Effect of stand age on soil respiration in managed vs unmanaged Scots pine stands

Richard Engholm

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Swedish University of Agricultural Sciences, SLU
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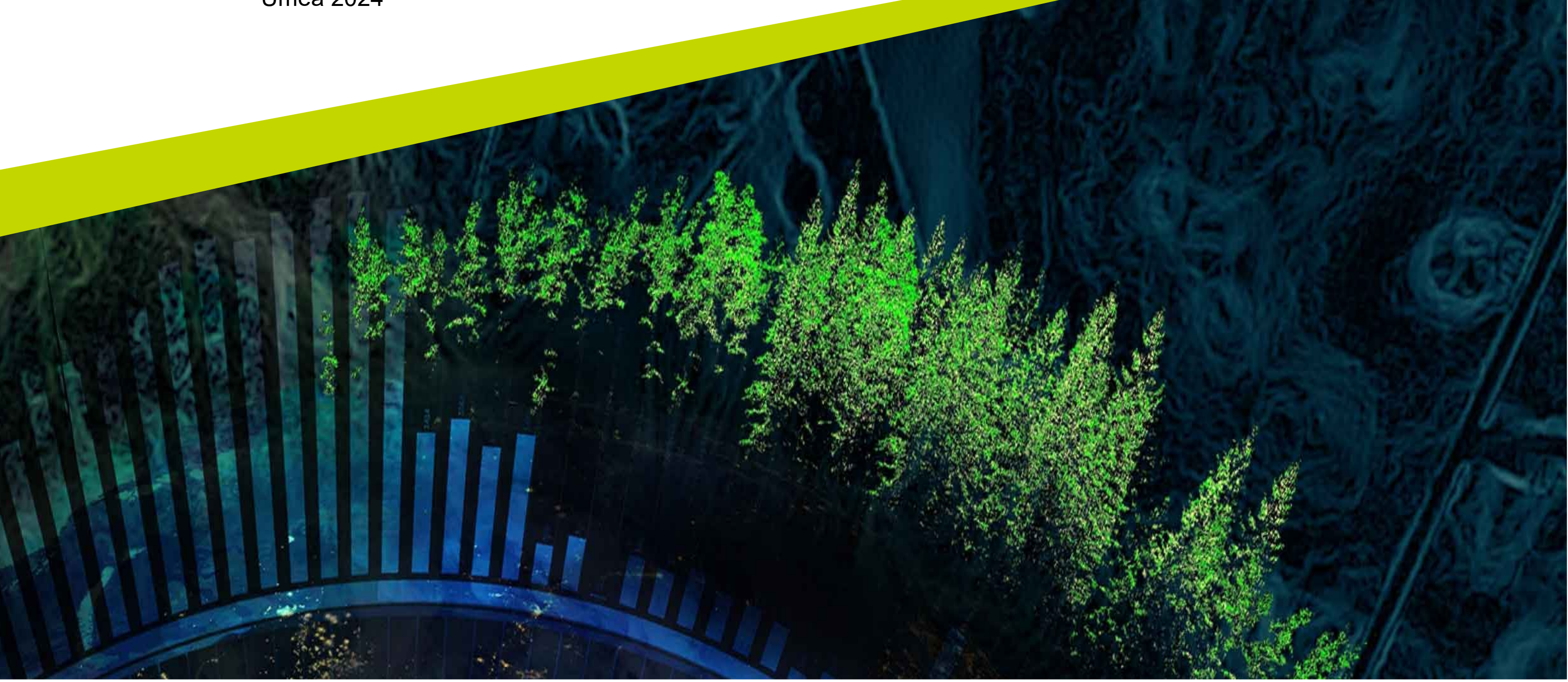

Effect of stand age on soil respiration in managed vs unmanaged Scots pine stands.

Beståndsålderns effekt på markrespiration i brukade vs icke brukade tallbestånd.

Richard Engholm

Supervisor:	**Zsofia Réka Stangl, Swedish University of Agricultural Sciences, Department of Forest Ecology and Management**
Assistant supervisor:	Michael J. Gundale, Swedish University of Agricultural Sciences, Department of Forest Ecology and Management
Examiner:	Järvi Järveoja, Swedish University of Agricultural Sciences, Department of Forest Ecology and Management

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Abstract

How the forests in Sweden and around the world have been, and are still today, managed is a hot debate. The rotation forestry that is commonly used in Sweden has been the focus of debate regarding whether it is a sustainable management method, and whether it should be changed. To gain a broader understanding of how forests change, and respond to intensive management over time, one way is to investigate carbon dioxide and its fluxes between soil and atmosphere. By conducting a measurement of the carbon dioxide fluxes from the soil into the atmosphere in a chronosequence with managed stands and stands that have not been managed since the last fire over a 375-time period. It could be seen that there are trends of higher respiration; autotrophic, heterotrophic, and total, rates in managed stands compared to the unmanaged stands. The most noticeable trend can be seen for stand ages between 15 and 45 years where thinning operations have occurred in the managed stands and lead to higher rates of respiration when comparing it to the unmanaged stands. Specifically, when comparing stands with an age lower than 90 years, I found that managed stands have higher rates of respiration compared to unmanaged stands. In addition, unmanaged stands with a stand age older than 110 years having very stable respiration rates between the ages 110 and 375 years.

Keywords: Chronosequence, Soil respiration, Total respiration, Autotrophic respiration, Heterotrophic respiration, Forestry

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Abbreviations

SR	Soil respiration
TR	Total respiration
HR	Heterotrophic respiration
AR	Autotrophic respiration

1. Introduction

How forests should be managed has been a debate for a long time, and the debate is still going on all around the world, Sweden being no exception to this. The European Union (EU) has a forest strategy for 2030, which is a vision to improve the quality and quantity of EU forests. With this strategy the EU wants to adapt forests in Europe to the new weather extremes, conditions, and ongoing climate change. In this strategy, the EU wants to for instance stop deforestation and prevent, preserve, and restore old forests in EU-countries (European Commission 2023). Sweden on the other hand have a slightly different approach to how they want to continue with the management of forests. This is because the Swedish forestry industry contributes many jobs from exported goods. During 2021, Sweden was the fourth highest exporter of forest products, with nearly 20 million tons of pulp, paper, cardboard, and sawed wood products, which corresponds to about 164 billion SEK (Skogsindustrierna 2023). With Sweden being a high exporting country for raw and fine materials also comes a high demand for jobs. During 2021 Swedish forestry contributed around 120,000 jobs, in various industries and forest management. When combining the number of jobs, exports, revenue, and conversion margin for processing the wood products, the Swedish forest industry contributed with 9-12% of the Swedish industries total turnover, conversion margin, exports, and employment (Ibid).

Swedish forests are dominated by two conifer tree species, Scots pine (*Pinus sylvestris* L.), and Norway spruce (*Picea abies* (L.) Karst), together with two broadleaf species of Birch, Silver birch (*Betula pendula* Roth) and Downy birch (*Betula pubescens* Ehrh.). The species distribution in Sweden, accounted as volume of living wood, are for pine 39.8%, spruce 38.8% and for the two birch species combined 13.0%. In the northern parts of Sweden, Västerbottens and Norrbottens county, the same species are the most dominant, but with a higher percentage of pine (49.3%) and birch (17.4%) and a lower percentage of spruce (30.0%). The high percentage of pine and spruce is typical for boreal forests, but their dominance is further enhanced in Sweden by the forestry industry: About 58% of Sweden's entire area is covered by managed forests, of which over 85% is monospecific plantations of pine or spruce (Riksskogstaxeringen 2023, Skogsstyrelsen 2023).

In Sweden the most common strategy for managing forests is rotation forestry and to implement pre-defined management steps throughout the rotation cycle. The rotation starts, and ends, with the cutting of a mature forest that has reached the desired size (Skogsstyrelsen 2014), which occurs at about 100 years for pine and spruce in northern Sweden. This is followed by soil scarification, to ensure a more successful growth of the seedlings, which are then planted or sowed as seeds (Skogsstyrelsen 2013). When the trees have reached a height of 2-7 meters a pre-commercial thinning (Skogsstyrelsen 2012) occurs, followed up with one or two further thinning when the height of the trees around 10-15 meters (Skogsstyrelsen 2015). The rotation has then reached the end, or the start, again when the trees have an age of about 100 years and are about 18 to 22 meters high and can then be clear-cut again. Subsequently, I will refer to forest plots that are managed according to this strategy as 'managed forest'. The term unmanaged forest, which is used in this thesis, can have several different meanings. However, to clarify the definition of unmanaged forest in this thesis, it describes a forest stand that has not been managed since the last fire. Fire is not always a term of unmanaged forest per se due to that fire can be used as a management method itself as a prescribed burning (Naturvårdsverket 2023).

One way to study differences between unmanaged and managed forests over a period is to use a chronosequence. In Chazdon (2013) a chronosequence is described as one or several series of forest sites that have different ages but have similar conditions in soil type, environment, and are located within the same climate zone. When comparing this to the definition from Walker et al. (2010), where they describe a chronosequence as a series of sites that are established from the same substrate or material with an exception from the time since when they were established. In this study two chronosequences were used, one consisting of managed- and one consisting of unmanaged Scots pine-dominated stands. The managed series have a reference year since the last clear cut and the unmanaged series have a reference year since the last fire.

A chronosequence can be used to measure differences between the two series or over a time frame of a specific series. In this thesis, the chronosequence was used to measure differences in soil respiration (SR) between managed and unmanaged sites and over a time period, in this thesis the time period is 0 to 375 years. In Phillips & Nickerson (2015) and Vallotton et al. (2023) SR is described as the biological activity in the soil profile with the exception that there are also non-biological processes that can influence respiration. Soil respiration is of high significance for the CO_2 budget of a forest stand. Marshall et al. (2023) used chamber measurements of CO_2 fluxes together with several other measurements, for example eddy covariance, to be able to calculate a carbon budget in a mature Scots pine stand, and the effect on the budget from nitrogen fertilization. In their analysis, they estimate, that the amount of CO_2 released from the soil on a yearly basis is approximately double the CO_2 released by respiration of the canopy of the dominant trees.

Soil respiration can also be described as the sum of autotrophic and heterotrophic processes. Heterotrophic respiration (HR) refers to CO_2 release from the decomposition processes of organic matter, while autotrophic respiration (AR) is the respiration of the understory vegetation and the roots. It was shown that thinning tends to increase HR (Çömez & Kaptanoğlu 2023, Lei et al. 2018). In Çömez & Kaptanoğlu (2023) they investigated how pre-commercial thinning influenced the SR with several different pre-commercial thinning strengths. One of the strengths they used was very similar to a pre-commercial thinning in Sweden, leaving 4000 individuals per hectare, which led to an increase in SR of about 67% directly after the pre-commercial thinning had occurred. In contrast, Aosaar et al. (2023) found no significant difference in SR between thinned and un-thinned sites, but they showed a trend of higher respiration rates in thinned sites.

In Song et al. (2019) they investigated how SR changes after prescribed burning. In their result, they showed that AR reached a low steady state directly after the burning, which remained for the following two years. The HR followed the same pattern and nearly the same respiration rate as for the non-burned forest during the first year, with no significant difference, but had lower respiration rate the second year after the burning. Soil respiration also changes with the age of forests. For example, Wang et al. (2013) investigated SR across three stand ages, 15, 25, and 35 years, and found that the 15 years old stand had the higher SR, compared to the 35-year-old stands. Kukumägi et al. (2017) have also investigated how the SR changes over stand ages and found similar results as Wang et al. (2013) did. Kukumägi et al. (2017) investigated SR for stands with an age between 2 and 82 years, in their result they found that the SR was lowest when the stand age was younger than 10 years and between 30 and 40 years, the highest SR was found in stands with an age between 10 and 30 years and increased again at a stand age older than 80 years. HR specifically was found to correlate to the net primary production, which is known to change over time in unmanaged forests (Xu et al. 2014). Peichl et al. (2023) investigated how the HR changes in managed stands with stand ages between 5 to 211 years. Similar to previous studies on total SR they found that HR was highest in stand ages younger than 25 years, then decreased until around 100 years, and slowly started to increase again until 211 years. These results can be correlated to the results from Xu et al. (2014) that HR will reach a steady state, and follow the change of the net primary production (NPP).

1.1 Aim and research questions

The aim with this master thesis is to examine, investigate and to get a broader understanding of if/how soil respiration of carbon dioxide, both autotrophic and heterotrophic, differs over longer time, a chronosequence, with stand age ranging from two to 376 years old, and between managed and unmanaged forests. This leads to the research questions of this thesis;

1. How does the soil respiration of CO_2 differ within each chronosequence, how does soil CO_2 respiration changes over time?
2. How does the soil respiration of CO_2 differ between each chronosequence, how does soil CO_2 respiration differ between managed and burned forest?

1.2 Hypothesis

1. Autotrophic respiration rate, as µmol ha^{-1} s^{-1}, will follow a similar time course in managed and unmanaged forests: It will increase and peak within the first 35 years, and decrease and reach a steady-state thereafter (Wang et al. 2013, Kukumägi et al. 2017).
2. Heterotrophic respiration rate, as µmol ha^{-1} s^{-1}, will have contrasting patterns over time in managed and unmanaged forests: In managed forest thinning operations will increase heterotrophic respiration repeatedly over the rotation cycle to rates exceeding that of unmanaged stands (Lei et al. 2018). In contrast, in unmanaged stands, heterotrophic respiration will be higher right after the fire event (Song et al. 2019) and decline and reach a steady state, following the change of NPP with stand age (Xu et al. 2014).
3. The total respiration rate, as µmol ha^{-1} s^{-1}, will be higher in managed forests compared to unmanaged forests within a comparable timeframe, stand age between 1 and 110 years. This is because management activities, most importantly thinning, was shown to increase heterotrophic respiration (Çömez & Kaptanoğlu 2023, Lei et al. 2018).

2. Materials and methods

2.1 Stand description

The data used in this study was collected from 36 stands around Arvidsjaur and Jokkmokk, Sweden latitude 64.83-66.55 (Figure 1)

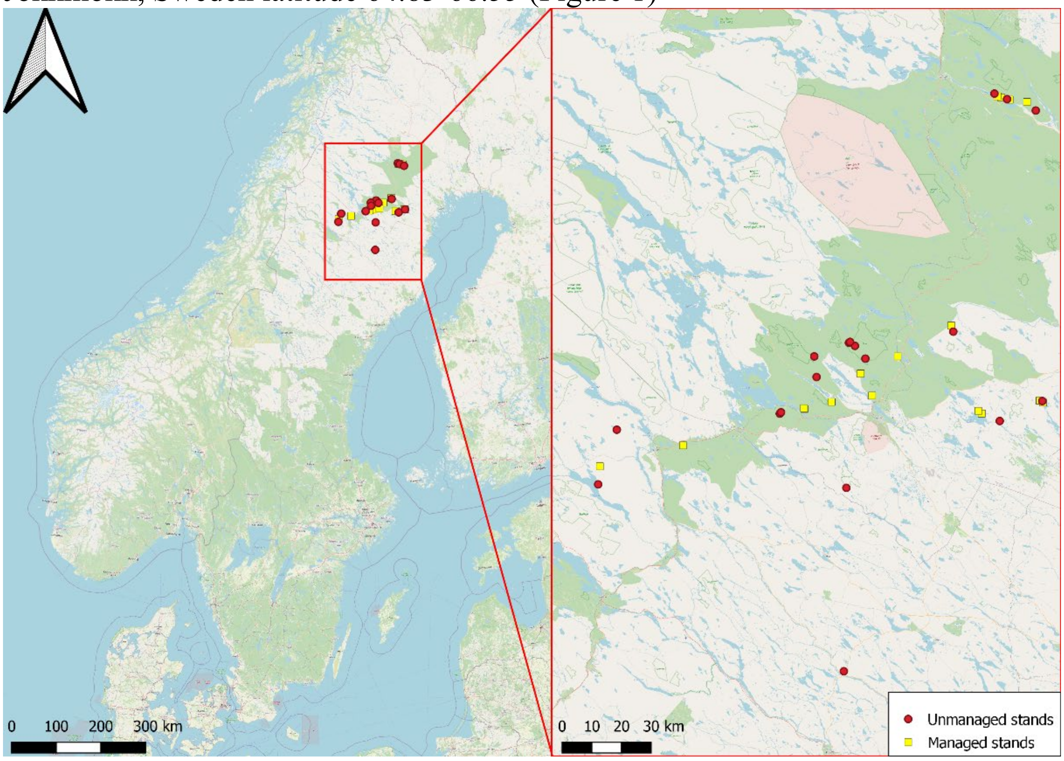

Figure 1. Location of unmanaged stands (red dots) and managed stands (yellow squares).

Arvidsjaur and Jokkmokk are located in the Swedish Lappland. The climate here is cold, with a winter season spanning for nearly 160 days and summer season of nearly 90 days (SMHI u.åa). In the four previous years the mean temperature over the whole year was between 0.97 and 2.98 °C in Arvidsjaur and 0.64 to 2.52 °C in Jokkmokk. The mean temperature during the summer months for the four previous years was approximately 14 °C except for the summer of 2021 (Table 1).

*Table 1. Mean temperature (℃) over the whole year and further divided for June, July and August. The mean temperature for the entire year in 2023 (marked with *) is calculated until the 4th of December 2023. Measurement stations used; Arvidsjaur A and Jokkmokk Flygplats (SMHI u.åb)*

Place	Year	Mean temperature whole year	Mean temperature in June	Mean temperature in July	Mean temperature in August
Arvidsjaur	2020	2.98	16.08	12.38	13.11
Arvidsjaur	2021	0.97	14.35	17.27	11.58
Arvidsjaur	2022	2.17	13.81	14.18	13.44
Arvidsjaur	2023	2.11*	14.22	14.30	13.67
Jokkmokk	2020	2.52	15.78	13.00	12.84
Jokkmokk	2021	0.64	14.75	17.20	11.56
Jokkmokk	2022	1.66	13.75	14.43	13.40
Jokkmokk	2023	1.84*	14.31	14.45	13.93

The precipitation in Arvidsjaur over the past four years was around 500 mm, while in Jokkmokk it was around 800 mm (Table 2). This precipitation is similar to the mean yearly precipitation in Sweden which is between 500 and 800 mm when excluding the areas with much higher and lower values; the mountain range in east, the southwest of Sweden and at islands in the Baltic Sea (SMHI). The precipitation for each of the summer months follow a similar pattern for the four years. There is one month with more precipitation than the rest of the two months (Table 2).

*Table 2. Total precipitation (mm) over the whole year and further divided for June, July and August. In total precipitation for the entire year in 2023 (marked with *) is calculated until the 4th of December 2023. Measurement stations used; Arvidsjaur A and Jokkmokk Flygplats (SMHI u.åc)*

Place	Year	Total precipitation whole year	Total precipitation in June	Total precipitation in July	Total precipitation in August
Arvidsjaur	2020	551.9	34.6	162.7	27.4
Arvidsjaur	2021	513.4	30.9	46.7	110.8
Arvidsjaur	2022	435.6	61.7	61.6	85.8
Arvidsjaur	2023	517.6*	55.5	89.8	109.4
Jokkmokk	2020	787.5	39.6	270.3	29.9
Jokkmokk	2021	878.1	48.7	46.6	243.4
Jokkmokk	2022	737.4	101.7	128.2	57.8
Jokkmokk	2023	807.4*	56.2	87.5	177.3

This study consists of two chronosequences; managed and unmanaged, each consisting of 18 Scots pine-dominated stands. The managed stands are stands that are being managed with a silviculture program suitable in the region, consisting of soil scarification, planting, pre-commercial thinning, thinnings and clear cut. The unmanaged stands have been left with no management since the last fire on each stand. The stands have an age distribution between 1 and 109, for the managed stands, and 4 and 375 years, for the unmanaged stands with 2022 as the reference year and the number in their identification represents how many years have passed since the last clear-cut or fire.

Table 3. Describes the stands that was used for measurements. The stands were decided during the summer of 2022 and the numbers represent the years since the last clear-cut or fire with year 2022 as the reference year to the age

Managed stands	**Unmanaged stands**
M1a	F4a
M1b	F4b
M2	F5
M13	F8
M18	F28
M24	F51
M32	F56a
M36	F56b
M39	F98
M42	F121
M61	F137
M65	F197
M71	F208
M80	F229
M94	F263
M100	F288
M102	F310
M109	F375

The sites were decided and set up during the summer of 2022. Each site was an area of one hectare with in total 14 measurement plots for SR: nine for total respiration (TR) and five for HR. TR and HR have been marked with four plastic sticks in each corner of the plot where the measurement should be taken, the HR plots have been trenched and cleaned to only have exposed soil on the plot.

The plots are distributed in a cross pattern at each site, with one HR and one TR in the middle. 28 meters from the middle at a 45° angle in each direction is one plot for TR followed by one HR and one TR at 56 meters from the middle in the same direction (Figure 2), resulting altogether in 9 TR and 5 HR plots.

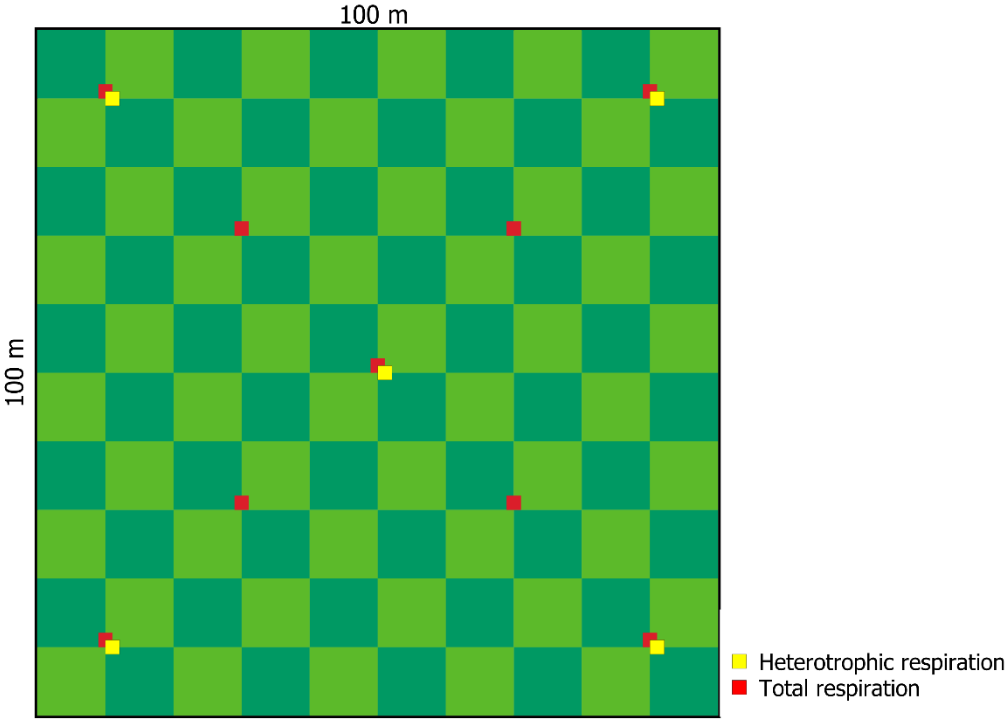

Figure 2. Illustrating the layout of where the measurements were taken at each site. Each site was an area of one hectare, 100x100 meters. In yellow is where the heterotrophic respiration was measured and in red is where the total respiration was measured.

2.2 Measurement of soil respiration

Data was collected during two periods in the summer of 2023, from June 5th to June 21st and from July 17th to August 4th. CO_2 flux data was collected by the static chamber method, using a Vaisala handheld device (GM70, © Vaisala 2015) connected with a Vaisala probe (GMP343, © Vaisala 2015) with a custom-made soil collar fitted with a lid. Parallel to each CO_2 flux measurement, so 14 times per site, soil moisture and soil temperature were recorded. This was done by using a soil moisture meter (HH2, © Delta-T Devices Ltd 2023) together with a connected soil moisture probe (ML3, © Delta-T Devices Ltd 2023) for soil moisture, and a thermometer for the soil temperature. A ruler was used to measure the height of the collar at each measurement.

The soil efflux measurement started with placing the collar on the plot for HR or TR, the collar was pushed into the soil about one centimeter which is done to minimize the airflow into the collar. When the collar was pushed into the soil the collar was left for one minute in order to let CO_2 concentration inside the collar stabilize. During the time that the CO_2 concentration stabilizes inside of the collar, the Vaisala with the probe connected was exposed to the surrounding air to have the reference CO_2 concentration. When the CO_2 concentration was stable in the soil and the Vaisala showed a CO_2 concentration like the atmospheric concentration, the lid with the Vaisala probe connected was placed over the collar and the measurement was started. Each measurement was 2 to 2½ minutes long and the CO_2 concentration was recorded every 5 seconds. During the measurement the CO_2 concentration was shown at the specific point together with the trend during the measurement, this trend was investigated during the measurement. The aim with each measurement was to have a steady increase in CO_2 concentration with a flattened end for the two minutes.

2.3 Data

2.3.1 Flux calculation

For calculating the flux at each measurement point the R package "FluxCalR" from Zhao (2019) was used. The package is used to calculate the flux of CO2 and/or CH4 in a static chamber over a set time. The flux is calculated as described in Eq. 1:

$$F = \frac{vol}{R * Ta * area} * \frac{dG}{dt} \qquad (1)$$

where

F is the flux rate (µmol $m^{-2}s^{-1}$),
vol is the volume of the chamber (l),
R is the universal gas constant (1 atm K^{-1} mol^{-1}),
Ta is the ambient temperature (K),
area is the area of the chamber base (m^2),
dG/dt is the rate of the measured gas concentration change over time t (ppm s^{-1}), (i.e. the slope of the linear regression).

The flux calculations started by selecting the dead band, which represents the time between that the lid was placed over the collar and the time until the CO_2 concentration was stable inside the collar again, as the starting point for the calculation. In previous studies they have used a dead band of 15 (Mills et al. 2011), 30 (Liu et al. 2019) and 60 (Courtois et al. 2019) seconds. After going through the raw data and analysed the beginning of each measurement, a dead band of 30 seconds was implemented. The slope of the linear regression was used to calculate the flux rate by fitting a straight line to the data points and selecting a timeframe that resulted in the highest R^2-value for the fit. This timeframe was typically at least 1 minute.

2.3.2 Autotrophic respiration.

AR was calculated from TR and HR as

$$\overline{\mathrm{AR_i}} = \frac{\Sigma \mathrm{TR_i}}{\mathrm{n}} - \frac{\Sigma \mathrm{HR_i}}{\mathrm{n}} \tag{2}$$

where

$\overline{AR_i}$ is the calculated mean of AR for the i:th site,

$\frac{\Sigma \mathrm{TR_i}}{\mathrm{n}}$ is the sum of the TR for the i:th site divided by number of measurements at each site,

$\frac{\Sigma \mathrm{HR_i}}{\mathrm{n}}$ is the sum of the HR for the i:th site divided by number of measurements at each site.

2.3.3 Upscaling respiration rate

The flux rates were calculated in the unit µmol m^{-2} s^{-1} for each site. The calculated flux rates were then upscaled to a mean value per hectare, which is the area of the site used for each site. The upscaling was used with

$$X_i = F_i \times 10000 \tag{3}$$

where

X_i is the flux rate for the i:th site (µmol ha^{-1} s^{-1}),

F_i is the flux rate for the i:th site (µmol m^{-2} s^{-1}).

The flux rate at the i:th site is then used for calculating the mean values for each site with

$$\overline{Y_i} = \frac{\Sigma X_i}{n} \tag{4}$$

where

$\overline{Y_i}$ is the mean respiration rate for the i:th site,

ΣX_i is the sum of the flux rate for the i:th site (µmol ha^{-1} s^{-1}),

n is the number of measurements for the specific respiration rate at each site.

2.3.4 Quality check and excluded measurements

During the quality check of the data there were seven plots and one site that stood out and had values that does not have a reasonable pattern, from the rest and was therefore not used. The plots that stood out from the rest of the measurements had 1) too high CO_2 concentration when the measurement started, leading to that there were either a decrease in the CO_2 concentration or that there was no change at all, 2) too few measurement points, which lead to a dead band that was more than half of the whole measurement period and a change in CO_2 concentration could not be reliably estimated. The seven plots that are not used were all from the measurement period in June and have in common that they have a too high starting value compared to the rest of the measurement. The plots that were not used can be seen in table 4.

Table 4. Sites and plot that was not used for measuring the flux rate due to errors in the measurements, either with to high CO_2 concentration when starting the measurement point, too short measurement period or higher mean HR than mean TR.

Stand	**Location in site**
M1a	1-56 TR
M36	Centre HR
M80	1-56 TR
M94	2-28 TR
F208	2-56 HR
F288	3-56 HR
F375	1-28 TR
F28	All locations

In addition, in site F28 the estimates of the HR were higher than that of the TR during the July/August measurement campaign. Since this is theoretically impossible, we concluded that there was a measurement error and excluded this data from further analysis. Furthermore, in June soil moisture was not measured at ten sites due to instrument failure.

2.3.5 Data analysis

To analyze the SR rate and how it changes between managed and unmanaged stands together with how it changes over time. Two linear models were conducted, one for stands with an age younger than 110 years (Model 1) and one for stands with an age older than 110 years (Model 2).

Model 1

lm(Respiration~Management*Age)

Model 2

lm(Respiration~Age)

In Model 1 and Model 2 the *Respiration* represents each respiration rate; HR, AR and TR, for younger and older stands. To test if there were any variance in each model ANOVA was used with a significance level of 0.05.

3. Result

3.1 Stand soil conditions

The mean soil temperature for the managed stands was 10.49 ± 3.16 ℃, with temperatures ranging from 4.26 to 16.16 ℃. Comparing this to the unmanaged stands where the mean soil temperature was 9.79 ± 3.03 ℃, with temperatures ranged from 3.61 to 15.69 ℃ (Figure 3). The difference in mean soil temperature was 0.7 ℃ together a difference in standard deviation of only 0.13 ℃. The span of the mean soil temperature was very close with under 1℃ in difference between the managed and unmanaged stands for the lowest and the highest mean soil temperature.

The mean soil moisture for the managed stands was 18.02 ± 7.86 vol%, with values ranging from 7.26 to 39.93 vol%. In the unmanaged stands the mean soil moisture was 17.26 ± 8.76 vol% and values ranged from 5.29 to 38.34 vol% (Figure 4). The difference in mean soil moisture was 0.76 vol% together with a difference in standard deviation of 0.9 vol%. The span of the mean soil moisture was very close with under 2 vol% in difference between the managed and unmanaged stands for the lowest and highest mean soil moisture.

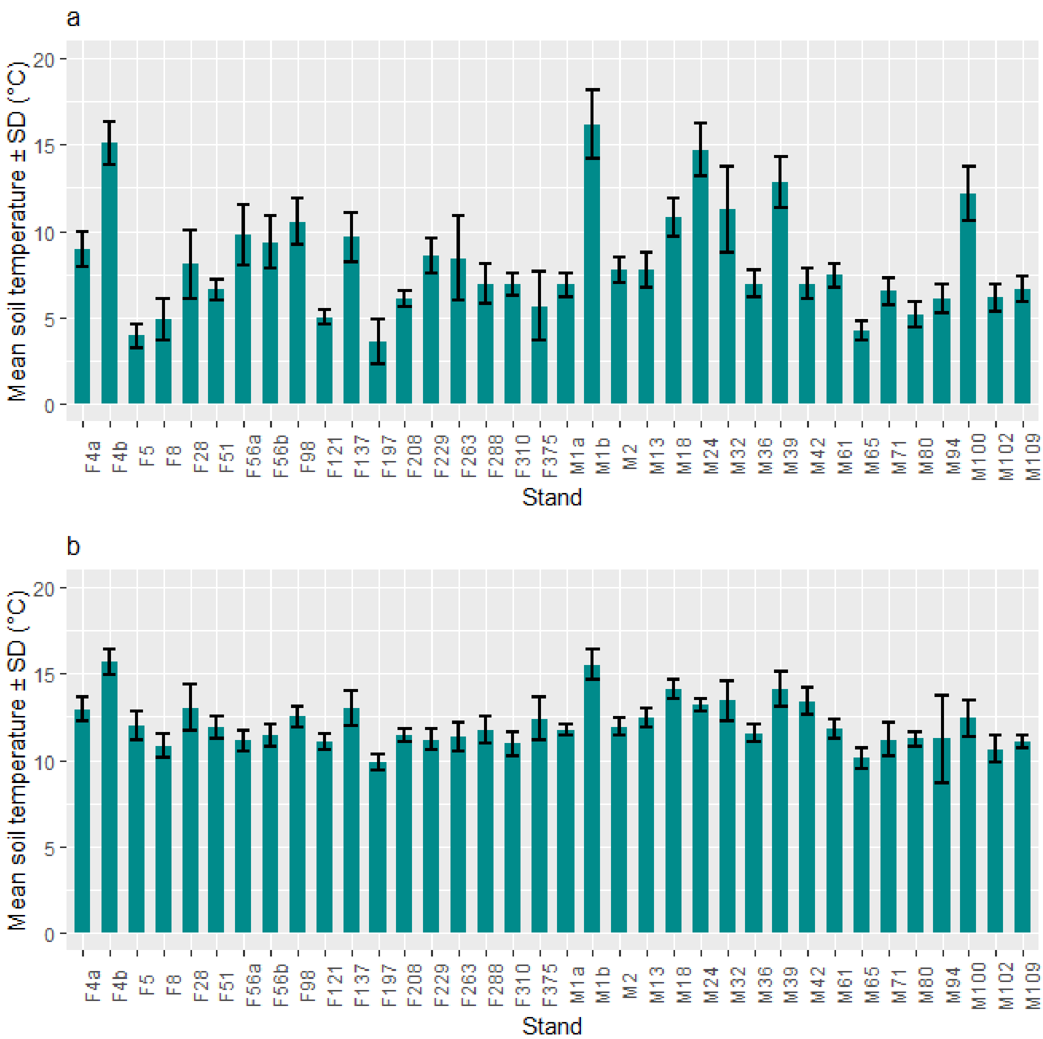

Figure 3. Mean soil temperature (°C) at each stand and period in June (a) and in July/August (b), the whiskers depict the standard deviation.

The mean soil temperature during the July period was less variable, with a standard deviation for all stands of 1.34°C, compared to the June period, which had a standard deviation for all stands of 3.12°C. The trend continued when investigating the mean soil temperature for each chronosequence type, in June the standard deviation was higher than in July (Table 5).

Table 5. Mean soil temperature (°C) with standard deviation for each period divided in chronosequence type and summed over all stands.

Period	**Managed stands mean**	**Unmanaged stands mean**	**All stands mean**
June	8.68 ± 3.41	7.67 ± 2.78	8.18 ± 3.12
July/August	12.29 ± 1.41	11.91 ± 1.27	12.10 ± 1.34

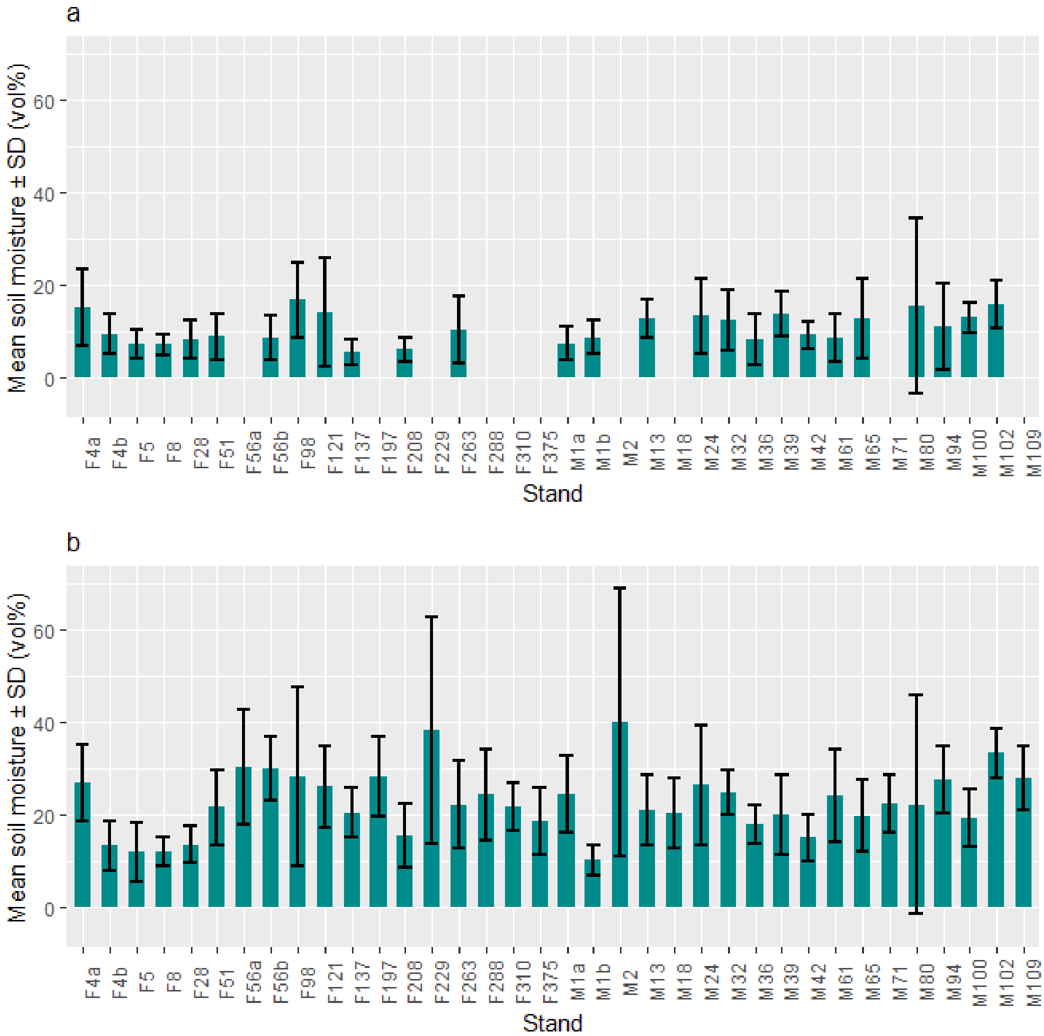

Figure 4. Soil moisture (vol%) at each stand and period in June (a) and in July/August (b), the whiskers depict the standard deviation. In the June period there are 10 stands that could not be measured due to faulty soil moisture meter.

The mean soil moisture during the June period was less variable compared to the July period, with standard deviation for all stands of 3.29vol% in June and 6.94vol% in July. The trend continued when investigating the mean soil moisture for each chronosequence type, in June the standard deviation was lower than in the July period (Table 6).

Table 6. Mean soil moisture (vol%) with standard deviation for each period divided in chronosequence type and summed over all stands.

Period	**Managed stands mean**	**Unmanaged stands mean**	**All stands mean**
June	11.50 ± 2.80	9.66 ± 3.65	10.65 ± 3.29
July/August	23.10 ± 6.66	22.32 ± 7.38	22.71 ± 6.94

3.2 Soil respiration for stand ages younger than 110 years

To compare SR in managed *vs* unmanaged stands, I first looked at stands with ages up to 110 years old, which was the age of the oldest managed stand in our chronosequence. The mean SR for stands with ages younger than 110 years was higher for the managed stands compared to the unmanaged stands, this except for the AR during the June period. The mean ± standard deviation value of TR in unmanaged stands was 26,171 ± 13,412 µmol ha^{-1} s^{-1} and in the managed stands was 32,112 ± 16,333 µmol ha^{-1} s^{-1}, this difference was not significantly different with p=0.198. The mean ± standard deviation value of HR in the unmanaged stands were 13,113 ± 6,684 µmol ha^{-1} s^{-1} and the managed stands 16,662 ± 8,513 µmol ha^{-1} s^{-1}, this different was not significantly different with p=0.137. The mean and standard deviation value of AR for the unmanaged stands were 13,058 ± 8,434 µmol ha^{-1} s^{-1} and for the managed stands 15,450 ± 9,258 µmol ha^{-1} s^{-1}, this difference was not significant with p=0.371.

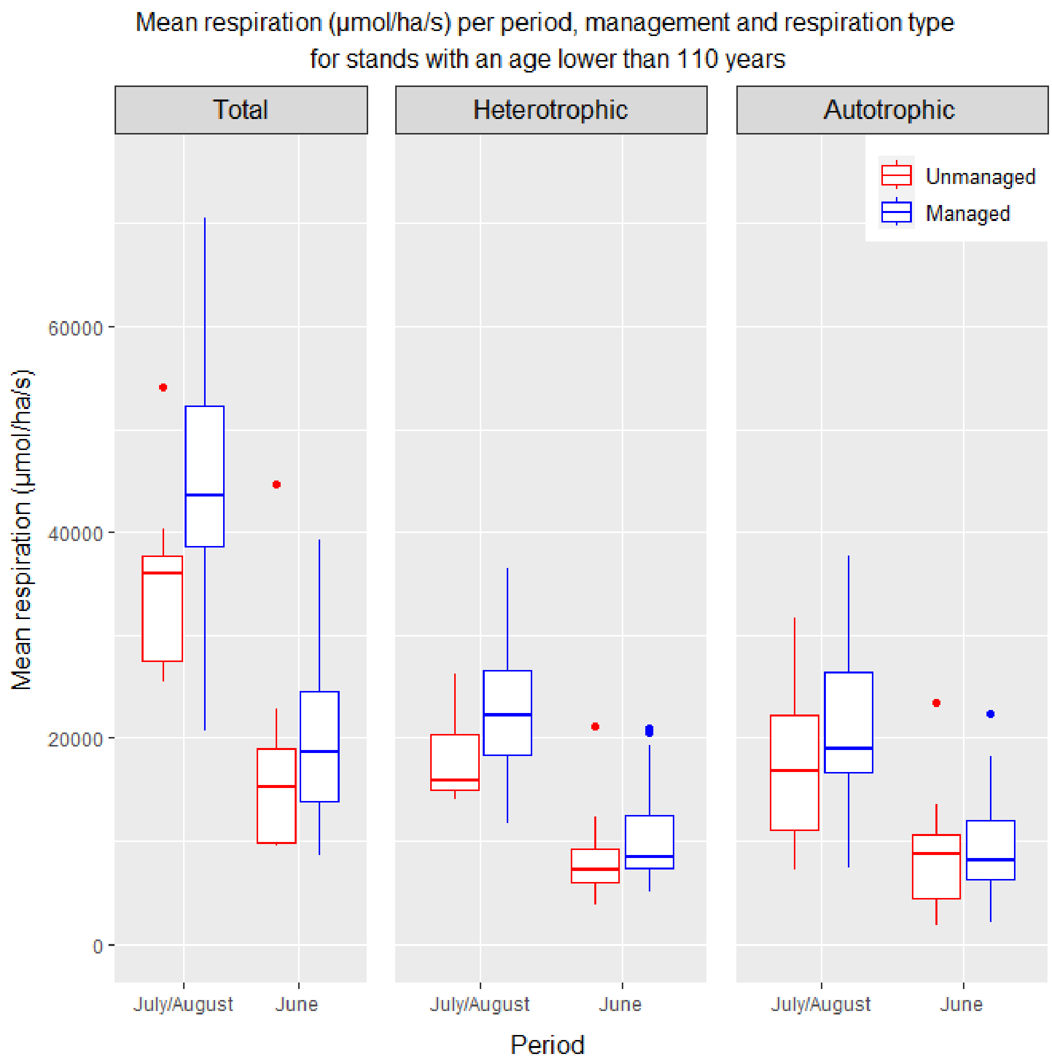

Figure 5. Mean respiration (µmol/ha/s) for stands with a stand age younger than 110 years, divided in total-, heterotrophic- and autotrophic respiration. The blue represents the managed stands and the red represent the unmanaged stands. The boxes represent the 25th percentile, at the bottom, the 75th percentile, at the top, and the mean value, the thicker line. The whiskers represents the minimum and maximum values.

The AR values for stands with an age younger than 110 years had different patterns for the managed and the unmanaged stands. The AR rate for the managed stands was lowest when the stand age was close to 0, the respiration rate increased with older stand age to a peak at a stand age of about 30 years. The AR rate for the unmanaged stands had decreasing respiration rate when the stand age was between 0 and 15 years. From a stand age of 15 and older the respiration rate increased and reached a peak when the stand age was closest to 110 years. The values when the stand age is close to 0 were very similar, for the unmanaged stands the values were between 6,728 to 12,401 µmol ha^{-1} s^{-1} for the two stands that the age was 4 years and for the managed stands the values were between 2,141 to 12,401 µmol ha^{-1} s^{-1} for the two stands when the stand age was 1 year. The values when the stand age was closest to 110 was for the unmanaged stands between 23,485 to 31,606 µmol ha^{-1} s^{-1} and for the managed stands the values were between 8,297 to 18,514 µmol ha^{-1} s^{-1}. The trend for the difference between the managed and unmanaged and how the CO2 concentration changes with stand age was nearly significantly different, with p-value=0.054.

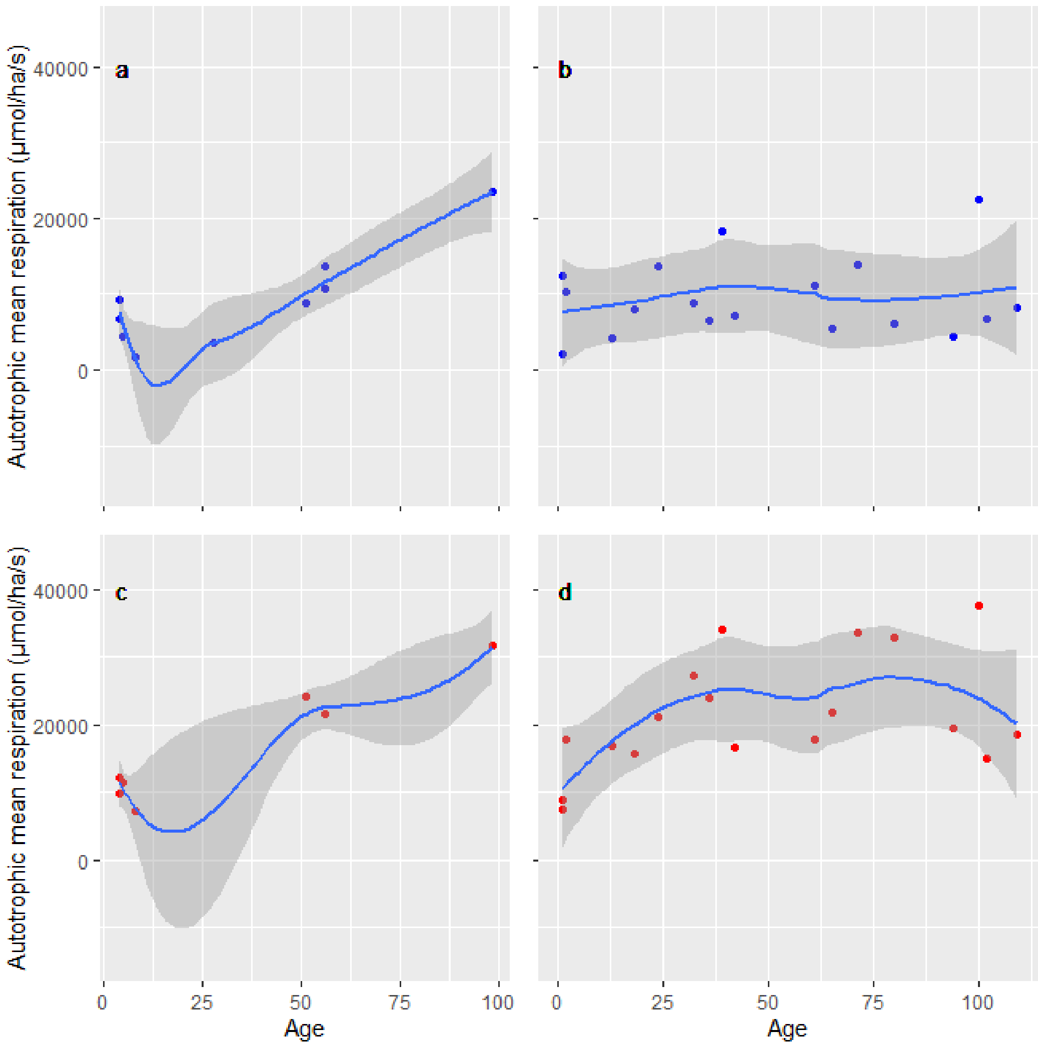

Figure 6. Illustrates autotrophic mean respiration (µmol/ha/s) for stands with a stand age younger than 110 years in June (in blue) for unmanaged (a) and managed (b) and in July/August (in red) for unmanaged (c) and managed (d). The light blue line represents the trend line and the grey area represents the confidence interval (0.95).

The HR for stands with an age younger than 110 years differed between managed and unmanaged stands. The HR rate for the managed stands was lowest when the stand age was close to 0 and from 70 to 110 years. The respiration rate reached a peak at around 40 years with a steady increase from a stand age of 5 years and a steady decrease until a stand age of around 65 years. The unmanaged stand had very small changes and was relatively stable over the whole 110 years and with an increase when the stand age was close to 110 years. The values when the age was close to 0 was for the unmanaged stands between 6,122 to 26,210 µmol ha^{-1} s^{-1} for the two stands that the age was 4 years and for the managed stands the values were between 6,419 to 19,944 µmol ha^{-1} s^{-1} for the stands that the age was 1 year. The values when the stand age was close to 110 years was for the unmanaged stands between 21,185 to 22,446 µmol ha^{-1} s^{-1} and for the managed stands between 6,873 to 24,485 µmol ha^{-1} s^{-1}. The trend for the difference between the managed and unmanaged and how the CO_2 concentration changes with stand age was not significantly different, with p-value=0.25.

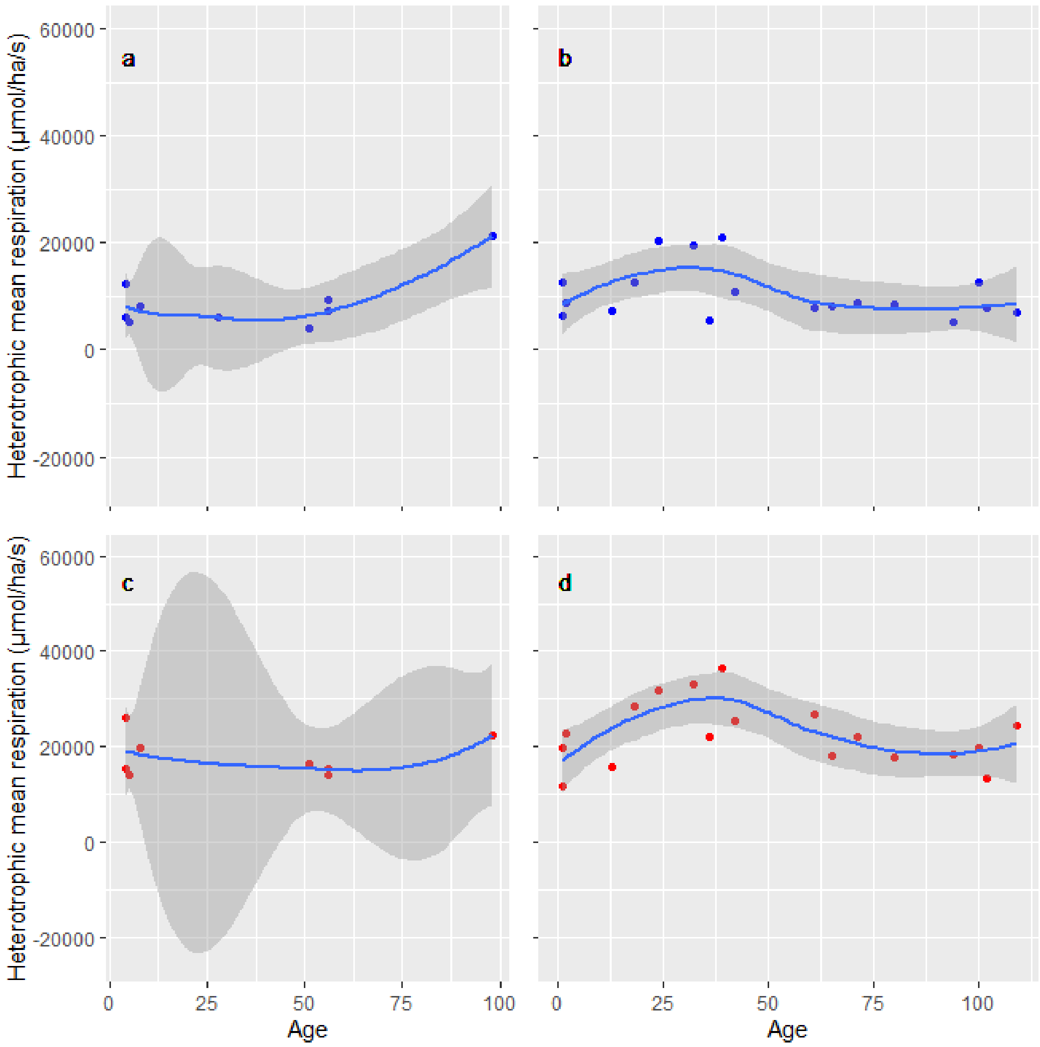

Figure 7. Illustrates heterotrophic mean respiration (µmol/ha/s) for stands with a stand age younger than 110 years in June (in blue) for unmanaged (a) and managed (b) and in July/August (in red) for unmanaged (c) and managed (d). The light blue line represents the trend line, and the grey area represents the confidence interval (0.95).

The TR for stand with a stand age younger than 110 years followed a quite unsimilar pattern between the managed and unmanaged stands. The TR rate for the managed stands was lowest when the stand age was close to 0, the respiration rate increased with higher stand ages and reached a peak when the stand age was around 40 years. When the stand ages were older than 40 years there was a steady but not so steep decrease until the stand age was 110 years. The TR rate for the unmanaged stands was lowest when the stand age was between 0 and around 30 years. When the stand age was older than 30 years there was a steady increase until the stand age was 110 years. The values when the stand age was close to 0 was for the unmanaged stands between 15,348 to 36,043 µmol ha^{-1} s^{-1}, for the two stands with an age of 4, and for the managed stands the values were between 8,561 to 27,344 µmol ha^{-1} s^{-1}, for the two stands that the stand age was 1. The trend for the difference between the managed and unmanaged and how the CO_2 concentration changes with stand age was nearly significantly different, with p-value=0.097.

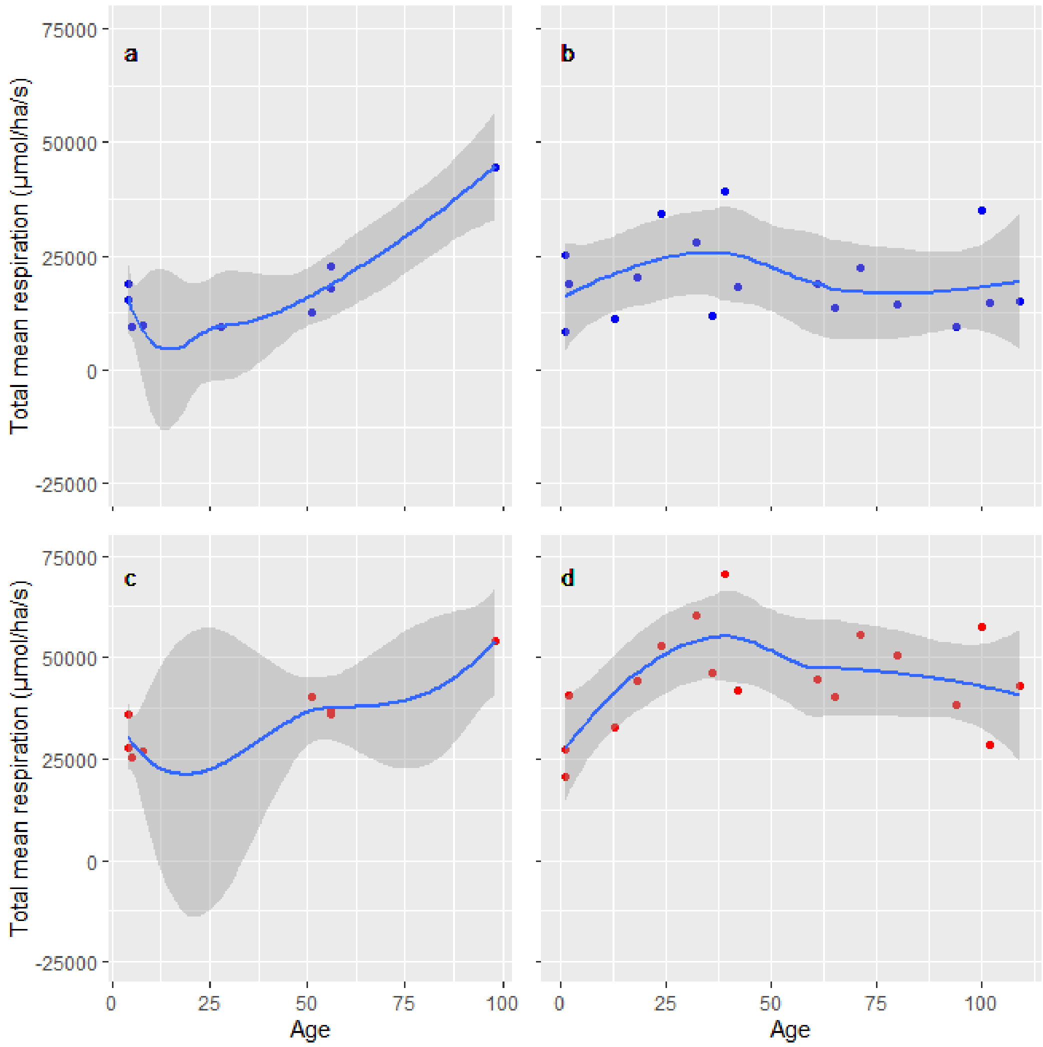

Figure 8. Illustrates total mean respiration (µmol/ha/s) for stands with a stand age younger than 110 years in June (in blue) for unmanaged (a) and managed (b) and in July/August (in red) for unmanaged (c) and managed (d). The light blue line represents the trend line, and the grey area represents the confidence interval (0.95).

3.3 Soil respiration for stand ages over 110 years

To evaluate SR in old-growth forests, we looked at the unmanaged stands older than 110 years separately. The mean SR for stand ages over 110 years follows the same pattern as for stands with ages under 110 years. This with higher values during the measurement period in July compared to the June period. The mean and standard deviation values for unmanaged TR measurements were 28,448 ± 13,896 μmol ha^{-1} s^{-1} for the HR the mean values were 13,097 ± 6,898 μmol ha^{-1} s^{-1} and for the AR the mean values were 15,351 ± 8,223 μmol ha^{-1} s^{-1}.

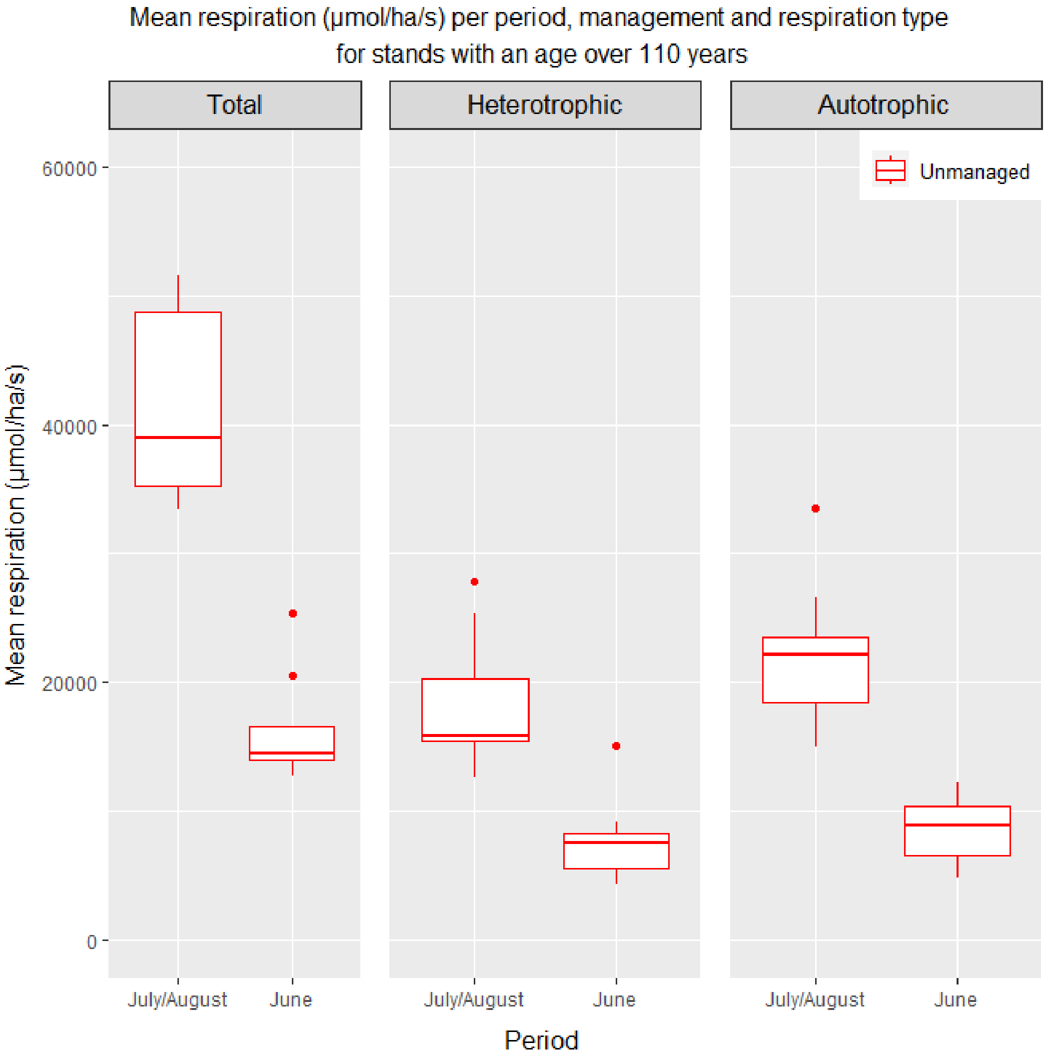

Figure 9. Mean soil respiration (μmol/ha/s) for stands with a stand age older than 110 years, divided in total-, heterotrophic- and autotrophic respiration. The boxes represent the 25th percentile, at the bottom, the 75th percentile, at the top, and the mean value, the thicker line. The whiskers represent the minimum and maximum values.

The AR values for stands with an age older than 110 years was stable between ages of 110 to 375. The AR rates was lowest when the stand age was close to 110 years and the rates was very stable until a stand age of around 320 years where there was a smaller increase until a stand age of 375 years. The AR trend for stands with an age older than 110 years differs from the trend of the stands with an age younger than 110 years. The respiration rate when the stand age is close to but younger than 110 years are quite much more than what the respiration rate is for stands that is older but close to 110 years. For the measurement period in June the values were very stable with values between 4,849 to 12,235 µmol ha^{-1} s^{-1}. The values in July were between 14,973 to 33,542 µmol ha^{-1} s^{-1}. The trend for the difference for how CO_2 concentration changes over time was not significant, with p-value ≫ 0.05.

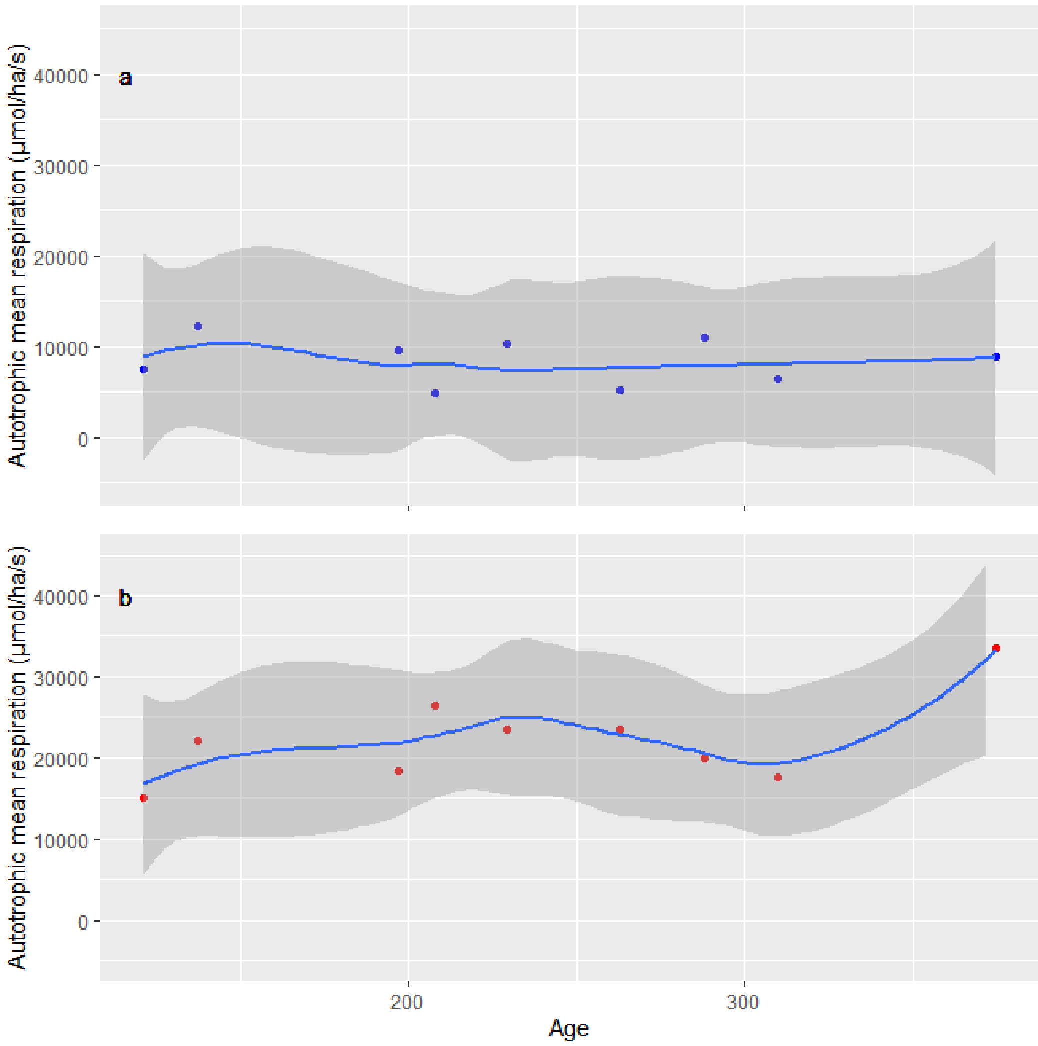

Figure 10. Illustrates autotrophic mean respiration (µmol/ha/s) for unmanaged stands with a stand age older than 110 years in June (in blue) (a) and in July/August (in red) (b). The light blue line represents the trend line, and the grey area represents the confidence interval (0.95).

The HR values for stands with an age older than 110 years was relatively stable and showed no clear trends for the years between 110 and 375. The HR rate decreased from when the stand age was 110 years until around 190 years, where there is a small increase but fast decreases again. The respiration rate then keeps nearly the same until 375 years. The respiration rate for stands older than 110 years was similar to the respiration rate for stands younger than 110 years. The trend for both younger and older stands is that the respiration rate is very stable for stand ages between 0 and 375 years, with only some small increases and decreases. The values during the measurement period in June was between 4,332 to 15,029 µmol ha^{-1} s^{-1} and for the measurement period in July the values were between 12,550 to 27,863 µmol ha^{-1} s^{-1}. The trend for the difference for how CO_2 concentration changes over time was not significant, with p-value ≫ 0.05.

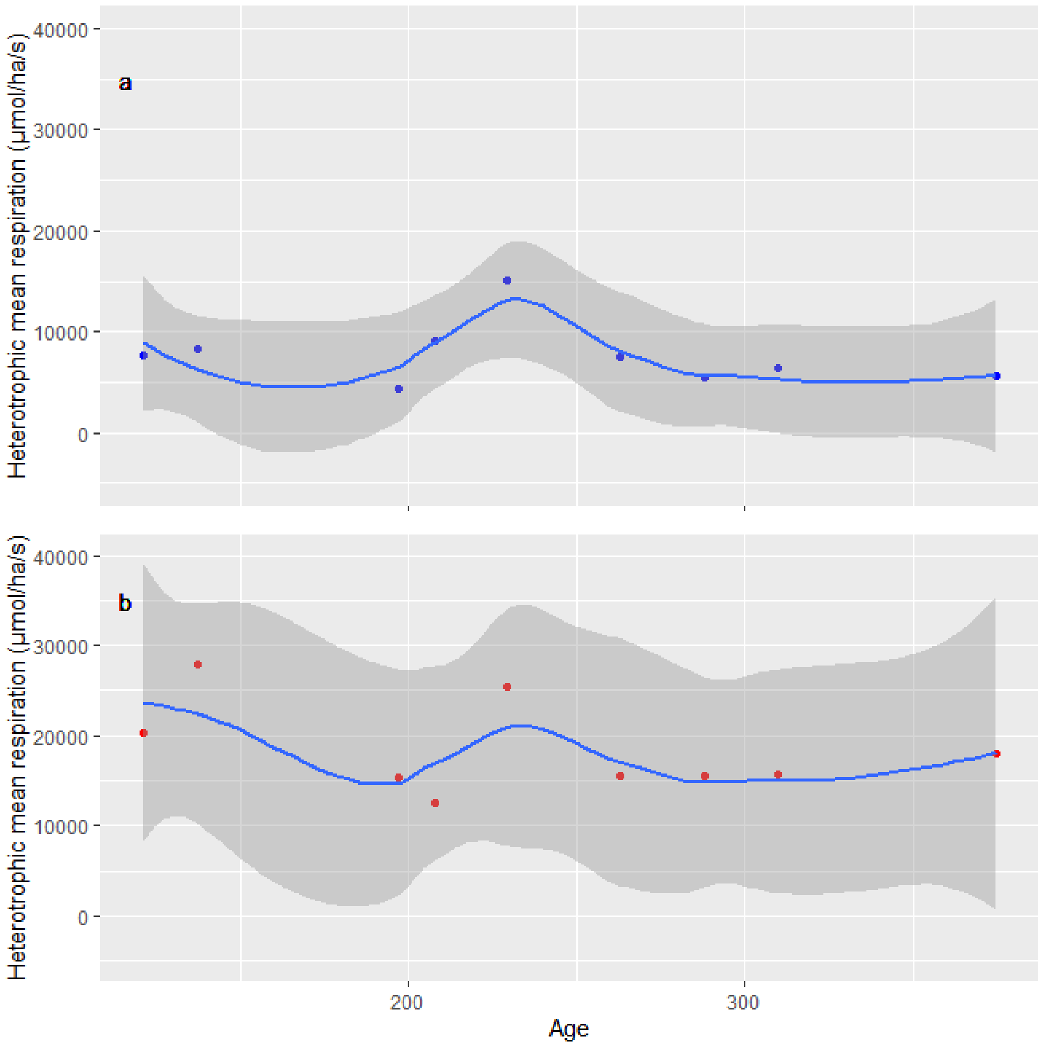

Figure 11. Illustrates heterotrophic mean respiration (µmol/ha/s) for stands with a stand age older than 110 years in June (in blue) (a) and in July/August (in red) (b). The light blue line represents the trend line and the grey area represents the confidence interval (0.95).

The TR values for stands with an age older than 110 years was quite stable and showed no clear trend between 110 to 375 years. The HR rate decreased from when the stand age was 110 years until around 190 years, where there is a small increase but fast decreases again. The TR trend for stand with an age older than 110 years differs quite much from the stand with an age younger than 110 years. For the stands with an age older than 110 years the trend was that the respiration rate keeps stable between 110 and 375 years and for stands younger than 110 years the trend was that there is a steady increase until a stand age of 110 years. The respiration rate then keeps nearly the same until 375 years with a small increase when the stand age is close to 375 years. The values during the measurement period in June were between 12,686 to 25,376 µmol ha^{-1} s^{-1} and during the measurement period in July the values were between 33,365 to 51,565 µmol ha^{-1} s^{-1}. The trend for the difference for how CO_2 concentration changes over time was not significant, with p-value ≫ 0.05.

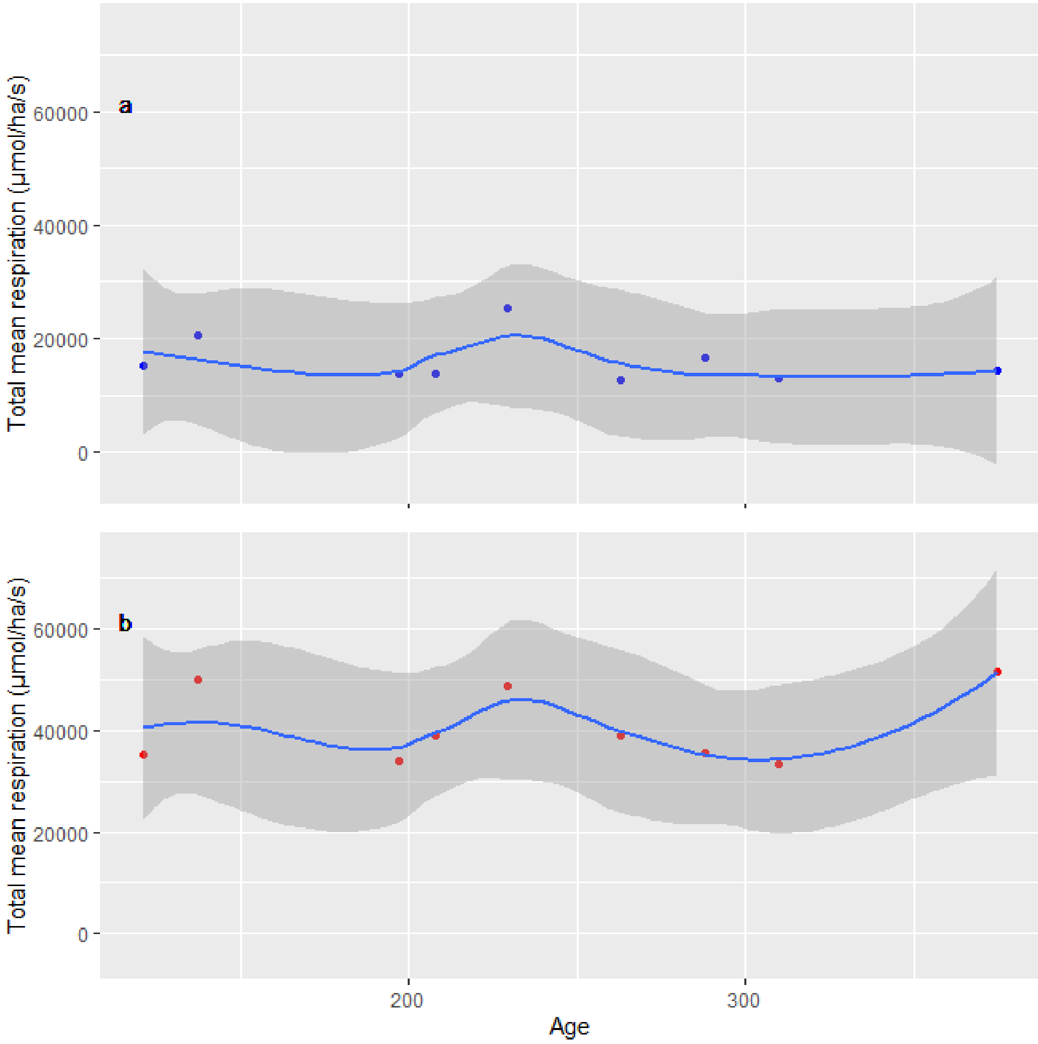

Figure 12. Illustrates total mean respiration (µmol/ha/s) for stands with a stand age older than 110 years in June (in blue) (a) and in July/August (in red) (b). The light blue line represents the trend line and the grey area represents the confidence interval (0.95).

4. Discussion

The aim with this thesis was to examine, investigate and to get a broader understanding of if and how soil respiration of CO2; autotrophic, heterotrophic, and total, differs over a 375-year period between managed and unmanaged forest. To explore this, a total of 36 forests stands, 18 managed and 18 unmanaged, was used for measurements of HR, TR, soil temperature and soil moistur. Managed forests stands were distributed over ages between 1 to 109 years with the last clear cut as the reference year to the age. The unmanaged forests stands were distributed over ages between 4 and 375 years with the last fire as the reference year to the age. With the difference in age distribution the forest stands were divided into stands with an age younger than 110 years and stands with an age older than 110 years. This was done to investigate the possible difference between the managed and the unmanaged stands within a suitable time frame.

First thing to consider when investigating and comparing the managed and unmanaged stands for stands with an age younger than 110 years is that the managed stands have a total of 18 stands per measurement period, compared to the unmanaged stands which only have 9 stands per measurement period. This together with that one stand is lacking from the data due to errors in the measurement, which is stand F28 from the measurement period in July.

4.1 Stand soil conditions

When investigating the stand soil conditions during the summer of 2023, the temperature was quite stable during the measurement period in July and unstable during the measurement period in June. This was also the same when investigating each measurement point and therefore the standard deviation at each site. The standard deviation was overall lower during the measurement period in July compared to June. When investigating how the air temperature was during the summer of 2023 compared to the three previous years, there was no larger differences between the years when not taking the year of 2021 in consideration, which was over one degree lower for the whole year. When comparing the soil temperature to the air temperature, there was a larger difference for the measurements during the June period compared to the July period. The soil temperature was around 5 to 6 degrees lower compared to the air temperature during June, and during July it was only around 1 degree lower. It is important to take in consideration that the mean air temperatures are taken from two measurement stations, and the soil temperature are from 36 stands.

When investigating the soil moisture, it followed the same pattern as the soil temperature, with higher values in July compared to June. For the soil moisture in July compared to June, the mean values were more than double for both managed and unmanaged stands. The standard deviation was higher during the measurement period in July compared to June, due to some places having very high values, nearly or over 100 vol%, compared to the measurement period in June, which had more stable values. The precipitation during the three previous years have been quite unstable with higher values in one summer month compared to the other two months. This pattern was quite the same as the previous years and this year was the month with the highest precipitation the August. When comparing the precipitation and the soil moisture it follows a similar pattern, June had lower precipitation and lower soil moisture compared to the July period.

When investigating both the soil moisture and the soil temperature from all stands there are small differences between the managed and the unmanaged stands. The differences for the mean soil temperature were lower than 1°C compared to the mean soil moisture where the difference was lower than 2 vol%. With this in consideration no correction for SR was done according to the differences in soil temperature nor soil moisture was made.

4.2 Soil respiration

When investigating the mean SR values for stands with a stand age younger than 110 years, there was no significant difference between the managed and the unmanaged stands. Although no significant differences were found, there were some differences between the managed and unmanaged stands. The most noticeable difference between them is that the unmanaged stands were more stable in the values and variation was much smaller compared to the managed stands which where the values had a larger span and a bigger spread between the lowest and the highest values. This pattern could be due to that SR in managed forest have shown to be significantly higher in stand ages lower than 40 years, which could lead to more fluctuation over a larger sample of stand ages. This was shown in Kukumägi et al. (2017) where they found out that SR was higher for stands with an age between 30 to 40 years together with the lowest SR in stands with an age younger than 10 years. Further, Peichl et al. (2023) found similar results but with the highest SR in stands with an age younger than 25 and then a decrease until a stand age of around 100 years. In comparison Aosaar et al. (2023) did not find any significant difference between thinned and un-thinned stands which could explain the pattern of having more stable respiration rates in the unmanaged stands.

When investigating the result for AR and comparing it to the hypothesis, where we predicted that both managed and the unmanaged stands would increase until around 35 years, and then decrease and reach a steady state. Inconsistent with this, the data showed managed and unmanaged stands did not follow the same pattern over the first 110 years since disturbance. In the unmanaged stands, AR initially decreased, when the stand age was close to 0, but then started to increase at an age around 15 years. This increase in respiration rate continued until a stand age of 110 years. This pattern is quite similar to the results from Song et al. (2019) which showed that the AR kept a steady state directly after the burning and remained steady for the next two following years. Comparing this to the managed stands, which immediately increased until about 40 years, and then flattened out, and then decreased again at an age around 80 years. The results show that the unmanaged stands reached a higher respiration rate when the stand age was close to 110 years, compared to managed stands. When investigating the results in this thesis and comparing it to the results from Wang et al. (2013) and Kukumägi et al. (2017) it does not follow the results from their articles, where they found a higher respiration rate at lower stands ages compared to the respiration at stands with higher age.

The AR for unmanaged stands over 110 years old showed a different pattern than younger stands. The respiration rate was much lower when the stand age is around 120 years compared to the respiration rate when it is close, but younger than, 110 years. After 110 years, AR increased until reaching a stand age of around 240 years, after which it declined until an age of 375 years. However, overall respiration was quite stable over this whole period. This pattern was more in line with the results from Wang et al. (2013) and Kukumägi et al. (2017) in contrast to the respiration patterns we observed in stands younger than 110 years.

I hypothesized that HR would have contrasting patterns over time in managed and unmanaged stands due to that multiple thinning events in managed forests would increase HR. When investigating the HR for stand ages younger than 110 years, it was observed that the unmanaged stands had very stable HR rates throughout the entire 110 years. However, a slight upward trend was noted as the stand age approached 110 years, deviated from the hypothesis. The managed stands have a contrasting pattern to the unmanaged stands, with an increase when the stand age is close to 0. This increase was continuous until an age of around 45 years, then decreases until an age of around 60 years and keeps stable until an age of 110 years. The increase in the middle of a stand age period may have been influenced by pre-commercial thinning and thinning events, which produce a lot of detrital inputs to soils (Skogsstyrelsen 2012). Overall, the result for HR aligns with the hypothesis, with the only inconsistent pattern occurring when the stand age was close to 110 years. This follows the results from Çömez & Kaptanoğlu (2023) and Lei et al. (2018) together with Peichl et al. (2023) which showed higher respiration rates after thinning operations and generally supports my hypothesis.

When investigating the HR for stands with an age older than 110 years, the unmanaged stands have a stable respiration rate with a small decrease directly after 110 years, and a small increase at an age of about 200 years. The respiration rate when the age is just over 110 years is close to the same as the respiration rate when the age is just under 110 years which nearly follows the results from Xu et al. (2014) and matches the hypothesis that it should flattens out and track net primary production at higher stand ages. Comparing this to the pattern that Peichl et al. (2023) found, which was that the HR would start to increase between stands ages of 100 and 211 years, the HR in this result have no trend of increasing nor decreasing at stand ages around then same time frame.

Regarding TR, my hypothesis was that the respiration rate in managed stands would be higher than unmanaged stands for stands with an age younger than 110 years. For the most part, the data supported this hypothesis, in that managed stands had a higher respiration rate for stands with an age between 0 and around 90 years. After around 90 years the unmanaged stands reached higher respiration rates than the managed stands. However, this only was evident for the measurement period in July, whereas for the measurement period in June the unmanaged stands showed higher values at around 60 years, but the respiration rate was overall lower than during the measurement period in July. The managed stands start with an increase in respiration rate when the stand age is close to 0 and increases until around a stand age of 45 years. This matches the hypothesis with that the heterotrophic rate should be influenced by the thinning operations and with the previous studies from Çömez & Kaptanoğlu (2023) and Lei et al. (2018). When investigating the TR for stands with an age older than 110 years the unmanaged stands have lower respiration rate when the stand age is just over 110 years compared to when the stand age is just under 110 years. This follows the pattern from Xu et al. (2014) where they found that HR keeps a steady state and follows the rate of the NPP when stand age reaches older ages. On the other hand, this does not follow the pattern from Peichl et al. (2023) where they found that the respiration rate increased between the ages 100 and 211 years which was not the case in this thesis.

5. Conclusion

In conclusion stand age and management method seems to have an influence on SR. One of the most noticeable trends that has been found in this thesis is that the thinning operations seems to have a positive influence on the SR. Between the age of 15 to 45 the SR increases quite rapidly in the managed stands compared to the unmanaged stands with the most noticeable respiration rate being HR. AR does also seem to be influenced by thinning operations and this trend seems to continue over a longer time frame and the influence from the thinning operations are less noticeable compared to the HR rate. Another trend in the SR rates is that the managed stands with an age younger than 90 years have higher respiration rates when comparing it to the unmanaged stands with the same age. During the ages 0 to 90 years the managed stands have higher rates of respiration than the unmanaged stands but between 90 and 110 years the unmanaged stands tend to exceed the managed stands in respiration rates.

I found that the unmanaged stands the respiration rate for stands with an age older than 110 years have very consistent rates throughout the stand age between 110 and 375 years. The TR rate for unmanaged stands with an age older than 110 years is mainly lower than the TR rate for both managed and unmanaged stands with a stand age lower than 110 years. Both HR and AR follow the same pattern for stands with a stand age older than 110 years compared to stands with an age lower than 110 years. The respiration rate in older stands is more stable and receive lower values.

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