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The Effects of Clear-Cutting a Hemiboreal Forest on Local CO_2 Fluxes in Norunda, Sweden

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Abstract

As CO_2 builds up in the atmosphere causing global climate change (IPCC, 2022) trees have become an international symbol of combatting this, and for good reason. Trees take up CO_2 which as a result combats these changes, and when these trees are cut down fewer individuals remain to take up the CO_2 that we humans emit (Chapin et al., 2011). This means that clear-cut areas don't act as the carbon sinks they once were, for many years to come (Grelle et al., 2023; Peichl et al., 2022). If forestry and timber production is not done sustainably it results in an increase of CO_2 in the atmosphere, which has global consequences (Chapin et al., 2011; Smith et al., 2021) if it is done on a large scale as it is today..

In this study the impact of clear-cutting a forest has on local CO_2 fluxes was studied by comparing such fluxes between the years 2022 and 2023, one year prior to and one year after a complete clear-cut of a hemiboreal forest. It was investigated whether there were any changes in flux between the two years as well as whether any major spatial variation in flux was present. The chosen study site is a Swedish flux and exchange measurement station, Norunda, owned by the Swedish research agency ICOS.

The study was performed by sorting CO_2 flux data into eight sectors depending on the wind direction of the measurement. A simplified flux footprint-proxy, being the lateral extent of the 70% flux footprint, was used to determine how far from the measurement tower the flux readings originated from. From this data, only the fluxes with a footprint length of 300 metres or less were used due to the extent of the clear cut. Eight means were then computed for each year, which were compared to each other and between the two years.

An increasing trend in NEP was observed in the first half of 2022, and a significant decrease in NEP, i.e. an increased uptake of CO_2, was found between the years 2022 and 2023. This confirmed the initial hypotheses and agreed with previous research. It was furthermore observed that a remarkable spatial variation in flux means was present in 2022, where the most productive quadrant was observed to be the East-facing. Aside from this, the spread of the data across all sectors in 2022 was much wider than in 2023, further underlining the conclusion that the clear-cutting did have a significant impact on the forest's NEP.

Future studies could now have the goal to investigate what could be causing this spatial difference in flux means in order to possibly define guidelines as to how a forest can be managed more sustainably from a CO_2 flux perspective. Another future study would keep looking into the evolution of the forest's NEP over the next decades to gain insight in how well this clear-cut forest regains its property as a carbon sink.

Key terms: CO_2 flux, Clear-cutting, Coniferous forest, Flux footprint, Sustainable forestry.

Contents

1. Introduction

It is today common knowledge that trees take up and store CO_2 , which counteracts the ongoing climate changes, and when said trees are cut down for various kinds of usage, fewer and fewer individuals remain to take up the CO_2 that we humans, one of multiple sources, emit (Chapin et al., 2011). One of the most well-known examples hereof is the Amazon deforestation where hundreds of thousands ha of forest have been cut down for feed crops, logging and mining (Graham, 2022). Not only does the harvesting process release CO_2 (Smith et al., 2021) but a more long term factor is that the deforested area no longer acts as the carbon sink it once was, and it takes years, if not decades, for the forest to once again gain a positive net ecosystem productivity (NEP) (Håkansson, 2022; Lindroth, 2023; Peichl et al., 2022). Both of these factors result in an increase of CO_2 in the atmosphere, which has consequences for both humans and ecosystems worldwide (Chapin et al., 2011; IPCC, 2022; Smith et al., 2021) if it is done on a large scale as it is today. However, the magnitude of the impact local forest clear-cutting has seems to not be as well known by the general public. This might or might not be due to a lack of *local* consequences of changing CO_2 flux, but the importance of changing global CO_2 fluxes resulting from forest clear-cutting on a bigger scale would be further highlighted if a change in these fluxes is observable on a small scale. If it is not observable however, then this would indicate that deforestation could potentially be done sustainably on a small scale. It has already been suggested by Lindroth et al. (2018), that selective thinning of this hemiboreal forest, that is leaving understory vegetation and only cutting down select trees, might be a way to harvest trees while sustaining the forests' annual net ecosystem productivity (NEP). Furthermore, another study conducted near this site by Vestin et al. (2022) suggests that harvesting the tree stumps does not increase CO_2 emission significantly compared to only harvesting the trees for their trunks. That is, there is potentially a way to harvest forests sustainably from a CO_2 flux perspective.

When CO_2 uptake and emission from forests, or any other land use type, is measured, it is the so-called CO_2 flux which is being gauged, and depending on the atmospheric conditions the CO_2 may originate from different geographical areas through time. Say, if there is a campfire nearby the observation tower, the CO_2 from the burning wood will only be registered by the sensor if the wind blows in the right direction. If the CO_2 from the fire is recorded by the sensor, the fire is within the observation tower's *flux footprint*. As one might expect, wind direction is not the only factor determining whether a given point on the ground is part of a tower's flux footprint. Surface roughness, atmospheric turbulence as well as the height above the vegetation at which the instrument is installed on the tower also influence a flux footprints areal extent (Vesala et al., 2008).

1.1 Research questions and hypotheses

In this paper the immediate impact on CO_2 flux caused by deforestation was studied on a local scale. In particular, two research questions were formulated as follows: How does flux data measured over a hemiboreal forest vary spatially and temporally? How do these measurements vary between two sequential years differentiated by a total clear cut? The hypotheses were that the measured fluxes would differ throughout the measurement period from January to June, and that the magnitude of these fluxes would display only minor differences spatially. Furthermore, it was hypothesised that clear-cutting would have a significant impact on the CO_2 flux readings. More specifically, it was believed to result in an increased release of CO_2, and that this increase would be uniform in all directions from the observation tower. A decrease in NEP was expected since similar tendencies have previously been observed by Vestin et al. (2020), Lindroth et al. (2018) and Amiro et al. (2010), and a more or less spatially uniform impact by the clear-cutting was expected due to the fact that the whole forest was cut down in a uniform manner. It has, however, been observed that some areas at the study site in Norunda are prone to waterlogging and can in some places have a high water table (Lindroth et al., 2018; Sundqvist et al., 2014) which can alter the CO_2 producing properties of the soil (Luo & Zhou, 2006).

1.2 Theoretical background

Trees and other types of green plants perform photosynthesis throughout their life cycle (Hess & McKnight, 2017). As this happens, CO_2 and water is taken up by the plant which is turned into glucose and O_2 catalysed by sunlight (Chapin et al., 2011). Plants also respire CO_2 and release water through their stomata. Soils release CO_2 as a result of decomposing organic matter and belowground plant respiration (Chapin et al., 2011). This balance can be expressed as an equality as shown here.

$$NEP = GPP - (R_{auto} + R_{het}) \qquad \textbf{\textit{eq. (1)}}$$

GPP describes the gross production of the ecosystem, and R denotes the respiration (release of CO_2) by plants (R_{auto}) and soil (R_{het}) respectively. NEP describes the net productivity of the whole ecosystem and is positive when there is a net *uptake* of CO_2 (Chapin et al., 2011)). As the forest in Norunda is clear-cut, the productive trees and plants are cut down, and some removed with others being left for decomposition. This leads to a drop in GPP meaning less CO_2 being taken up by the forest, and an increase of R_{het} as the dead understory and branches decompose (Chapin et al., 2011). Autotrophic respiration stops as the trees are logged as the process of photosynthesis is halted. This all leads to a decrease of NEP, the magnitude of which depends on the extent of the disturbance, which in this case extends to the whole forested area. Finding a significant decrease of NEP was therefore expected.

This balance of CO_2 uptake and release from a forest (NEP) is typically positive for the most of the forest's life, and even as they transit into the old-growth phase (Luyssaert et al., 2008). However, when a major disturbance occurs, such as a forest fire or a clear-cutting event, the forest has to regenerate in order to keep up with the release of CO_2 from all the decomposing organic matter which is typically left on the ground after such an event (Luyssaert et al., 2008). Before the ecosystem reaches a net uptake of CO_2, the forest has to have a sufficient amount of living vegetation, which can take multiple years. This makes the clear-cut area a carbon source than it was before (Luyssaert et al., 2008; Peichl et al., 2022).

The atmospheric turbulence, wind speed and -direction varies throughout the day, causing the source area from which the tower measures CO_2 flux (*flux footprint*) to change (Chu et al., 2021). Other relevant attributing factors are surface roughness and the instrument's height above the canopies. Modelling this property therefore has its challenges, and even as a user of this kind of model, some decisions have to be made. One of which is the required flux percentage captured, that is deciding how representative the footprint has to be. In accordance with mathematical theory, the entire flux footprint area is infinitely large, so defining a percentage threshold of flux influence (e.g. 50% or 70%) is a necessity (Vesala et al., 2008).

The above-mentioned factors would lead to complications if footprint modelling were to be performed during the clear-cutting event, due to the changing surface roughness and canopy height (illustrated in a drone image in Fig. 2). Because of this, the comparison between fluxes was done between measurements from before the clear-cutting had commenced and from after was completely clear-cut.

2. Methodology

2.1 Study site

The chosen site to conduct the study is an 800 x 800 metre area at the Norunda Research Station which has since 2014 been part of the Swedish research agency Integrated Carbon Observation System (ICOS). The station is located 30 km north of the city of Uppsala, 100 km north north-west of the Swedish capital, Stockholm (see Fig. 1). Since its establishment in 1994 it has been used for studying fluxes of trace gases, mainly CO_2 and CH_4 (methane), as well as the exchange of water and energy, and recently, atmospheric concentrations of biogenic volatile organic compounds (BVOCs). The primary methods used for measuring these on site are gradient and eddy covariance analysis (*ICOS*, n.d.).

The climate in the region is mild, with monthly average temperatures reaching just below 0℃ in winter and peaking around 18℃ in summer. The area gets around 565 mm of precipitation in a year (based on data from between 1991 and 2020), and the wind tends to blow from the south-west typically blowing at a speed between 2 and 4 m/s (*ICOS*, n.d.).

The Station itself consists of a 102 m tall measurement tower on which the measurement equipment is mounted at three heights; 36, 58 and 100 m. The data which were used in this case concerned CO_2 flux, as well as atmospheric conditions such as wind speed and -direction, at the height of 36 metres.

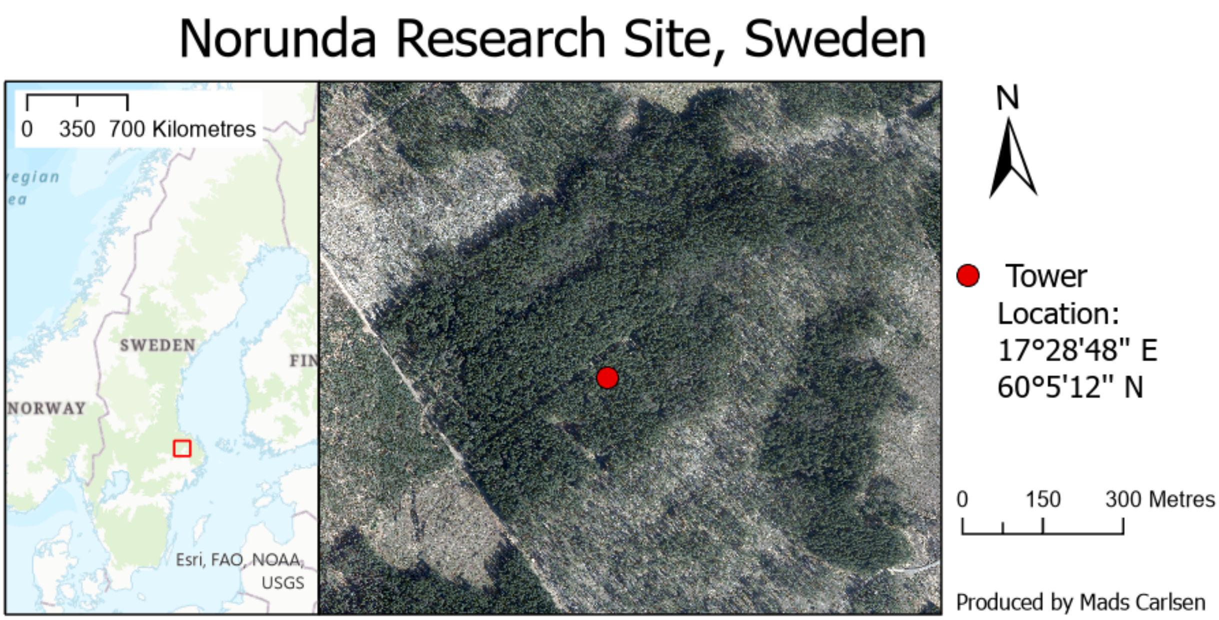

Figure 1: Showing the research site and its spatial extent before the clear-cutting commenced, with the tower indicated by the red dot. Please note that the red box in the map to the left is not representative of the aerial photograph's areal extent, but only serves the purpose of indicating where the site is located. Aerial photo delivered by Lantmäteriet (2022).

Norunda Research Site, Sweden

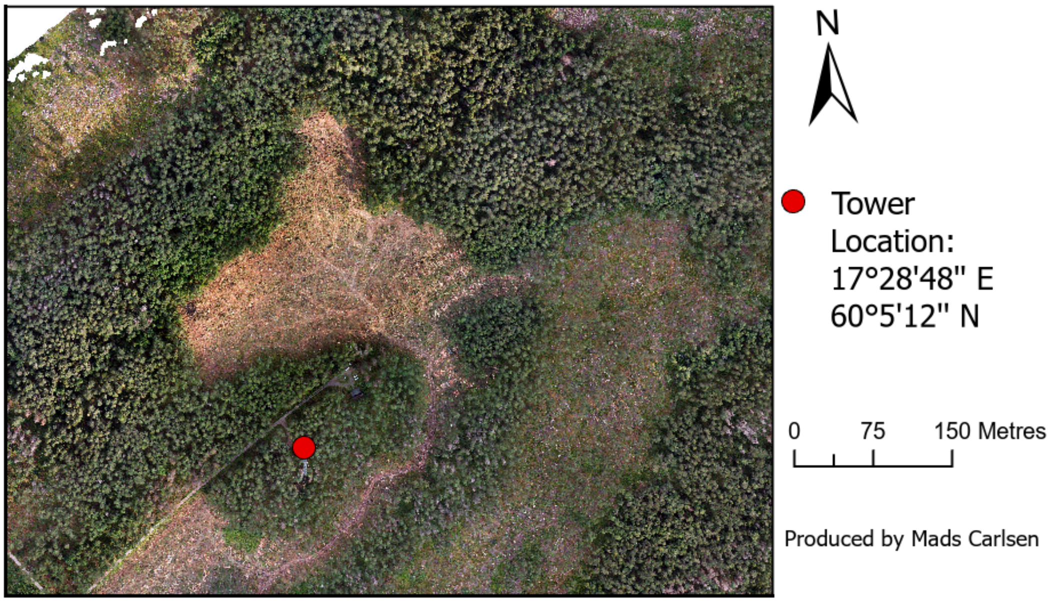

Figure 2: Showing the research site during the clear-cutting, with the tower indicated by the red dot. Please note that this figure does <u>*not*</u> *depict the final result of the clear-cutting. Aerial photo delivered by Lantmäteriet (2022), dissemination permit: LM2023/039813.*

The forest surrounding the tower is owned and managed by the common of the Norunda jurisdictional district (Norunda Härad), and has been managed for more than 200 years. Before the clear-cutting commenced, Scots Pine (Pinus sylvestris) and Norway Spruce (Picea abies) were the most common species in this local forest, with only a small percentage of deciduous trees. The logging of the forest started in July of 2022 and went on till autumn that year, where the trees and the understory in a 300 m radius of the tower were cut down. The logs were removed but treetops, branches and small trees were left on site (*ICOS*, n.d.).

2.2 Data and thresholds

This analysis was carried out using half-hourly gap filled data from 2022 and 2023 on CO_2 flux and footprint lengths measured with a sonic anemometer (Gill HS-50) and an infrared gas analyser (Licor Li-7200) (Mölder & Kljun, 2023) measured at this site. In both years the data used was from the first part of the year, from January 1st 12am (00:00) to June 14th 12am since this was the extent of the 2023 data, as well as it being assumed to be a sufficient amount of data.

A footprint distance threshold of 70% was chosen as this was thought to be fairly representative as well as having a manageable spatial extent. Additionally, modelling the footprints' 2-dimensional extent was considered too extensive and unnecessary in this particular study, so only the 1D footprint's lateral extent was considered. Since the average vegetation height and surface roughness changes from before to after the clear-cutting event, the 70% footprint distances were recalculated considering these newly changed parameters.

2.3 Flux analysis

The half-hourly CO_2 flux data were to be sorted into eight groups/sectors determined by the wind-direction. This would be done to inspect whether there was a significant difference to be found between measurements originating from different parts of the area. However, far from all the flux measurements originated from an area only within the forest's/clear-cut's proximity. This was evident from the 70% distances, which describe the length of the footprint from which 70% of the recorded CO_2 flux is gauged. Therefore, a maximum distance of 300 metres from the tower was settled upon, where 70% of the fluxes originating from a source area longer than 300 metres were discarded.

After having limited the extent of the flux source area, the values were sorted into eight sectors depending on the measurement's wind direction. These sectors were all 45° wide and spanned the intervals [0°- 45°), [45°- 90°), …, [315°- 360°) respectively (see Fig. 3). The data were now sorted into the eight sectors, each with a 70% distance no greater than 300 metres away from the tower. This sorting of the flux data was performed on the datasets from both 2022 and 2023.

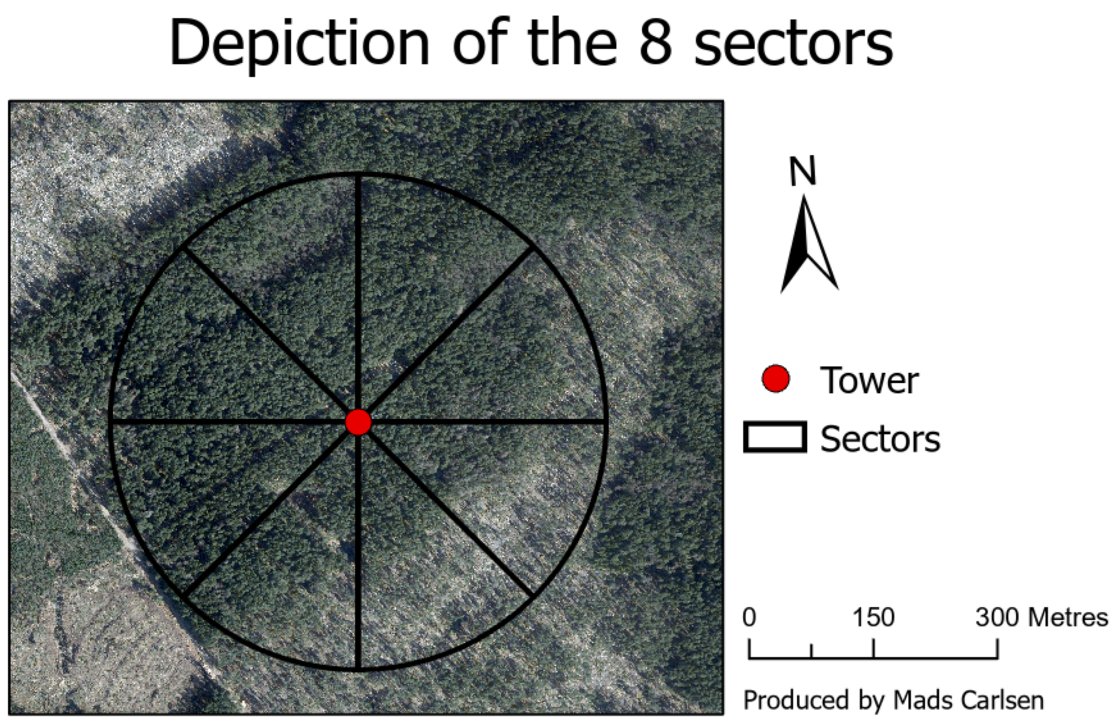

Figure 3: Displaying the separation of the study area into eight 45 degree wide sectors. The circle is 300 metres in radius.

The daily flux averages throughout the measurement period were found, initially disregarding the eitgh sectors. These averages were then plotted as a time series to inspect the evolution of fluxes throughout the first half of the year. This was done for both years in order to compare the way clear-cutting influences this half-yearly evolution (see Fig. 4). After this, the average CO_2 flux measured from each sector throughout the whole period was calculated. These sector-wise flux means were then plotted in a bar chart, along with their individual 1st and 3rd quartiles. This was done to visualise the spatial as well as temporal change in CO_2 flux before and after the clear-cutting event. The quartiles were implemented to display any seasonal variability within the data. They illustrate below which point the lower 25% of the readings were situated (1st quartile) and above which point the upper 25% (3rd quartile) were situated.

3. Results

Having conducted the analysis described above, the daily average flux values from both years were plotted as a time series for interpretation and comparison, as displayed below.

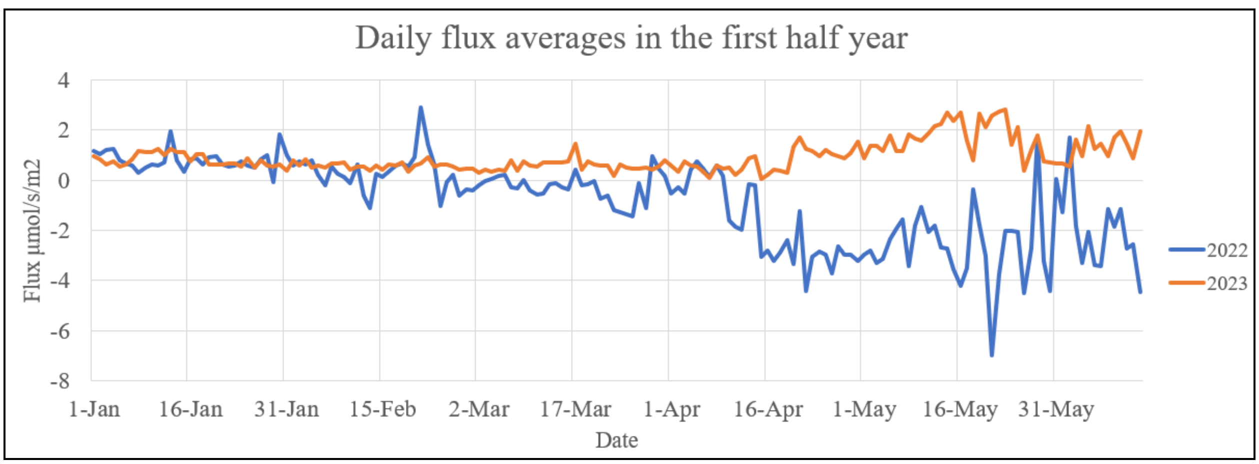

Figure 4: Showing daily average flux throughout the first half of the years 2022 and 2023 from January 1st till June 14th.

As it can be seen in fig. 4, the half annual trend of the forest's CO_2 flux (blue line - 2022) is generally downward. This was expected since the transition from winter to summer should result in the plants becoming more productive and thus take up more CO_2. Contrasting this, the year 2023 displayed a similar trend in the winter period, but remained stable until the end of April when the soil became more active, after which a higher flux of CO_2 was observed. A net release of CO_2 was observed in this period of time since the process of breaking down dead plant material is catalysed by the warmer weather. Furthermore, in 2023 there is little to no vegetation left to absorb the CO_2 being released, which is believed to be a major contributor to the difference observed between the years.

The eight sector means then were found and plotted in for visual interpretation (see Fig. 5). Although none of the means from the year 2022 are positive, and vice versa for the year 2023, the whiskers on the plot show that the data series do have a rather high variability. All whiskers from the 2022 series even extend beyond 0 into the positive side (net emissions of CO2), and some beyond the reach of the whiskers from 2023 (in Sectors 1, 2, 4, 7 and 8). This was most likely due to the weather conditions in the winter and early spring months of 2022, resulting in NEP properties very similar to what was found in those months in 2023.

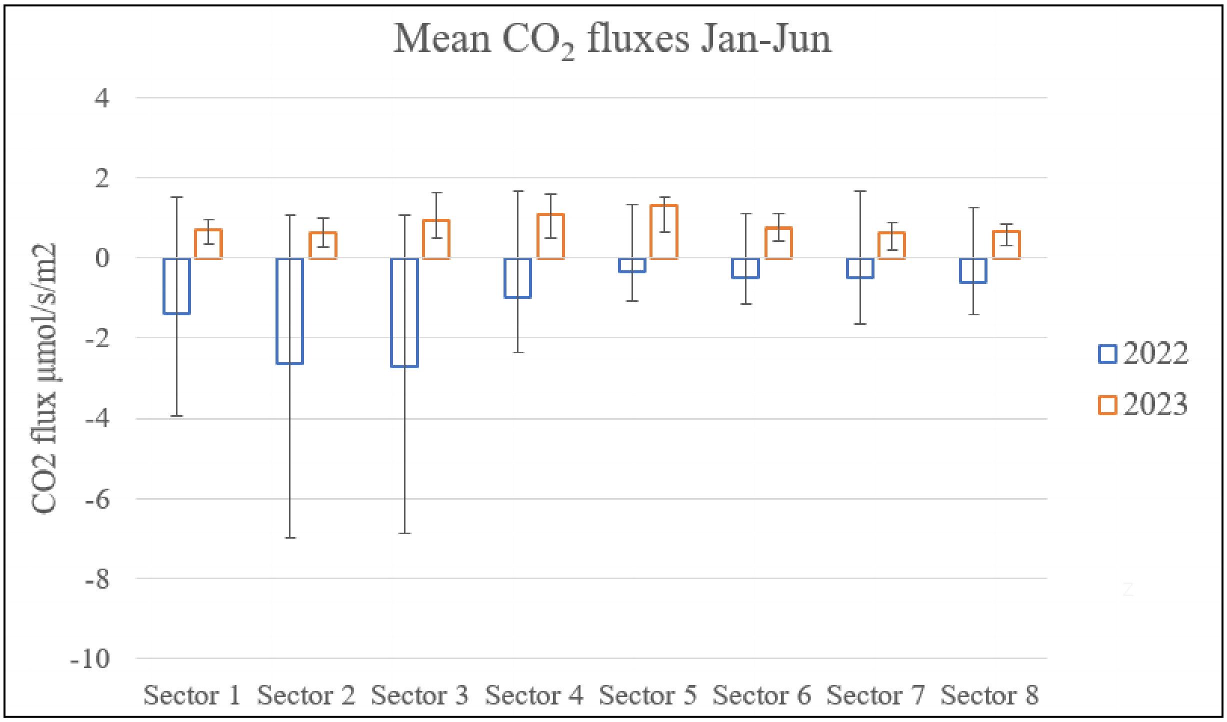

Figure 5: Showing the mean CO_2 fluxes in each sector in the period from January 1st to June 14th, as well as the 1st (in the negative direction) and 3rd (in the positive direction) quartiles illustrated by the whiskers.

The two years display different trends in CO_2 flux, but the presence of trees and understory vegetation does seemingly introduce a significant element of variability. The variability of the datasets, particularly the one from 2022, is further illustrated by the following histograms showing the data distribution of two sectors throughout the two half years.

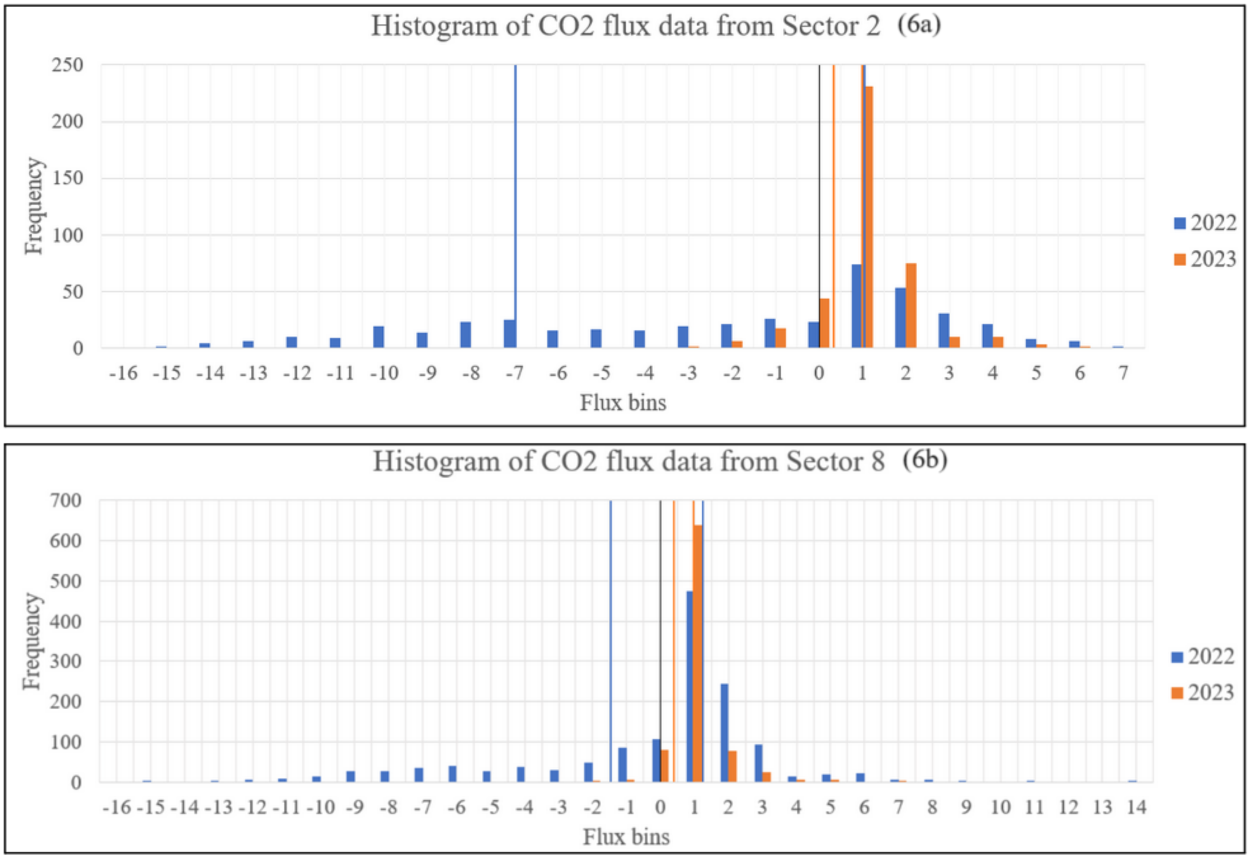

Figure 6a & b: Histograms showing the spread of data values captured from Sectors 2 and 8 respectively, comparing the years 2022 and 2023. The bins are of the unit μmol/s/m^2 as they describe intervals of flux. The slim blue and orange bars stretching from the top to the bottom illustrate the 1st (left most) and 3rd (right most) quartiles of each year. Please note the different x- and y-axes.

It can be seen in Fig 6a and b that there is a high variability in the measurements from 2022, whereas the variability is much lower in magnitude in 2023 after the forest has been cut down. This means that the average fluxes from each sector do not tell the whole story, and that the spread of the data is also noteworthy. This spread can also be seen in Table 1 below showing both the mean flux in each sector, the number of valid observations, as well as the standard deviations. As the colour scheme highlights, the standard deviations (square root of variance) were clearly higher in 2022, where the highest were seen in Sectors 2 (see. Fig 6a) and 3, both reaching beyond a standard deviation of 5. This variation (illustrated by the whiskers) does however only vary significantly in the negative direction across all eight sectors. In the positive direction, the 2022 3rd quartiles differed by at most 0.59 μmol/s/m^2, whereas in the negative direction, the 1st quartiles differed by at most 5.87 μmol/s/m^2. Since all sectors contain data from all six months included in this analysis the variation in the positive direction is likely due to winter conditions.

Table 1: Showing the average flux from each sector for 2022 and 2023 as well as their standard deviations and the number of valid measurements considered. The colours represent the magnitude and relative "positivity" of the fluxes and standard deviations. The blue bars under the number of readings help illustrate the fairly wide distribution of the number of readings.

	Flux means [µmol/m2/s]		Number of readings		Standard Deviation	
	2022	**2023**	**2022**	**2023**	**2022**	**2023**
Sector 1	-1.40	0.72	655	260	4.20092	0.98322
Sector 2	-2.65	0.63	377	176	5.01664	1.08399
Sector 3	-2.71	0.94	250	109	5.6041	1.18484
Sector 4	-0.99	1.07	328	369	4.82175	1.3678
Sector 5	-0.35	1.30	903	362	3.4609	1.38608
Sector 6	-0.50	0.73	1714	718	3.59677	0.79456
Sector 7	-0.51	0.62	1002	161	3.77065	0.88008
Sector 8	-0.62	0.65	1281	311	3.57936	0.78192

When the growing season arrives and the trees should theoretically be at their most productive, it is seemingly, as shown in Fig. 5, only Sectors 1, 2 and 3 which display a drastically higher NEP when the forest was present. Sector 3 proved to be the sector with the lowest mean CO_2 flux (highest mean NEP), but Sector 2 followed closely, with a mean only 0.06 µmol/s/m^2 higher. Furthermore, Sector 2 did have a slightly lower 1st quartile (seen in Fig. 5), but since there was no significant variation to be found between these two sectors they seemed to be equally productive. This means that the most productive quadrant in 2022 was found to be between 45°-135°. Sectors 1 and 4 had similar flux means, but Sector 1 has a much lower 1st quartile, indicating that this sector was likely to be more productive than Sector 4.

Note how the orange quartile lines in both figure 6a and b seem to not capture the values up till fluxes of 1, but this is due to the layout of the diagram. The bars occurring at flux bin 1 capture all fluxes between 0 and 1 µmol/s/m^2, which is where more than 50% of the measurements were situated in both cases. This is why the 1st and 3rd quartile lines are situated as they are - simply due to the x-axes' "coarse" resolution. If the x-axes were of a 0.5 or 0.25 µmol/s/m^2 resolution this would be more apparent, but this would make a comparison between the two years harder to interpret.

4. Discussion

4.1 Interpretation of results

Considering the science of CO_2 fluxes from forests (photosynthesis vs. respiration) it was expected that the productivity of the forest would increase as winter turns to spring and eventually to summer. This did show in the results which also display the unevenness of the CO_2 flux while the forest still stood. Furthermore, a distinct difference in average CO_2 flux was expected to be found between the two years. One thing which seemed to be significantly impacted by the clear-cutting event was the variability of the CO_2 flux, which decreased greatly from 2022 to 2023 after the forest was harvested. Along with this, all means across the 8 sectors were negative in 2022 and all turned positive in 2023 which does seem to agree with what Vestin et al. (2020), Lindroth et al. (2018) and Amiro (2010) have found previously - that clear-cutting a forest or forested patch decreases the NEP on a short term basis. The spread in the 2022 data illustrates the dynamic NEP of the forest throughout the first half of the year, which is partially explained by seasonal variability of NPP due to changing temperatures and incoming PAR. Another interesting observation is how much the 2022 means vary across the eight sectors, as well as the variance of the 1st quartiles that same year. The seasonal variation is apparent from the large variance within each sector in 2022, and if all sectors were to perform similarly in terms of NEP the 1st and 3rd quartiles should have similar spans across all sectors, and the means should be equally uniform. This was however not the case, showing clear variation between sectors, suggesting that there is one or more unevenly distributed CO_2 flux controlling factors at play. Since saturated soil can limit CO_2 production from heterotrophic respiration (Luo & Zhou, 2006) and the water table at Norunda has been observed to be shallow (Lindroth et al., 2018; Vestin et al., 2022), this might be an important controlling factor when it comes to CO_2 fluxes at this site. These two sectors might be significantly wetter than the other six, both supplying plenty of water to the vegetation and lowering heterotrophic respiration. It would therefore be of interest to look into any possible spatial unevenly distributed properties of the soil which might have an impact on CO_2 production.

Another interesting aspect to look into would be the effect sorting data monthly would have on the variability within each sector. Additionally, potentially lower variability would not be the only benefit of sorting differently; reducing the number of sorting categories from eight sectors to five or six months, each month would increase the bin size. That is, the fewer the bins/categories, the more data per bin/category which should lead to an even more accurate result. The reason this sector wise categorisation was implemented was to illustrate the very uneven distribution of wind direction, but also to shine a light on whether there is a significant difference in measured NEP depending on which direction the source area lies in. There might be areas which are wetter than others, or areas with more dense vegetation which would likely influence the readings significantly.

4.2 Sources of error and considerations

One possible source of uncertainty could be the sorting of data according to wind direction when the analysis was carried out. This was done assuming that all six months were more or less equally represented in each sector, such that one sector did not only contain data from e.g. spring and summer. Upon a glance over the data distributed into the eight groups all six months did seem to be represented more or less equally, leading to the assumption that the spread of the data would differ insignificantly between sectors. However, whether the spread of data was equal or not, it was present and obscures the truth to some extent. Alternatively, sorting the data according to month would be an interesting aspect to inspect, but was only considered in the final phase of this project and therefore left for a future study.

As previously mentioned, this study utilises only the lateral extent of the flux source area, which could be viewed as single-directional footprints. Compared to using a 2-dimensional footprint this only gives a shallow insight into the spatial extent of the flux source area. It would therefore be necessary to employ 2-dimensional footprints if a more thorough analysis were to be conducted. These footprints can be modelled but require data on many specific factors such as wind direction, atmospheric turbulence, vegetation height and surface roughness. This was not considered necessary in order to answer this specific aim, but if the more exact extent of the source area is needed this method should be reconsidered.

Another potential source of inaccuracy is the fact that the data utilised was both modelled and gap filled. This means that in order to accommodate for missing flux values these were filled using values measured at very similar conditions. Furthermore, the lateral extent of the footprints were modelled based on physical properties like surface roughness, which are difficult to accurately estimate. This introduces potential inaccuracies as a tradeoff for more usable data, which in turn is meant to improve the results' accuracy. However, since this technique is used commonly it must be because it is a beneficial tradeoff, meaning that this aspect of the data analysis is likely not an error source to be concerned with.

Considering these sources of error is inevitably done with the results in mind - they are important whether the hypothesis is confirmed or not. When the hypothesis is confirmed, one might be inclined to overlook error sources, whereas when the hypothesis is firmly rejected, one might scrutinise one's work more thoroughly. This human tendency contradicts the fact that reality might not be the way it's hypothesised to be. That is why a future study must be unbiased and not be in favour of proving the hypothesis, but rather attempting to falsify it.

4.3 Future studies

A future study which could serve well as an extension of this one could be to examine the forest floor conditions in this area around the tower. The purpose of this would be to locate areas with different CO_2 emitting or -limiting properties causing differences in mean CO_2 flux, such as areas prone to water logging. As mentioned, it has been reported that this area is prone to waterlogging and has areas with a high water table (Lindroth et al., 2018; Sundqvist et al., 2014; Vestin et al., 2022). This could potentially help clarify why the means differ between sectors as much as they do, but more importantly help understand what makes a forest a good carbon sink.

Another continuation of this study could, as previously mentioned, be of a similar kind as this one, only then sorting the data according to month rather than wind direction. Now that the analysis has been conducted considering wind direction, and thereby looking into the general source area of the flux, trying to lower the data variation by taking seasonal variability into account would be an interesting next step. This would indirectly take factors like incoming PAR, soil- and air temperature into account to some extent, which could improve the results' accuracy.

Finally, this study did only look at the immediate effect of clear-cutting, comparing flux data from within the five and a half months prior to the cutting to flux data measured between three to eight months after the cutting ended. It is therefore advisable to continue studying the forest as it regrows in order to gain a view of the situation on a greater scale timewise, which is matter for a broader future study.

4.4 Perspectivation

A coniferous forest was the subject of this study, but whether a deciduous forest would respond similarly to how a coniferous forest would is potentially a subject for further analysis. Since deciduous trees have to regrow their leaves every spring/summer one could argue that they would be more productive than conifers in this part of the year (though they do produce more compostable litter later in the year), although many other factors determine a tree's productivity (Chapin et al., 2011). If this is the case, conducting a similar type of analysis on deciduous forests could potentially yield different results from what was found in this and similar studies. This of course depends on the time of year, but might either way be relevant in the near future. As the climate changes, deciduous trees might find a suitable habitat farther and farther polewards and start migrating, a trend which has been documented previously (Boisvert‐Marsh & Blois, 2021). This means that a larger and larger area world-wide, especially in the northern hemisphere, could potentially be occupied by deciduous forest. Today the world is already covered by large areas of deciduous forest which in some places are being clear-cut. This means that if this type of forest potentially responds differently than a conifer forest, it would be valuable to know how deciduous forests respond to tinning and clear-cutting. Lindroth (2018) found strong indications that harvesting a hemiboreal forest by thinning it instead of clear-cutting it could be a sustainable management method, maintaining the NEP over time. Furthermore, if this is the case with deciduous forests, knowing the magnitude of the maximum thinning percentage of a given forest would allow wood production for harvesting to continue more sustainably, both in deciduous and coniferous forests. Furthermore, research by Vestin et al. (2022) in Norunda suggests that stump harvesting does not have a substantial impact on the CO_2 fluxes compared with clear-cutting and soil scarification. They do note that further research is necessary in order to draw a solid conclusion, but if it is the case, the yield of thinning a forest sustainably could potentially be greater when harvesting the stumps as well.

As previously mentioned, a forest does not regain its carbon sink properties right away after a disturbance, but requires multiple years to regain this property. One estimate said it takes less than 10 years for a south Swedish boreal forest to regain neutrality (CB; Carbon Balance), that is the point in time where a forest's annual NEP becomes positive (Peichl et al., 2022). Peichl et al. (2022) further estimated that a period of 18 years is required for such a forest to balance out the CO_2 emitted in its first years prior to becoming a carbon sink (CCP; Carbon Compensation Point). Peichl et al. (2022) finally reach an approximation of 138 years for optimum rotation (ORP; Optimum Rotation Period), which would result in 86.5 tonnes of sequestered carbon per hectare every rotation. Other slightly newer estimates point towards a CB period of 16 years and reaching CCP after 39 years, with an optimum rotation period of 155 years (Lindroth, 2023). Lindroth (2023) further summarises estimates reached using different models to approach this issue, reaching CB periods of 8-12 years, CCP of 18-27 years, and ORP 70-100 years and compares this to what others (Grelle et al., 2023; Peichl et al., 2022) have previously found. Although these results differ substantially, they do supply each other in creating a reliable method to reach more accurate estimates of when a forest becomes a net carbon sink, carbon neutral, and when harvesting from a forest is most beneficial from a carbon budget perspective. Estimating this accurately could have large potential in combating the rising amount of CO_2 in the atmosphere by helping setting guidelines as to how to cultivate the optimal carbon sequestering forests. Although this study does not explain how the forest will develop next decades, it does confirm what Håkansson (2022), Vestin et al. (2020), Lindroth et al. (2018) and Amiro et al. (2010) observed/described about the immediate decrease in NEP. One could hypothesise that the now clear-cut forest in Norunda will regrow to a CB point in about a decade, and keeping in mind what Lindroth et al. (2018) found in Norunda, observing the CO_2 fluxes in the next years could give valuable insight into how sustainable this type of forestry is on this type of forest.

5. Conclusion

It has previously been observed that clear-cuts of a forest results in a direct net release of CO_2 (Amiro et al., 2010; Håkansson, 2022; Lindroth, 2023; Vestin et al., 2020). A generally lower NEP was observed in 2023 after the clear-cut compared to 2022 before the clear-cut, which agrees with the background theory and previous studies. It was hypothesised that the CO_2 fluxes from the hemiboreal forest would decrease as the temperature increased during the period from January to June. This was proved to be the case, although the measured fluxes did display a rather high variance. This is suspected to be caused by a combination of spatial variation in CO_2 consuming/-emitting properties (GPP contra R_{het}), due to differing soil water content, and wind direction. In this study wind direction was the variable chosen for sorting the data due to an interest in whether results would vary spatially. There was not much variation in the post clear-cut results, but the pre-clear-cutting data did show a wide spread within the sectors. Furthermore, the resulting flux means differed significantly more between sectors before clear-cutting than the means after the clear-cutting. This is thought to be caused by potentially differing water quantities in the soil, since water logging has been observed in this area previously, which is known to alter heterotrophic respiration. Aside from altering the soil's respiration, it would also mean that more water is readily available for plants to take up and use for photosynthesis further increasing the NEP.

The 1st quartile was observed to vary significantly between sectors before the clear-cut, which further suggests that seasonal variation is not the only factor influencing the forest's productivity. This was also speculated to be due to areas of the soil being more water saturated than others. Which specific factors in Norunda could be responsible for these variations could be relevant to look into because it clearly influences how well a forest takes up CO_2. This could become the purpose of a rising number of forests as climate change becomes a bigger and bigger issue. Therefore, determining how to make a forest as productive as possible could be of high importance in the near future.

Nevertheless, there was a clear difference in CO_2 fluxes between 2022, before the clearing, and in 2023, which means that small-scale forest clear-cutting does have an observable impact on the local CO_2 flux. This further highlights the fact that large scale deforestation has a more or less immediate effect *globally* many magnitudes greater than what is found in this and other small-scale studies. As the Scottish saying goes; "*Many a mickle makes a muckle"* meaning many small amounts accumulate and grow into one large amount. This does however seem to be mitigable in the long run according to Lindroth et al. (2018) and Vestin et al. (2020). They suggest that the right management can result in forestry with a smaller long-term impact on the atmospheric CO_2 levels.

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