7. These time series illustrate the effect of thinnings on soil carbon stocks for whole simulation period. Number and year of thinnings can be seen by rapid increase in SOC after thinning. Simulations for all thinning treatments were started from the values shown in Fig 5. The no thinning treatment (I) showed a continuous buildup of soil carbon at most of the sites. In contrast, one very heavy thinning treatment showed a continuous decrease after thinning. Treatments A, B and D have variable trends with moderate effect on soil carbon.

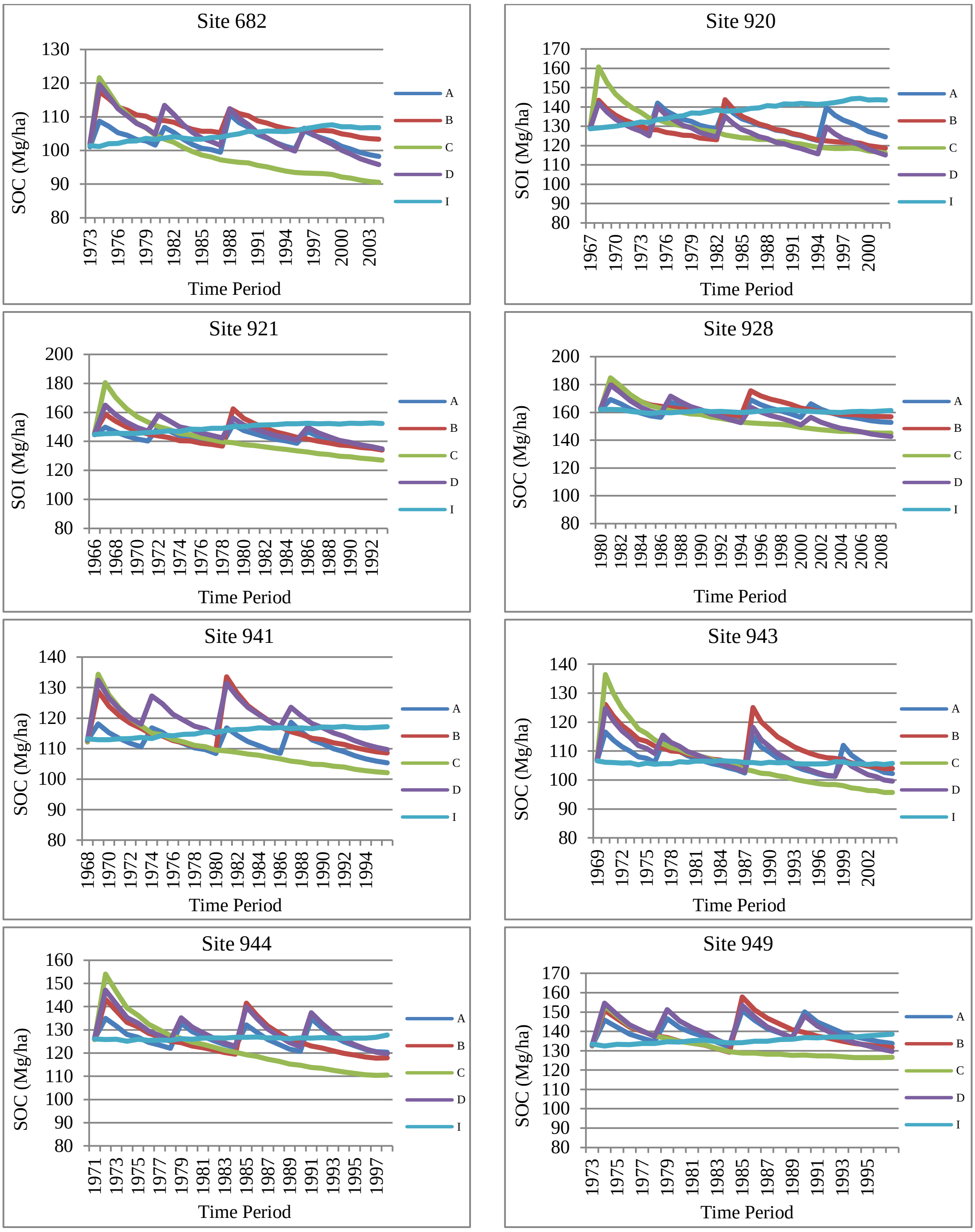


Figure 7: Simulated SOC time series for thinning treatments

4.3. Simulated soil carbon stocks at the end of thinning period

Simulated soil carbon stocks in the final year of simulation are displayed in Fig. 8. Starting from the same point, thinning treatments has ended up at different soil carbon values. No thinning (treatment I) and one very heavy thinning (treatment C) showed a clear trend at most of the sites, with highest and lowest values of soil carbon, respectively. Treatment A, B, and D did not show any trend.

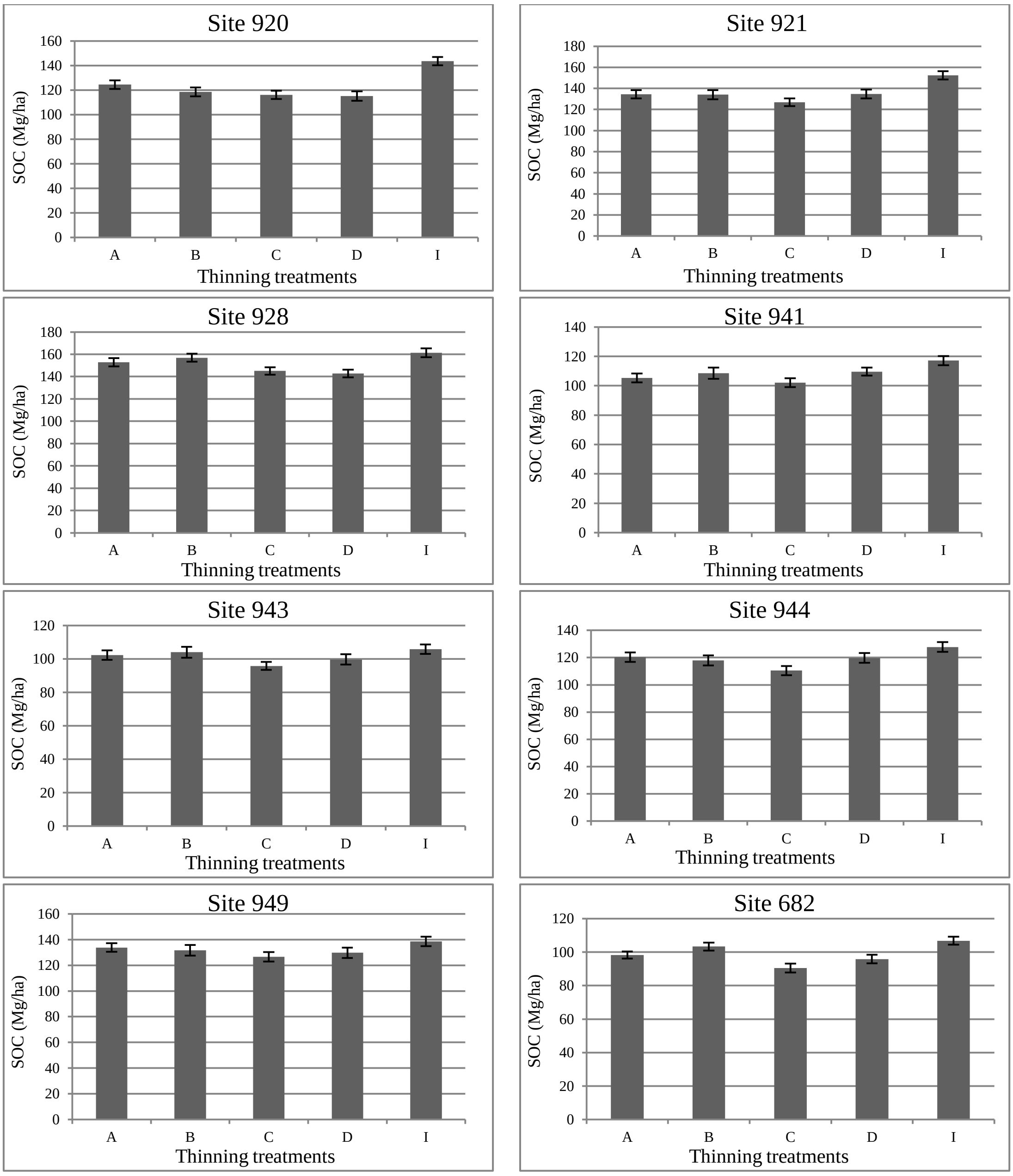


Figure 8: Soil carbon stocks in the last year of simulation for thinning treatments with 95% confidence limits

4.4. Effect of thinning treatments on soil carbon stocks

Thinning treatments had significant effect on soil carbon. Total average change and per year average change in SOC between first and last year of simulation were significant *($P \leq 0.000$)* (Appendix 9). The no thinning treatment (I) showed an increase in soil carbon from initial state while all other treatments have shown a reduction. One very heavy thinning treatment (C) showed highest negative effect on soil carbon. Treatment A, B and D were statistically similar (Fig 9).

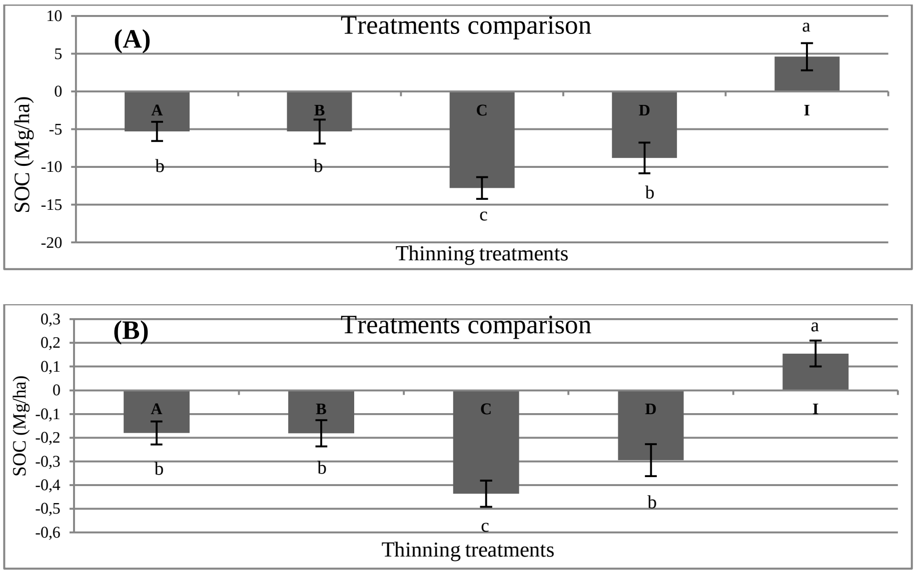


Figure 9: Total average change (A) and per year average change (B) in SOC between first and last year of simulations, ±SE

4.5. Temperature and precipitation

Sensitivity analysis results showed that simulation of SOC with Yasso07 is sensitive to both climate parameters (temperature and precipitation).

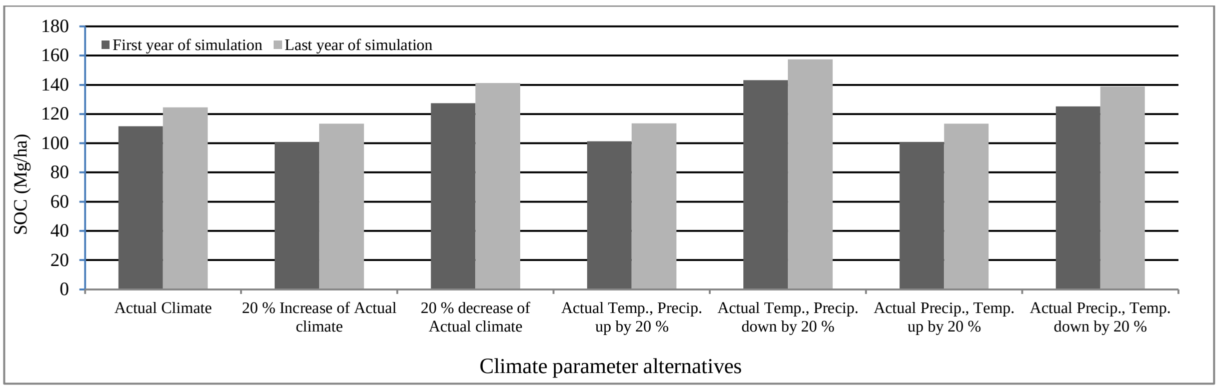


Figure 10: Sensitivity of soil carbon stocks to varied climate

Increasing the yearly temperature and precipitation by 20 % negatively affected the SOC while the opposite was observed by decreasing these two. Highest soil carbon stocks were observed with actual temperature and a 20 % lower precipitation. This has increased the SOC by 32 Mg ha^{-1}, as compared to actual climate data. A 20 % increase only in one parameter (keeping the other to actual value) or in both parameters at a time, had similar negative effect on SOC (Fig 10).

5. Discussion

5.1. Methodology

In this study, the SOC and change in carbon stocks were estimated using a modeling technique. The model, Yasso07, is applicable throughout the world including temperate and boreal regions. As the data sets used to develop this model were mainly taken from Northern Europe and America, it is probably applicable in Sweden. Although Yasso07 is simple, it takes into account all important aspects of soil carbon accumulation (for example input, output, and climate). Temperature and precipitation being the only climate parameters in Yasso07, are proved to be the major controlling factors of litter decomposition (Tuomi et al., 2009). Since, the Yasso07 has been used on large scale with results being similar to measured one (Tuomi et al., 2009), its accuracy is reliable.

Soil carbon stocks were estimated on the basis of average litter input of around thirty years, which could be questioned. Generally, soil carbon stocks are the result of hundreds of years of litter input and carbon buildup process; however, studies have also been conducted to assess the soil carbon stocks with Yasso07 by giving average litter input of fourteen years (Liski et al., 2006).

Average measurement and simulation period of all sites was thirty years but it varied from 24 to 36 years. This means that the same numbers of thinnings were completed in different period of times at different sites. This had made it difficult to compare the sites for the effect of thinning on SOC. However, the average of eight sites was used to evaluate the effect of thinning on soil carbon stocks. Furthermore, the different time from first thinning to final felling reflects differences in site fertility and this variation is also found in normal managed forests.

5.2. Reliability of input data

Accuracy and reliability of input data are crucial for reliable results. Reliability of the litter production estimates depends on accuracy of the information used in different steps. We compiled the litter production by using the stand biomass and compartment specific turnover rates. Studies by Lehtonen (2005) and Peltoniemi et al. (2004) have reported that stand biomass can be estimated using stand data and species specific biomass functions. We used accurately measured tree diameter and tree height data for our biomass functions, which were especially developed for Sweden (Marklund, 1998).

Generally, it is also advised to use the local turnover rates for litter production. Even though, we did not find local turnover rates for all tree compartments, the values we used were taken from studies conducted in temperate to boreal regions. Another short-cut we had to take was to use the same turnover rates for all growth years, but these rates may vary between the years. It is also advisable to perform a reality check of estimated litter production with measured litter production but it was not possible in our case.

Litter from understory woody and non-woody ground vegetation also contributes to soil carbon accumulation but we assumed these to zero. Dense Norway spruce stands older than 30 years, does not possess considerable understory vegetation (Hansen et al., 2009). Stand age at most of our sites was around thirty year or higher. Some ground vegetation may occur in open stands just after thinning, but in dense or very open stands it struggle to grow, either by shortage of light or due to risk of desiccation (Saetre et al., 1997). Understory woody vegetation was also removed during early years of stand establishment.

Woody litter size classes were assumed on the basis of tree age and diameter at breast height. For most of the sites litter from branches and coarse roots were assumed to be around 2 cm thick and litter from stem and stumps around 10 cm thick (Table 5). It is true that most of the stems of trees that died due to natural mortality were smaller than 10 cm but this litter size class also includes stumps. Most of the stumps created during thinning had higher diameter than 10 cm.

Although several options were available for climate data, data from the Swedish meteorological and hydrological institute was probably most accurate for the present sites. Even though climate of southern Sweden does not vary greatly from site to site, we took the climate data from closest weather point for each site.

5.3. Initial state of soil carbon

Measured soil carbon stocks were not available for the selected sites to compare the results but studies have been conducted on regional basis in the whole of Sweden. Our simulated SOC stocks (Fig 5) are consistant with Stendahl et al. (2010), who used Q soil carbon model and field inventory data. Furthermore, measured Swedish national mean SOC in Norway spruce dominated stands is 92 Mgha^{-1} (Stendahl et al., 2010), which also support our results because soil carbon stocks are higher in southern Sweden. An average SOC stock of eight sites was 127 Mgha^{-1} which is also according to the regional trend.

Stendahl et al. (2010) have also suggested a correlation between soil carbon stocks, latitude and site index but we did not find clear trend with respect to latitude. Possibly, it is due to small difference in latitude among sites. However, there exists a tendency towards higher SOC stocks at high site index sites. The highest SOC stock (161 Mg ha^{-1}) was observed at site 928, having a site index of 38 m. Conversely, lowest site index among the study sites was 28 and SOC stock was 106 Mgha^{-1} (Fig 5, Table 2). Highest soil carbon stocks at site 928 may also be due to age of the stands which was least among all. Young stands produce more litter than old one; however, we could not find the same trend for other sites. We also did not see any clear correlation of SOC stocks with basal area.

5.4. Effect of thinning on soil carbon

Results show that thinning treatments have significantly affected the SOC; however, the effect was not very large (Fig 9). Previous studies results on the effect of thinning are mixed. This study results are consistent with Vesterdal et al. (1995) who suggested a decrease in SOC after thinning, against Selig et al. (2008) who reported an increase, and similar to Moghaddas and Stephens (2007) and Nilsen and Strand (2008) who reported a little effect. However; experimental conditions in all these studies were not similar to that in our case. Therefore; it is difficult to compare the results because very few studies have been conducted on permanent thinning experiment with similar conditions.

Thinning can change the soil temperature (Selig et al., 2008) which may ultimately increases the decomposition rate of organic matter (Slodicak et al., 2005). Furthermore, mechanized thinning results in soil compaction (Makineci, 2005), which also affects the decomposition rate and nutrient cycling (Wilpert and Schäffer, 2006). We relate the reduced SOC to change in microclimate, reduced biomass and ultimately less litter input, also reported by Novak and Slodicak (2004). However, studies have also shown that litter from thinning contains more nutrients than litter from un-thinned stands (López-Serrano et al., 2005). Furthermore, Vesterdal et al. (1995) have reported an increase in soil carbon stocks with light thinning. It is also unclear that how long lasting this thinning effect will be because soil organic matter and soil carbon has the ability to recover to pre-harvest levels (Nave et al., 2010).

All the thinning treatments except I (no thinning), have negatively affected the SOC. Four treatments showed a statistically significant reduction in total SOC in last year of simulation (Fig 9). The rate of change in SOC varied from 0.155 Mg $ha^{-1}yr^{-1}$ for treatment I to -0.437 Mg $ha^{-1}yr^{-1}$ for treatment C. Highest negative rate of change was found in treatment C, and it is most likely due to intensive removal of biomass, followed by reduced litter production and quick decomposition of OM. Positive rate of change in treatment I might be due to continuous litter input and slow decomposition rate of organic matter.

5.5. Temperature and precipitation

Sensitivity analysis results showed the importance of climate parameters for soil carbon accumulation. Negative effect of rise in temperature and precipitation might be due to increased decomposition rate, runoff and leaching effect. High temperature and changed rainfall might have affected the turnover rates of OM. Alternatively, reduced temperature and precipitation would have favored the microclimate for soil carbon accumulation by reducing the activity of decomposers. Among all, a combination of 20 % reduced precipitation and actual temperature had largest effect. This also suggests that variations in precipitation have more pronounced effect than temperature.

6. Conclusion

The work showed that soil carbon stocks and changes in carbon flux can be studied using the Yasso07 model. We conclude that thinning or biomass harvesting has negative effect on SOC stocks. However, this negative effect is not very large, unless the harvest intensity is unusually high. Normal to heavy thinning practices have small negative effect. Consequently, current thinning practices do not impose any serious threat in terms of SOC depletion. We also conclude that litter input to soil, temperature and precipitation have pronounced effect on soil carbon accumulation. For future perspectives, we suggest to evaluate the long term effect of thinning on soil carbon stocks and how long it takes to recover to pre-harvest levels.

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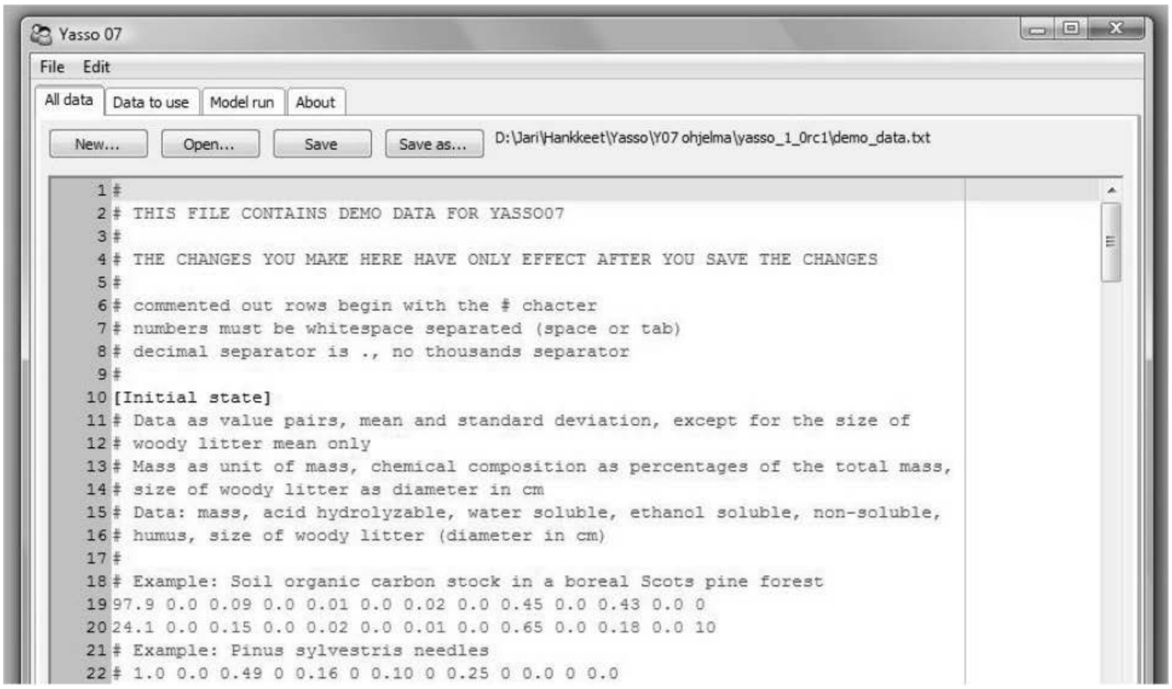
Appendix list

Appendix 1: Model parameters

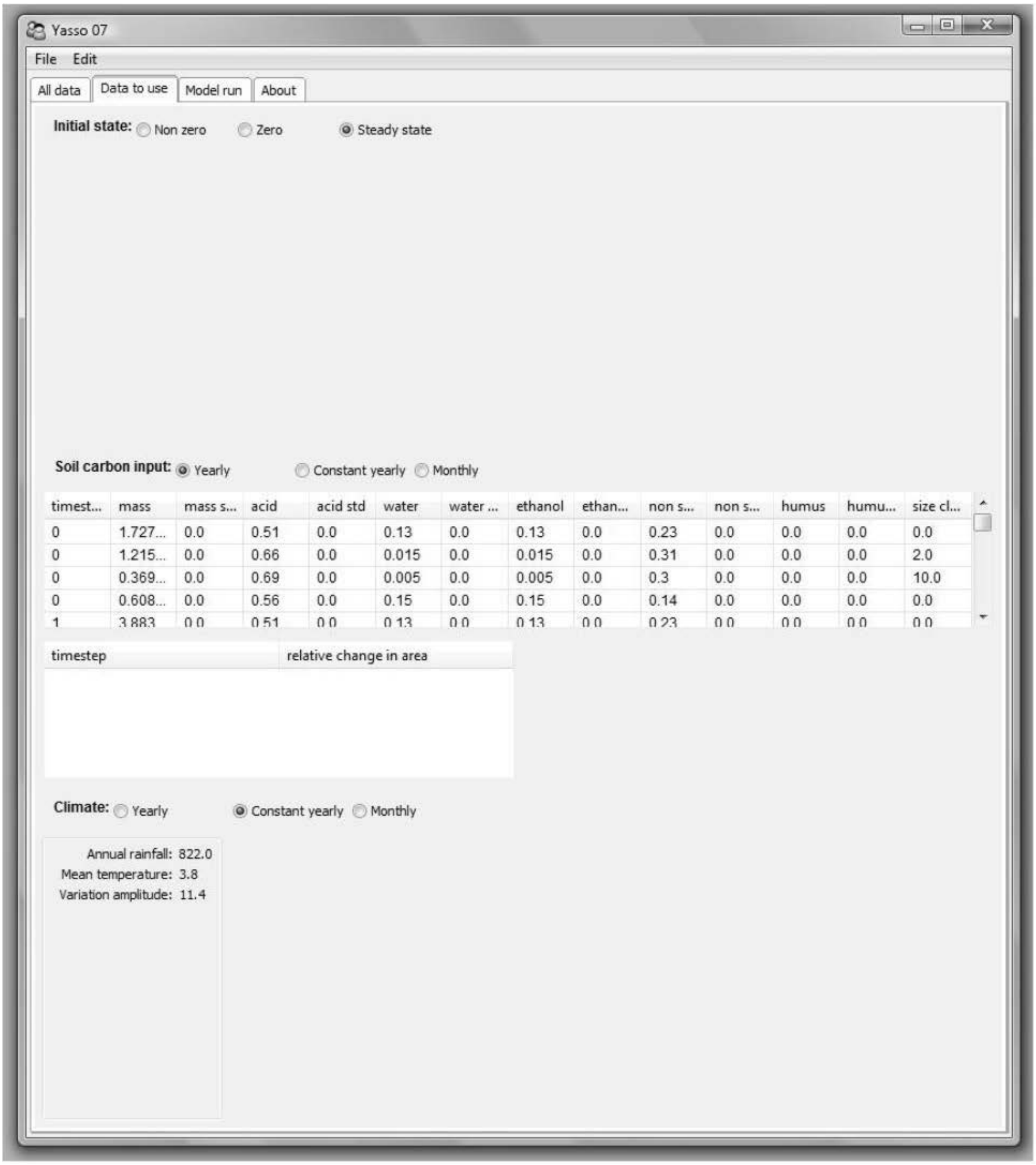
Parameter	Value	Unit	Interpretation
α_A	0.72 ± 0.09	a^{-1}	decomposition rate of A
α_W	5.9 ± 0.8	a^{-1}	decomposition rate of W
α_E	$0.28^{+0.07}_{-0.04}$	a^{-1}	decomposition rate of E
α_N	$0.031^{+0.011}_{-0.004}$	a^{-1}	decomposition rate of N
p_1	0.48 ± 0.06	–	relative mass flow, W → A
p_2	$0.01^{+0.15}_{-0.01}$	–	relative mass flow, E → A
p_3	$0.83^{+0.16}_{-0.23}$	–	relative mass flow, N → A
p_4	$0.99^{+0.01}_{-0.05}$	–	relative mass flow, A → W
p_5	$0.00^{+0.08}_{-0.00}$	–	relative mass flow, E → W
p_6	$0.01^{+0.20}_{-0.01}$	–	relative mass flow, N → W
p_7	$0.00^{+0.01}_{-0.00}$	–	relative mass flow, A → E
p_8	$0.00^{+0.01}_{-0.00}$	–	relative mass flow, W → E
p_9	$0.02^{+0.23}_{-0.02}$	–	relative mass flow, N → E
p_{10}	$0.00^{+0.01}_{-0.00}$	–	relative mass flow, A → N
p_{11}	0.015 ± 0.015	–	relative mass flow, W → N
p_{12}	$0.95^{+0.05}_{-0.16}$	–	relative mass flow, E → N
ω_1	-0.151 ± 0.008	$a^{-1}m^{-1}$	precipitation induced leaching (Europe)
ω_2	$0.000^{+0.0}_{-0.002}$	$a^{-1}m^{-1}$	precipitation induced leaching (Americas)
β_1	9.5 ± 2.0	10^{-2}°C^{-1}	temperature dependence
β_2	$-1.4^{+0.6}_{-0.9}$	10^{-3}°C^{-2}	temperature dependence
γ	-1.21 ± 0.14	m^{-1}	precipitation dependence
p_H	4.5 ± 0.8	10^{-3}	mass flow to humus
α_H	$1.6^{+0.3}_{-0.2}$	$10^{-3}\ a^{-1}$	humus decomposition rate
ϕ_1	-1.71 ± 0.16	cm^{-1}	first order size dependence
ϕ_2	0.86 ± 0.10	cm^{-2}	second order size dependence
r	0.306 ± 0.013	–	size dependence power

A: Acid soluble, W: Water soluble, E: Ethanol soluble, N: Non-soluble

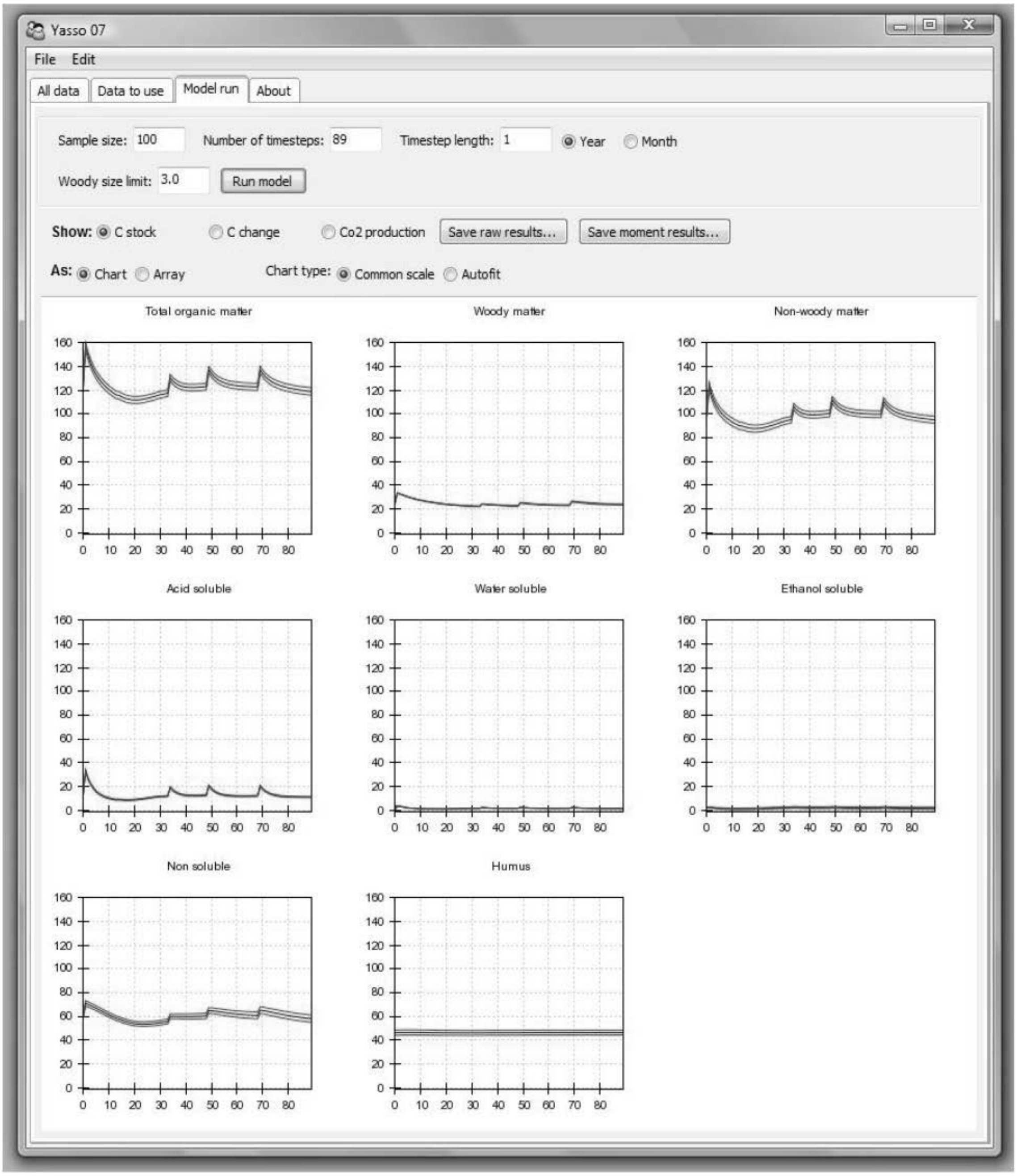
Appendix 2: Model data input page



Appendix 3: Model window to select the data for simulation



Appendix 4: Model run and data output page



Appendix 5: Compiling the precipitation data (e-5mm/s) - example

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total (e-5mm/s)	Total (mm/yr)
1966	3.0	1.7	0.3	2.2	3.4	3	2	2.6	2.8	2.9	4.2	1.6	29.7	770
1967	3.6	0.94	2.3	2.2	2.3	2.8	3.9	2.2	4.6	4	4.1	1.6	34.5	895
1968	2.5	1.8	3.1	2.6	1.6	1.7	6.2	2.9	5.2	3.8	2.9	3	37.3	967
1969	4.7	2	2.3	2.7	3	2.5	2.1	3.5	2.4	5.1	4	1.5	35.8	928
1970	3.2	2	3.2	0.83	2.4	3	2.5	4.6	4.4	2.5	1.7	3	33.3	864
1971	2.5	1.5	1.4	1.4	2.8	3.3	2.3	3.8	3.8	3.4	3	2.6	31.8	824
1972	2.2	3.4	1	2.1	1.6	3.6	3.1	2.9	3	2.7	1.2	3.4	30.2	783
1973	3.0	2.4	1.9	0.85	2.1	3.3	2.8	4.7	4.1	4.5	4	3.6	37.3	966
1974	3.1	1.6	0.89	0.91	1.2	1.5	4.3	3	2.4	2.6	1.6	2.4	25.5	661
1975	2.9	1.4	1.8	1.1	3	4.4	3	5.5	4.2	5.1	3.9	2.5	38.8	1006
1976	3.1	2.5	1.8	0.5	3.1	2.3	2.2	2.9	3.7	3.8	4.6	2	32.5	842
1977	4.9	2.9	2.9	1.5	3.8	3.2	1.1	3	4.6	1.9	4.1	2.2	36.1	936
1978	2.5	1	1.4	3	2.2	1.3	2.1	2.6	3.1	2.6	1.9	2	25.7	666
1979	3.9	2.4	0.85	2.7	3.5	4.7	1.1	3	1.8	2.7	3.2	1.7	31.6	818
1980	2.2	1.9	2.1	1.6	1.5	1.8	1.5	3.9	2.1	3.1	2.7	4.7	29.1	754
1981	2.1	2.7	3	3.7	2.8	2.6	1.2	3.9	4	0.83	1.6	3.2	31.6	820
1982	4.4	1.9	1.7	3.1	2.7	3.1	2.4	1.4	2.8	1.3	2.9	2.3	30	778
1983	1.5	2.3	0.6	2.8	1.7	1.2	3.1	1.1	2.2	3.3	4.1	2.8	26.7	692
1984	2.4	2.2	4.3	3	3.4	2.7	2.8	2.2	3.2	2.7	1.3	1.8	32	829
1985	4.0	4	2.1	3.5	2.1	5.6	2.3	2.2	2.1	3.7	3.5	1.7	36.8	954
1986	2.2	3.3	2.1	4.8	4	2.9	5.1	4.7	2.2	4.8	2.8	2.4	41.3	1070
1987	2.5	1.9	1.3	2.9	2.8	2.4	3.6	3.8	2.7	7.1	2.8	4	37.8	980
1988	3.2	2.7	3.7	4.9	2.9	5.8	4.7	2.4	2.4	5.7	3.3	4.9	46.6	1208
1989	3.3	2.4	2.8	4.4	4.2	2.1	3.4	3.3	2.8	2.1	0.96	4.3	36.1	935
1990	3.1	2.9	3.1	4.3	2.7	1.5	2.6	4	0.83	5.5	4.2	2.2	36.9	957
1991	1.9	0.94	1.9	0.71	3.2	4.3	2.2	1.9	4.3	3.1	5.6	4.7	34.8	901
1992	4.2	4.5	4.3	3.6	3.1	2.2	1.5	2.4	4.2	1.9	4.5	4.3	40.7	1055
1993	3.3	0.95	2.1	2.6	2.3	2.6	3.2	3	4	6.5	3.3	5.4	39.3	1017
Mean	3.1	2.2	2.2	2.5	2.7	2.9	2.8	3.1	3.2	3.5	3.1	2.9	34.3	888

Appendix 6: Compiling the temperature data (Kelvin) - example

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean (K)	Mean (°C)	Amplitude (°C)
1966	277	273	274	279	285	286	288	288	287	281	279	270	281	7.4	9.1
1967	274	269	275	278	283	286	287	288	286	282	280	279	280	7.3	9.6
1968	278	273	271	279	283	287	288	288	286	283	279	275	281	7.6	8.5
1969	275	274	277	280	284	286	289	287	286	282	277	275	281	7.7	7.5
1970	272	272	272	281	283	287	289	287	286	282	274	279	280	7.0	8.5
1971	278	276	275	280	284	287	289	287	286	280	275	278	281	8.0	7.0
1972	274	272	272	277	285	286	289	287	286	282	278	278	280	7.1	8.5
1973	276	277	279	282	284	288	290	288	285	282	277	276	282	8.9	7.2
1974	273	272	272	278	284	287	289	288	287	281	273	267	279	6.0	10.9
1975	274	275	274	279	284	287	289	287	284	283	278	274	281	7.5	7.6
1976	273	270	271	276	282	286	287	288	286	282	280	275	280	6.5	8.4
1977	275	279	277	279	283	285	287	287	286	281	275	274	281	7.4	6.6
1978	271	269	276	280	283	287	290	288	285	281	278	272	280	6.8	10.9
1979	274	275	277	281	286	290	290	287	286	284	277	278	282	9.0	7.9
1980	278	273	271	278	282	286	288	287	285	279	278	276	280	7.0	8.8
1981	275	275	275	279	284	288	287	289	287	281	275	278	281	7.8	6.8
1982	275	274	280	280	285	287	288	289	285	283	280	279	282	9.0	7.2
1983	278	275	278	281	284	287	288	288	287	283	278	276	282	8.7	6.7
1984	276	274	277	279	284	289	288	288	287	283	278	277	282	8.7	7.8
1985	275	270	273	280	282	286	287	288	286	282	279	275	280	6.9	8.9
1986	276	277	276	279	284	288	289	288	285	282	276	276	281	8.2	6.6
1987	272	275	280	279	284	288	288	288	286	281	278	271	281	7.7	8.8
1988	271	277	274	279	283	286	289	288	285	282	277	277	281	7.6	8.8
1989	272	275	274	280	283	287	288	286	286	282	274	274	280	6.8	7.8
1990	275	277	278	281	285	287	289	289	287	283	279	278	282	9.1	7.1
1991	278	273	275	278	284	287	287	287	286	282	282	278	281	8.2	7.3
1992	276	277	277	280	284	288	288	288	286	283	280	277	282	8.9	6.1
1993	276	273	274	280	283	288	290	290	287	283	278	279	282	8.5	8.4
Mean	275	274	275	279	284	287	288	288	286	282	278	276	281	7.7	8.0

Appendix 7: Compiling the average litter input (Mg ha^{-1}) data for initial state -example

	Treatments															Average		
Yr.	A			B			C			D			I					
	Class 1	Class 2	Class 3	Class 1	Class 2	Class 3	Class 1	Class 2	Class 3	Class 1	Class 2	Class 3	Class 1	Class 2	Class 3	Class 1	Class 2	Class 3
73	8.5	26	3.8	10	34	4.6	11	38	4.9	11	40	5.2	2.1	1.6	2.0	8.8	28	4.1
74	1.6	0.9	0.7	1.6	1.0	0.8	1.2	0.6	0.4	1.2	0.6	0.4	2.3	1.7	2.0	1.6	1.0	0.9
75	1.6	0.9	0.7	1.6	1.0	0.8	1.2	0.6	0.4	1.2	0.6	0.4	2.3	1.7	2.0	1.6	1.0	0.9
76	1.6	0.9	0.7	1.6	1.0	0.8	1.2	0.6	0.4	1.2	0.6	0.4	2.3	1.7	2.0	1.6	1.0	0.9
77	1.6	0.9	0.7	1.6	1.0	0.8	1.2	0.6	0.4	1.2	0.6	0.4	2.3	1.7	2.0	1.6	1.0	0.9
78	6.6	21.0	3.4	1.9	1.2	0.8	1.5	0.8	0.5	7.0	25.0	3.6	2.5	1.8	2.1	3.9	10.0	2.1
79	1.6	0.9	0.7	1.7	1.1	0.8	1.9	1.1	0.6	1.2	0.7	0.5	2.7	1.9	2.3	1.8	1.1	1.0
80	1.6	0.9	0.7	1.7	1.1	0.8	1.9	1.1	0.6	1.2	0.7	0.5	2.7	1.9	2.3	1.8	1.1	1.0
81	1.6	0.9	0.7	1.7	1.1	0.8	1.9	1.1	0.6	1.2	0.7	0.5	2.7	1.9	2.3	1.8	1.1	1.0
82	1.6	0.9	0.7	1.7	1.1	0.8	1.9	1.1	0.6	1.2	0.7	0.5	2.7	1.9	2.3	1.8	1.1	1.0
83	1.6	0.9	0.7	1.7	1.1	0.8	1.9	1.1	0.6	1.2	0.7	0.5	2.7	1.9	2.3	1.8	1.1	1.0
84	9.0	33.3	5.5	12.4	48.9	7.6	2.3	1.3	0.8	9.1	37.0	5.8	2.9	2.1	2.4	7.1	24.5	4.4
85	1.6	1.0	0.8	1.6	1.1	0.9	2.5	1.4	0.9	1.1	0.7	0.5	2.9	2.1	2.5	2.0	1.3	1.1
86	1.6	1.0	0.8	1.6	1.1	0.9	2.5	1.4	0.9	1.1	0.7	0.5	2.9	2.1	2.5	2.0	1.3	1.1
87	1.6	1.0	0.8	1.6	1.1	0.9	2.5	1.4	0.9	1.1	0.7	0.5	2.9	2.1	2.5	2.0	1.3	1.1
88	1.6	1.0	0.8	1.6	1.1	0.9	2.5	1.4	0.9	1.1	0.7	0.5	2.9	2.1	2.5	2.0	1.3	1.1
90	6.4	23.7	4.4	1.8	1.2	1.0	2.7	1.5	1.0	5.2	21.4	4.0	3.0	2.2	2.6	3.8	10.0	2.6
91	1.8	1.2	1.0	2.1	1.4	1.1	2.9	1.7	1.2	1.3	0.9	0.6	3.1	2.2	2.7	2.2	1.5	1.3
92	1.8	1.2	1.0	2.1	1.4	1.1	2.9	1.7	1.2	1.3	0.9	0.6	3.1	2.2	2.7	2.2	1.5	1.3
93	1.8	1.2	1.0	2.1	1.4	1.1	2.9	1.7	1.2	1.3	0.9	0.6	3.1	2.2	2.7	2.2	1.5	1.3
94	1.8	1.2	1.0	2.1	1.4	1.1	2.9	1.7	1.2	1.3	0.9	0.6	3.1	2.2	2.7	2.2	1.5	1.3
95	1.8	1.2	1.0	2.1	1.4	1.1	2.9	1.7	1.2	1.3	0.9	0.6	3.1	2.2	2.7	2.2	1.5	1.3
96	1.8	1.2	1.0	2.1	1.4	1.1	2.9	1.7	1.2	1.3	0.9	0.6	3.1	2.2	2.7	2.2	1.5	1.3
97	2.1	1.3	1.1	2.3	1.6	1.3	3.1	1.8	1.3	1.5	1.0	0.7	3.1	2.3	2.8	2.4	1.6	1.5
Total																63	98	36
Average of 24 years																2.6	4.1	1.5

Classes are litter size classes (Table 5)

Years are 1973 to onward.

Appendix 8: Chemical composition of litter

Relative proportion to Yasso07 compartments

Litter type	Yasso 07 compartments				
	A	W	E	N	H
Fine root	0.5508	0.1331	0.0665	0.2496	0.0000
Needle	0.4826	0.1317	0.0658	0.3199	0.0000
Branch, Coarse root	0.6300	0.0300	0.0000	0.3300	0.0000
Stem, Stump	0.7000	0.0050	0.0050	0.2800	0.0000

Appendix 9. Analysis of variance

Factor	Levels	Values
Sites	8	682, 920, 921, 928, 941, 943, 944, 949
Treatments	5	A, B, C, D, I

Analysis of variance for total average change in SOC between first and last measurement

Source	Df	Seq SS	Adj SS	Adj MS	F	P
Treatments	4	1329.75	1329.75	332.44	21.90	0.000
Sites	7	343.03	343.03	49.00	3.23	0.012
Error	28	425.04	425.04	15.18		
Total	39	2097.82				

S = 3.89615, R-Sq. = 79.74% R-Sq (adj) = 71.78%

Analysis of variance for per year average change in SOC between first and last measurements

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Treatments	4	1.52792	1.52792	0.38198	24.23	0.000
Sites	7	0.45188	0.45188	0.06455	4.09	0.003
Error	28	0.44140	0.44140	0.01576		
Total	39	2.42121				

S = 0.125556 R-Sq = 81.77% R-Sq (adj) = 74.61%

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