General Comments:

This manuscript investigates the relationship between fire induced changes in ecosystem C and N stocks and climate in Sweden. The manuscript addresses relevant and important scientific questions related to the influence of climate on boreal forest fire C and N emissions and redistribution within an ecosystem. The novel dataset of field measurements along gradients in climate is valuable to the scientific community. However, the methods are unclear in several places, and the excessive use of abbreviations hinders both readability and comprehension. The
manuscript needs additional plots showing their raw data and model fits to aid in the interpretation of the methods and results. The relationships between boreal forest fire C and N emissions and precipitation, temperature, and soil moisture are a key finding in this study but are not strongly represented in the figures. Overall, the manuscript represents an important contribution to the scientific community, but it needs minor adjustments to make the overall presentation well-structured and clear.

(Response)

Thank you for the time taken to make these comments. They are both critical and helpful. In the following responses we aim to clarify the content and provide model fit diagrams where requested and possible. Our main results regard the pathways by which climate affects C and N losses by assessing several multiple regression models at a time. We therefore believe the path diagram figures to better represent these relationships than separately plotting individual multiple regression hyperplanes which would be difficult to interpret and also not be possible with more than 2 explanatory variables. All original data is provided as a supplement to the manuscript.

All author responses are labeled with the **(Response)** tag and colored blue to contrast the reviewer's original black (manuscript text) and red (reviewer comment) color coding.

Specific Comments:

Comment 1

Page 2, line 25: The predominant disturbance to this C balance is approximately centurial outbreaks of wildfire (Bond-Lamberty et al., 2007).

This sentence sounds like the author is suggesting the carbon balance in boreal forests is predominantly determined by wildfire outbreaks that occur once every century. While the return interval of fire in a local area of the boreal forest is centurial, boreal forest fires occur every year. I suggest re-wording this sentence for clarity.

(Response)

We agree that this is unclear, so we have modified the text to the following:

"The predominant disturbance to this C balance in the boreal region are yearly outbreaks of wildfires which reoccur in individual forest stands at the centurial timescale (Bond-Lamberty et al., 2007)."

Comment 2

Page 2, line 30: Along with a changing climate, these effects have the power to influence community structure and process rates shaping future forest C and N cycles on decadal to centurial timescales.

It is unclear what "process rates" the author is referring to.

(Response)

We agree this is vague, so we now modify the sentence to specifically refer to some key processes of interest:

"Along with a changing climate, these effects have the power to influence community structure and processes such as soil respiration and nutrient cycling which can shape future forest C and N cycles on decadal to centurial timescales (Johnstone et al., 2020; Mekonnen et al., 2019)."

Comment 3

Page 2, line 31: Changing patterns of temperature and precipitation in recent decades have caused increases in frequency, intensity and size of fires with further amplification predicted in the future.

The author needs to specify if they are referring to fires globally or regionally (Eurasian boreal forest fires).

(Response)

Agreed, the modified text is:

"…size of fires across the global boreal region with further amplification..."

Comment 4

Page 2, line 40: These factors dictate fuel availability, a highly temporal measure of the proportion of total fuel that is readily combustible.

I'm not sure what a "highly temporal measure" means. If the author is referring to the high temporal variability in available fuel, the phrase could be changed to "a highly temporally variable measure."

(Response)

Agreed, this could be worded better. It was meant that fuel availability is rapidly fluctuating in response to environmental conditions. Suggested text:

"These factors control fuel availability, a measure of the instantaneous proportion of total fuel that is readily combustible."

Comment 5

Page 2, line 45: Spatial arrangement of overstory fuel loads has also been shown to have a strong impact on fire severity and intensity and distinguishes the boreal wildfire regimes of the North American and Eurasian continents (Rogers et al., 2015).

The major difference in the boreal wildfire regimes in North America and Eurasia is the dominant tree species and corresponding ecosystem characteristics. The spatial arrangement of overstory fuels certainly contributes to crown fire behavior in the North American boreal forest, but the underlying reason for the difference is tree species. See Rogers et al., 2015.

(Response)

We would consider the underlying factors controlling fire behavior (e.g. presence/absence of crown fire) to be the physical properties of the trees and that species composition is just a tendency towards sets of those physical traits. Because our plots are almost completely pine dominant we only test for the effects on fire severity of physical variation instead of species variation. We can modify the text to acknowledge these different perspectives.

“Composition of tree species, with their associated fire adaptation strategies, has also been shown to have a strong impact on fire severity and intensity and distinguishes the boreal wildfire regimes of the North American and Eurasian continents (Rogers et al., 2015).”

Comment 6

Page 2, line 56: While total area burned may be evaluated through remote sensing (Ruiz et al., 2012), per area emissions are generally derived from labor intensive field sampling which are extrapolated to the larger scale either directly or through weighting by poorly constrained free parameters such as total fuel load (French et al., 2004; Soja et al., 2004). This field sampling has been regionally limited and biased towards a few high intensity burn complexes in North America which may in turn bias global emission estimates (van Leeuwen 60 et al., 2014).

The authors describe the commonly called “bottom-up” approach to calculate emissions, but fail to address alternative methods to calculate emissions, such as a “top-down” based approach (Ichoku and Ellison et al., 2014). Carbon emissions per unit area are calculated using a bottom-up approach as the product of fuel loading, combustion completeness and the carbon content of fuel. While some fire emissions inventories do rely on extrapolated field measurements to estimate one or more of the variables needed in the bottom-up approach, many rely on remote sensing observations (van der Werf et al., 2017; Veraverbeke et al., 2015).

(Response)

We acknowledge that different methods can be sorted into the broad categories of top-down and bottom-up. The manuscript has a dual role in comparing cross-regional C emission estimates as well as assessing drivers of local meter-scale C stock change in ecosystems. We retain focus on methodology that satisfies both of these research aims and this paragraph can be rephrased to (i) acknowledge and summarize larger-scale approaches and (ii) emphasize that spatial coverage of these fine scale measurements are lacking. Suggested text:

"Boreal C emissions due to a single wildfire can be calculated by multiplying total area burned by estimates of C emissions per area (French et al., 2004). While total area burned may be evaluated directly through remote sensing (Ruiz et al., 2012), per area C emissions are generally derived from labor intensive field sampling which is extrapolated to the larger scale either directly or through weighting by remotely sensed data (e.g. topography, vegetation cover) or poorly constrained free parameters such as total fuel load (French et al., 2004; Soja et al., 2004; van der Werf et al., 2017; Veraverbeke et al., 2015; Kaiseret al., 2012). This field sampling has been regionally limited and biased towards a few high intensity burn complexes in North America which may in turn bias global emission estimates (van Leeuwen et al., 2014; Akagi et al., 2011). For example, the Eurasian boreal region is dominated by relatively fire resistant overstory vegetation that avoids excessive heating by promoting lower intensity ground and surface fires than that in boreal North America, which is more prone to spread rapid flaming combustion throughout the canopy (Rogers et al., 2015; de Groot et al., 2013a). C loss in a group of Siberian boreal forest surface fires was found to be 0.88 kg C m^{-2}(Ivanova et al., 2011) which is about a quarter of what is typical in North American wildfire (3.3 kg C m^{-2}) (Boby et al., 2010; Walker et al., 2020) and about one fifth of an extreme wildfire in Fennoscandia (4.5 kg C m^{-2}) Granath et al. (2021). Although Eurasia contains over 70% of the boreal global land area (de Groot et al.,2013a) and about 50% (20 Mha yr^{-1}) of its yearly burnt area (Rogers et al., 2015), methodologies for estimating global and regional C emissions are severely lacking ground validation and meter scale assessments of drivers of C loss variability from this region (van der Werf et al., 2017; Kaiser et al., 2012)"

Comment 7

The methods section is missing a detailed description of fire severity in each of the 50 burnt plots. This omittance (and missing subsequent discussion) incumbers the interpretation of the results. The manuscript would also greatly benefit from the inclusion of an overview of the ecosystems sampled (by dominant tree species, for example) in each of the burnt plots. A histogram showing fire severity and ecosystem type could be helpful.

(Response)

Our ecosystems were mostly pine dominant, upland forests and can be considered a single ecosystem type. We agree this is essential background knowledge and have added an additional section in the results section to address your comment:

"3.1 Survey of burnt plot vegetation

The 50 burn plot overstories were largely pine dominant with a percentage of spruce stems between 25-50% in 5 plots, between 50-75% in 3 plots and 2 plots with greater than 75%. Birch stems were less than 25% in 44 plots and between 25-50% in 6 plots, of which only 1 of the 6 was spruce dominant. All plots showed visible charring of tree boles though only 3 plots had greater than 1% plot wide canopy blackening. These plots were pine dominant with 2 having less than 1% spruce while the other had 6 spruce of the 27 stems within the sampled area. Prefire aboveground overstory C and N were estimated as4.46 ± 0.738 kg $m^{-2}$and 0.0385 ± 0.00621 kg m^{-2}, respectively, with 5.31% of C (0.237 ± 0.0321 kg m^{-2}) and 12.3%8of N (0.00474 ± 0.000641 kg m^{-2}) coming from pine and spruce needles. The 50 burnt plots had a large percentage tree mortality (45.0 ± 8.76%) compared to control (4.21 ± 1.63%). Total C and N loss, as well as char layer mass, was not correlated to canopy browning, blackening nor increased mortality in burnt plots relative to control.

Understory coverage was reduced to 10.2 ± 5.15% of its estimated prefire values. This laid bare the surface layer of charred material present in all plots. This layer was conglomerated and easily separable from lower layers and new litter additions which were mostly needles. Upon breaking apart the layer, it was found to be completely blackened throughout."

Comment 8

Page 4, line 100: Sentinel-2 infrared imagery taken during the time of fire assisted in delineating the exact locations of burnt plots by placing them where there had been a strong and consistent infrared signal that was well within the mapped final fire boundaries.

The method described here should be more quantitative. How was a "strong and consistent" infrared signal determined?

(Response)

True, this is unspecific. Our highest goal was to ensure good pair plot matching which we accomplished with a relatively objective and quantitative series of filters. We aimed to then have burnt plots close to the highest intensity pixels within the burn scar, for which we used the sentinel imagery. This was done to encourage sampling within the more developed parts of the fire rather than selecting plots only suffering heating along its periphery but not to quantiatvely compare active fire intensity across burnt plots. Suggested change:

"Sentinel-2 infrared imagery was used to locate planned burnt plots near pixels showing the highest intensity within the mapped final burn scar perimeter. This gave greater certainty the plots experienced a more developed fire effect rather than peripheral heating alone."

Comment 9

Page 4, line 112: Due to their documented effects on emissions, long and short term approximations of moisture were introduced as exogenous variables to models in order to test the ability of the study design to isolate variation in C and N stock losses to the effects of climate. Long term moisture was represented by the TEM used in plot selection while short term moisture balance used the Standardized Precipitation-Evapotranspiration Index (SPEI) over the period January to June 2018 (i.e. spei06 2018-06) to capture the desiccation process leading up to the fire season.

The methods described here are vague. What models were these variables introduced to? Is the goal to isolate variation in C and N stock losses caused by variability in climate? Why is long term moisture determined using only soil moisture, but short-term moisture is quantified using precipitation and evapotranspiration? Where did the SPEI data come from? The reference is Unclear.

(Response)

We have now modified the text to provide more specific explanations. Yes, one key goal is to isolate the variation of fire severity with climate. Long term moisture is actually approximated by the two separate parts, the topo-edaphic component (TEM), and the climate components (MAT and MAP), but there is no long term data on evapotranspiration. SPEI came from “SPEIbase”, a global database of these values, now explicitly referenced. The following is suggested:

“Due to their documented effects on emissions, long and short term approximations of moisture were considered in this study. Long term moisture approximations were separated into a topo-edaphic component (TEM), and climatic component (MAP and MAT). Short term moisture was approximated over the first 6 months of 2018 using the Standardized Precipitation-Evapotranspiration Index (SPEI), which is calculated as the difference in precipitation and evapotranspiration in a given area, with data from the SPEIBase (Beguería et al., 2019) (i.e. spei06 2018-06) to capture the fuel desiccation process leading up to the fire season. SPEI was also compared to summer 2018 anomalies in temperature and precipitation, i.e. the difference in the 2018 June, July, and August average of these values from those during the same months averaged over the period from 1961 to 2017.”

Comment 10

Page 5, line 123: Each compartment was further sorted by weight into characteristic features to form compartment compositional variables (CCVs) which were used in regression to test for relationships between compartment composition and the quantity and quality of fuel loading as well as C and N loss.

More detail is needed. What type of regression was performed? How were the relationships quantified? What metrics were used? What exactly are compartment compositional variables and how were they defined? What is meant by “quality of fuel loading”? The methodology described here is ambiguous.

(Response)

This paragraph was meant to be an introduction to the concepts with more specifics to follow. By quality of fuel loading it was meant bulk density, C_R, N_R, and CCVs.. But we agree the vagueness at this point in the text can cause confusion. We will keep it more introductory and direct the reader to later text for more details with the following:

“Each compartment was further sorted by weight into sets of characteristic components, here called compartment compositional variables~(CCVs), which are to be specifically defined for each compartment in the following sections.”

The metrics and regressions are explained at line 195, with the text becoming more clear with the following change:

“All CCVs described in this text were assessed for their direct correlations to C and N stock losses as well as their ability to improve the multiple regression models presented in the results section by using both original variables and their principal components produced by the PCA method in statsmodels.”

Comment 11

Page 5, line 137: Duff samples were taken near the mineral cores by excavating four soil volumes (at least 400 cm3 each) and trimming the mineral and moss/litter layers off the bottom and top of the volumes respectively, then recording the final dimensions of the residual duff sample. Duff and mineral soils were kept frozen until

portions were freeze dried for separate analysis. Moss/litter samples were collected at approximately equal intervals along the soil profile transects in a 553 cm3 steel container with attention to preservation of the natural in situ volume. Char was similarly collected in a 112 cm3 container. On the upper surface of the char layer were small portions of dry, unburnt material, much of which may be new additions of litter to the forest floor. This material was discarded from the char collection and was not included in stock estimates.

More information is needed on the sample collection protocol. How was the size of the duff and moss/litter sample collected determined? What, if any, steps were taken to avoid duff compaction? Was volume measured in situ?

(Response)

Duff:

We now describe this protocol in more detail. A large block of soil (~30 * 30 cm ground area) was carefully dug out with a long spade. The mineral and moss/litter layers were trimmed off. Then the block was trimmed down extensively to remove the edges (several cm) that were assumed to have greatest disturbance. The final sample was trimmed to right angles with very sharp scissors. This sample was then measured in millimeters with a ruler to record volume in situ and stored. We took relatively large duff samples in attempts to reduce sampling error. We tried several methods of duff sampling (including coring) and this one seemed to avoid compaction associated with more conventional coring approaches

Moss/litter:

We now describe this protocol in more detail. We walked across the two transects bisecting each plot cutting squares of moss/litter layer with a sharp knife. The squares were carefully laid into a container of known volume until that container was full. We could estimate from the soil profile measurements how many samples we would need to take when walking across the transect. We therefore knew how much samples should be spaced to spread across the plot area. The sample count was always at least 1 from each of the 4 plot quadrants.

Suggested change:

“Duff samples were taken near the mineral cores by excavating four soil volumes, trimming the mineral and moss/litter layers off the bottom and top of the volumes respectively, and then gently cutting right angles with sharp scissors to measure the 3 dimensions in millimeters~(collected samples were at least 400~cm^3 each). Duff and mineral soils were kept frozen until portions were freeze dried for separate analysis. Moss/litter samples were collected by cutting squares, with attention to preservation of the natural in situ volume, until filling a 553~cm^3 steel container. Char was similarly collected in a 112~cm^3 container. At least one sample each of moss/litter and char were acquired from each plot quadrant, though more were taken at equal spacing along a transect to fill the containers if the layer was thin.”

Comment 12

Page 6, line 156: In all plots, understory was clearly distinguished from overstory by pronounced height differences and samples were taken from control plots by cutting all non-moss, non-tree plant material at the surface of the soil from within four 40 x 40 cm2 patches. Patches were chosen for their representativeness of plant abundance and composition for the portion of the plot that was vegetated, which was always all non bare rock surface.

The methodology described here is not quantitative. What defined “pronounced height differences”? What metrics were used to select patches, or were the choices purely subjective?

(Response)

Pronounced height differences meant that the understory was less than a meter tall and the overstory greater than several meters tall without much vegetation heights in between. But this was vague and can be changed.

We practiced established methods of ‘random’ or stratified sampling but found the small sample size and area to often produce understory estimates that were clearly not representative of the whole plot. Our solution was to perform transects through the plot noting estimated percentage dominance and coverage of the plant functional groups and then placing the square cutting perimeter to represent this. We believe this method to be much more consistent at capturing functional group dominance across plots than attempts at random or stratified sampling with such a small portion of the total plot area.

Suggested change:

“Understory samples were taken from control plots by cutting all non-moss, non-tree plant material at the surface of the soil from within four 40×40 cm2 patches. To reduce sampling error due to small areal coverage of the plot the sample patches were chosen by performing transects through the entire plot noting visual estimates of coverage and proportions of plant functional groups (i.e. graminoids, forbs, shrubs, and pteridophytes) and selecting representative patches for the portion of the plot that was vegetated, which was always all non bare rock surface. These values were applied to a visual estimate of non bare rock surface area of the burnt plots as an approximation of its prefire understory coverage. CCVs for understory were determined by sorting the sampled understory plant material and measuring dried weights of the functional groups graminoid, forb, shrub, and pteridophyte."

Comment 13

Page 6, line 169: All samples were pulverized, except the mineral soil where only the fine earth fraction (< 2 mm) was analyzed (C and N content was set to 0 for the coarse fraction), and run through a Costech ECS4010 elemental analyzer to produce ratios of C and N weight to sample total weight (CR and NR respectively).

More information is needed on the elemental analyzer used to calculate the ratios. How were the samples prepared? What was the measurement protocol? How was the instrument calibrated? Also, the abbreviations are confusing. Perhaps consider changing to carbon (nitrogen) mass percentage or something similar.

(Response)

The samples were pulverized and placed in tin capsules. They were then combusted and separated using gas chromatography and then measured separately for their total amount using their thermal conductivity all within the Costech ECS 4010 elemental analyzer

Suggested change:

"All samples were pulverized, except the mineral soil where only the fine earth fraction (<2 mm) was analyzed (C and N content was set to 0 for the coarse fraction) and packed in tin capsules. The capsules were combusted in a Costech ECS 4010 elemental analyzer, equipped with a 2 m packed chromatographic column for gas separation, to produce ratios of C and N weight to sample total weight (CR and NR respectively). After every 10 samples, standardized acetanilide (from the company Elemental Microanalysis, Okehampton, United Kingdom) was run to calibrate the machine within 1%."

We would like to reserve the use of percentages as a colloquialism while leaving key variables as they appear in calculation to maintain consistency.

Comment 14

Page 6, line 185: Changes between control and burnt plots were first calculated by subtracting control plot values of a variable from those of its burnt pair thereby forming a single distribution of 50 elements for statistical testing.

This sentence should be re-worded for clarity. Or, an equation could be introduced here using the delta (D) notation to indicate change. Additionally, the author does not state exactly what variables are compared between control and burnt plots in this sentence.

(Response)

Suggested change: “Unless otherwise noted, all measured changes between control and burnt plots..”

Comment 15

Page 7, line 192: Simple regression was performed using the stats.linregress method from SciPy

(Virtanen et al., 2020) providing significance (p), correlation (r), and slope (b). Multiple regression was carried out with the OLS method in the Python 3 statsmodels package (Seabold and Perktold, 2010) with models evaluated in order of increasing Akaike information criterion. Standardized regression coefficients (B) were produced by normalizing all variables (converting to z scores) before regression. CCVs were assessed in regression models both using original variables and their principal components produced by the PCA method in statsmodels.

What type of regression was performed? Linear, least squares, orthogonal distance? OLS needs

to be defined. It is unclear what is meant by CCVs were assessed in regression models. What were they assessed for? Akaike information criterion needs a reference.

(Response)

Ordinary least squares regression was used. OLS is the name of the method from the statsmodels package; it's just a label for computer code rather than an acronym or generic procedure. The CCVs were checked for correlation to C and N losses as well as to improve regression analyses in the results section (to no avail). AIC can be referenced. Suggested changes:

“All regression analyses used the ordinary least squares approach to estimate a function for a single response variable based on linear combinations of the predictor variables and an intercept term. Simple regression was performed using the stats.linregress method from SciPy~(Virtanen et al., 2020) providing significance~(p), correlation~(r), and slope~(b). Multiple regression was carried out with the OLS method in the Python~3 statsmodels package~(Seabold and Perktold, 2010) with models evaluated in order of increasing Akaike information criterion~(Akaike, 1974). Standardized regression coefficients~(β) were produced by normalizing all variables~(i.e. converting to z scores) before regression. All CCVs described in this text were assessed for their direct correlations to C and N stock losses as well as their ability to improve the regression models presented in the results sections by using both original variables and their principal components produced by the PCA method in statsmodels.”

Comment 16

Page 7, line 212: The largest total loss of C in burnt plot compartments due to fire was from the duff layer (Fig. 2a) About three quarters of the moss/litter C was removed from burnt plots, comprising about half as much as the total amount of C that was removed from the duff layer. Understory C removal due to fire was near complete, but had a relatively small contribution to overall elemental stocks and their changes. Of the average amount of C lost from these three compartments, 54.3% was found in the averaged char layer and only 0.19% in the increased C found in burnt plot mineral layers which themselves had no significant overall change in C between control and burnt plots.

This sentence is confusing. Does this mean 54.3% of the C lost from duff, moss/litter and understory was redistributed into the char layer? Was the rest emitted to the atmosphere?

(Response)

We rephrase to state that an “equivalent amount” was found in the char, to avoid misleading the reader to believe we have evidence of what proportions of each compartment’s C are going where.

“Char layer C averaged across the 50 burnt plots was equivalent to 54.3% of the average C lost due to fire from the combined understory and organic compartments.”

Comment 17

Page 7, line 204: Section 3.1

This section is difficult to follow. Maybe consider adding subsections for clarity and readability.

(Response)

Agreed, we now give a subsubsection for each paragraph.

Comment 18

Section 3 Results:

It would be helpful to see how these results vary as a function of ecosystem type to extrapolate the results to other boreal regions.

(Response)

The plots occur within a set of fairly homogenous, upland, pine-dominant Fennoscandian boreal forest. We were not able to identify any factors separating the ecosystem into types that are subject to different fire patterns (except what we display continuously as opposed to categorically, e.g. organic layer depth, climate). We agree it is very helpful to have more background on the ecosystems (especially dominant overstory) and have included that in the added results section concerning vegetation (also included a few comments above).

“3.1 Survey of burnt plot vegetation

The 50 burn plot overstories were largely pine dominant with a percentage of spruce stems between 25-50% in 5 plots, between 50-75% in 3 plots and 2 plots with greater than 75%. Birch stems were less than 25% in 44 plots and between 25-50% in 6 plots, of which only 1 of the 6 was spruce dominant. All plots showed visible charring of tree boles though only 3 plots had greater than 1% plot wide canopy blackening. These plots were pine dominant with 2 having less than 1% spruce while the other had 6 spruce of the 27 stems within the sampled area. Prefire aboveground overstory C and N were estimated as4.46 ± 0.738 kg $m^{-2}$and 0.0385 ± 0.00621 kg m^{-2}, respectively, with 5.31% of C (0.237 ± 0.0321 kg m^{-2}) and 12.3%8of N (0.00474 ± 0.000641 kg m^{-2}) coming from pine and spruce needles. The 50 burnt plots had a large percentage tree mortality (45.0 ± 8.76%) compared to control (4.21 ± 1.63%). Total C and N loss, as well as char layer mass, was not correlated to canopy browning, blackening nor increased mortality in burnt plots relative to control.

Understory coverage was reduced to 10.2±5.15% of its estimated prefire values. This laid bare the surface layer of charred material present in all plots. This layer was conglomerated and easily separable from lower layers and new litter additions which were mostly needles. Upon breaking apart the layer, it was found to be completely blackened throughout."

(Comment)

The authors mention adding variables to models to improve fits in numerous places in the results, but do not adequately describe the models or variable combinations in the methods.

(Response)

True. Though hundreds of models were tested and it would be impractical to list them all. We can rephrase to more clearly separate the CCVs and "fuel arrangement" factors from the results by stating that they were used to test for their direct correlations to C and N loss as well as a supplement in *all* presented regressions for their ability to improve them.

Line 197: "All CCVs described in this text were assessed for their direct correlations to C and N stock losses as well as their ability to improve the multiple regression models presented in the results section by using both original variables and their principal components produced by the PCA method in statsmodels. The effects of C and N stock arrangement amongst forest compartments were tested by entering the per plot ratios of the sums of different combinations of compartment C and N stocks into regression analyses both directly and to improve all models presented in the results section."

(Comment)

The results focus primarily on the redistribution of C and N into different forest pools (or compartments). Perhaps the title of the manuscript should be changed to reflect this focus?

We agree this is a central focus but we opt to use the word "restructured" since it can be defined specifically to refer to proportional distribution of total amounts across compartments as well as changing bulk density and weight concentrations. This can be made clear by splitting hypothesis 1 (Line 80) into two parts:

"1. Fire significantly reduced C and N stocks across forest compartments

2. Fire restructured organic layer C and N stocks by increasing overall bulk density and adjusting their weight concentrations across residual compartments and a newly formed pyrogenic layer."

The title has been revised to the following: "Climatic Variation Drives Wildfire Loss and Restructuring of Carbon and Nitrogen in Boreal Forests".

Comment 19

Page 8, line 235: To quantify the relative contribution of fire induced changes in organic layer depth, bulk density and elemental weight ratios on organic layer C and N losses they were linearly combined and entered into multiple regression.

More information is needed to describe the multiple regression. "entered into" is unclear. Do the authors mean they performed a multiple regression on the linearly combined variables? What is meant by linearly combined? Added? The following discussion concerning the combination of variables in an attempt to explain changes in C and N stocks is unclear. Plots showing the raw data and model fits would be tremendously helpful in understanding this Section.

(Response)

Linearly combined is a specific, strictly defined term meaning they form an expression where they are each multiplied by a constant (which is the beta value to be estimated in regression) and then added together.

Per plot-pair C (and N) losses are calculated by the equation

$$\text{Loss} = -1 * [\text{BurntPlot}(\text{BulkDensity} * \text{Depth} * C_R) – \text{ControlPlot}(\text{BulkDensity} * \text{Depth} * C_R)]$$

which is not a linear combination of the individual variables but of their burn-control separated products. Here linear regression is used as a convenient way for estimating the contributions of the variation of the change (i.e. plot paired burn minus control) of these variables on C and N losses at the sacrifice of model fit. A linear model was constructed like this

$$Loss = -1 * [\beta_1 * \Delta BulkDensity + \beta_2 * \Delta Depth + \beta_3 * \Delta C_R + \beta_0]$$

with the variables converted to z scores. The β estimates then represent the relative influence of the fire induced change of the variables on the stock loss. This was done to show that changes to each of the variables due to fire have a nearly equivalent influence on losses of C. This is important knowledge because it is sometimes assumed that change in depth is the strongest signifier of C change or that C_R can be approximated with reference data and the same value can be applied to both control and burn plot stock estimates. It also can support explanations or open up questions, such as to ask why total N is lesser influenced by bulk density and elemental concentration than C.

The R^2 value is given just to show that the linear approximation of the ideal relation is not poorly fitting. Discrepancy from 1 is just from purposely using an inferior model and likely not providing any intuitive information. Plotting would require a hyperplane in 4 dimensions, which is infeasible, and deviation from a perfect fit would come only from the noise due to the inferior model selection. Therefore we opt to provide only the valuable β values.

Suggested change:

“3.2.6 Statistical contribution of measured changes to C and N losses

To quantify the relative statistical contributions of the variation of fire induced changes in organic layer depth, bulk density and elemental weight ratios they were used as predictor variables in multiple regression to explain organic layer C and N losses. The C loss regression produced a model of fit of R^2= 0.865 and standardized regression coefficients for changes in depth (β= -0.670), bulk density (β= -0.633) and C_R(β= -0.583). N loss produced a model fit of R^2 = 0.777 and coefficients for loss of depth (β= -0.599), bulk density (β= -0.398) and N_R (β= -0.382). This shows that changes of these variables due to fire all had a strong effect on C and N stock loss estimates. Measured change in organic layer depth is the strongest determinant of losses of N. However, for C bulk density and elemental weight ratios are nearly as important as depth.”

Comment 20

Section 3.3

While the p values are significant, the correlations are poor. The author should more fully address the low correlations.

(Response)

The correlations were discussed in manuscript at the following lines:

Line 265 - MAT is confounding MAP to explain C loss

Line 295 - MAT confounds or influences fire weather patterns that determine char production

Line 353 - MAP is mediated by fuel build up.

The strength of the effect fuel build up itself is then discussed with a paragraph added at line 398:

“Fuel loading has been found to have a varied strength of control on boreal wildfire C loss globally. This study found total C loss to relate to belowground C in simple regression with an R2 of 0.494 and to aboveground C insignificantly. These results are within the broad range found in Walker et al. (2020) where total C losses across 4 North American boreal ecoregions were directly related to prefire belowground C with R^2 values of 0.024 (insignificant), 0.07, 0.051, and 0.579 and to respective prefire aboveground C with 0.229, 0.005 (insignificant), 0.101, and 0.336. Little is known what factors dictate the strength of these controls and what portions of unexplained variation can be attributed to either additional measurable factors, methodological error or stochastic fire processes for a particular wildfire event. This study attempted to address these issues by testing many measurable ecosystem properties across several ecosystem C storage compartments finding the organic layer C stock along with its climate related prefire fuel conditioning and combustion susceptibility to be most predictive of C loss (Fig. 4a). These trends were demonstrated using a consistent methodology that incorporates high replication and broad spatial coverage, thereby offering better constraints on remaining unexplained variation across the region than might be provided by sampling a single burn scar or comparing results from different study designs.”

Comment 21

Page 9 line 266: MAT was negatively quadratically related to losses in CO (p = 0.008, R2 = 0.186)

and NO (p = 0.002, R2 = 0.233), both peaking near 4°C.

There is no clear description of applying a quadratic model fit to the variables in the methods.

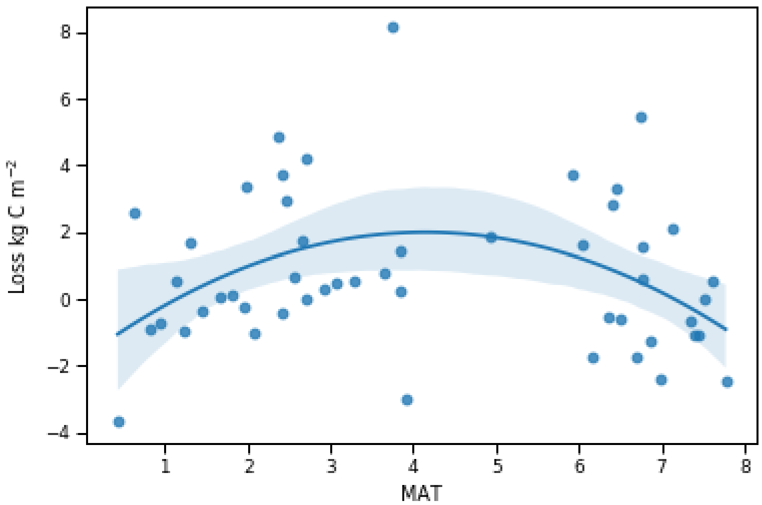
Again, plots of the data and model fits would be extremely helpful.

(Response)

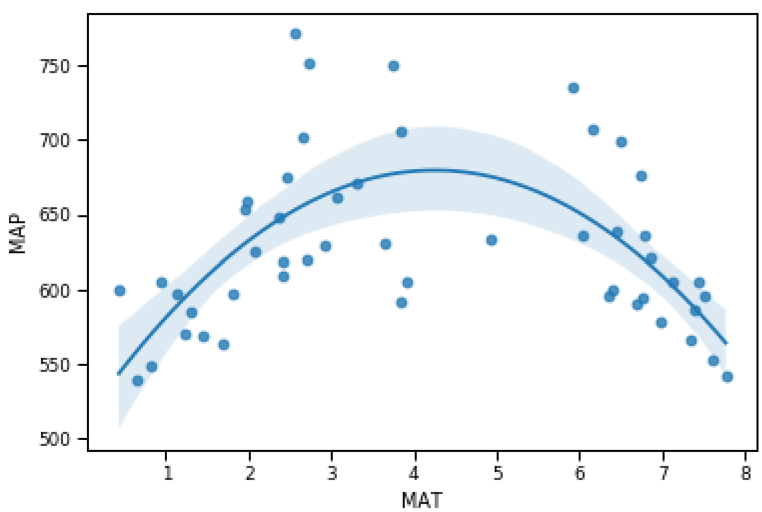
The methods section explained linear multiple regression (Line 193) which was used with a quadratic fit for MAT and MAT^2 variables in the form

$$Loss = b_1 * MAT^2 + b_2 * MAT + b_0$$

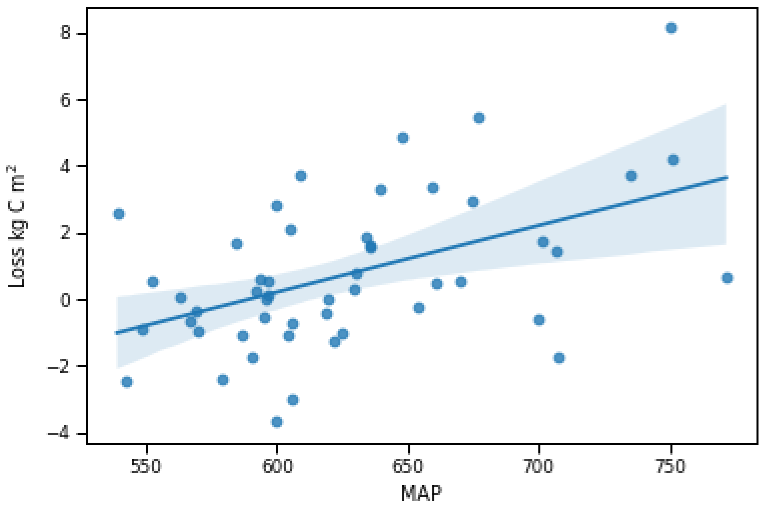
where b_1 was found to be negative meaning the hyperplane equation can be represented as a plot in reduced dimensions as an upside down parabola peaking at 4°C. The model fit had low R^2 and was determined to be due to confounding with MAP (Line 267). Here is the lower dimensional representation of the model:

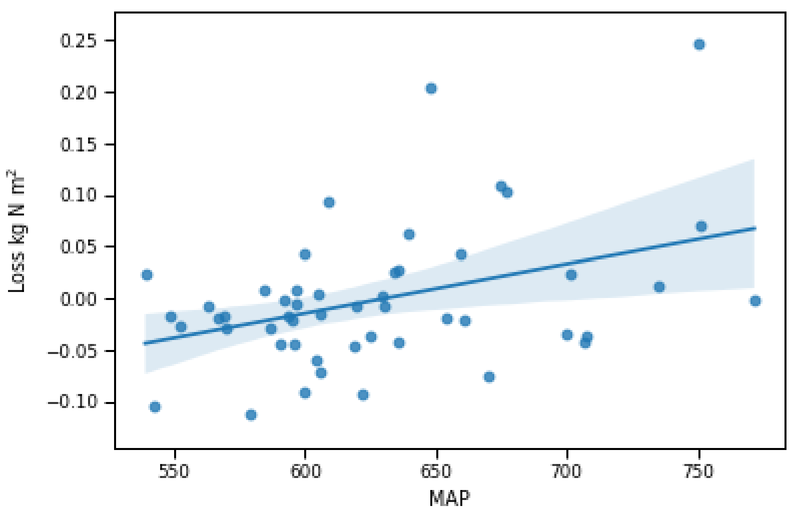


The relation of MAT to MAP:



And the univariate regressions for MAP vs C or N loss:





Suggested change: “In multiple regression, MAT and MAT^2 formed a negative quadratic relation to losses in C”

Comment 22

Section 4.3

Has the transport of N via aerosol emissions from nearby fires or even re-distribution within the same area due to a fire been considered?

(Response)

Yes, we considered this possibility and now explicitly acknowledge it in the manuscript (Line 319).

"However, material may have been added from downward movement of overstory components during the time of fire or deposition of aerosols coming from outside the plot. By selecting plots well within the final fire perimeter it was assumed that incoming and outgoing aerosols during the fire would be approximately equal and that extended aerosol deposition from more remote sources would deposit equally on control and burnt plots."

Technical Corrections

Suggested changes in red.

Page 1, line 22: The balance of C transferred between atmospheric and terrestrial stocks on the a yearly timescale is dictated by rates of terrestrial net primary production and respiration, which are strongly controlled by temperature, moisture and nitrogen (N) availability.

(Response)

accepted

Page 2, line 29: Further, bioavailability of energy sources and nutrients is substantially affected as elements such as C and N are lost, and their chemical structure is altered by heating.

(Response)

accepted

Page 2, line 30: Along with a changing climate, these effects have the power to influence community structure and process rates, thereby shaping future forest C and N cycles on decadal to centurial timescales.

(Response)

Suggested:

“Along with a changing climate, these effects have the power to influence community structure and processes such as soil respiration and nutrient cycling which can shape future forest C and N cycles on decadal to centurial timescales”

Page 2, line 38: However, in order for this fuel to be available to ignite and propagate sustain fire, it must be sufficiently dried and spatially arranged to be susceptible amenable to high heat and oxygen exposure during an active fire.

(Response)

accepted

Page 2, line 40: Therefore, boreal wildfire models often incorporate short term fire weather variables (e.g. drought indices, temperature, wind speed, relative humidity) and separate as well as separate fuel loads into distinct compartments, such as surface litter, to address the temporal variability in fuel availability. Fuel structure which influences ignition and rate of spread, and the more compactly arranged layers below which act as a heat reservoir that supports extending smoldering combustion over days to weeks.

(Response)

Suggested:

“Therefore, boreal wildfire models often incorporate short term fire weather variables (e.g. drought indices, temperature, wind speed, relative humidity) and separate soil fuel loads into distinct compartments such as surface litter, which influences ignition and rate of spread, and the more compactly arranged layers below, which act as a heat reservoir that supports extending smoldering over days to weeks (de Groot et al., 2003; Van Wagner, 1987; Rabin et al., 2017; Kasischkeet al., 2005; Wiggins et al., 2020).”

Page 2, line 49: Fuel chemical composition chemistry, arrangement, moisture content, applied heat and oxygen availability in turn have all been related to the efficiency of the combustion reaction during fire and therefore emission chemistry and the charring of remaining nonvolatilized fuel.

Suggest adding reference: Lobert, J.M. and Warnatz, J., 1993. Emissions from the combustion process in vegetation. Fire in the Environment, 13, pp.15-37.

(Response)

Thank you for the reference suggested. It has been added.

Page 3, line 60: For example, the Eurasian boreal region is dominated by relatively fire resistant vegetation that promotes lower intensity fire (Rogers et al., 2015; de Groot et al., 2013a) and C loss (0.88 kgC/m2) (Ivanovaet al., 2011) than that in typical (Walker et al., 2020) North American wildfire (3.3 kgC/m2) (Boby et al., 2010; Walker et al., 2020).

Are the C loss estimates an average over many years? More description is needed.

(Response)

We have now revised the text to clarify this:

"For example, the Eurasian boreal region is dominated by relatively fire resistant vegetation that promotes lower intensity fire than that in boreal North America (Rogers et al., 2015;de Groot et al., 2013a). C loss due to a group of Siberian fires was found to be 0.88 kgC/m2(Ivanova et al., 2011) which is about a quarter of what is typical in North American wildfire (3.3 kgC/m2) (Boby et al., 2010; Walker et al., 2020)..."

Page 3, line 64: Although Though Eurasia contains over 70% of the boreal global land area (de Groot et al., 2013a), and about 50% (20 Mha/yr) of its yearly burnt area (Rogers et al., 2015), wildfire emissions from this region are severely under sampled in the field (van Leeuwen et al., 2014).

(Response)

accepted

(Comment)

Missing many references. Suggest adding the following:

Akagi, S.K., Yokelson, R.J., Wiedinmyer, C., Alvarado, M.J., Reid, J.S., Karl, T., Crounse, J.D. and

Wennberg, P.O., 2011. Emission factors for open and domestic biomass burning for use in atmospheric models. Atmospheric Chemistry and Physics, 11(9), pp.4039-4072.

Andreae MO. Emission of trace gases and aerosols from biomass burning–an updated assessment. Atmospheric Chemistry and Physics. 2019 Jul 4;19(13):8523-46.

Andreae MO, Merlet P. Emission of trace gases and aerosols from biomass burning. Global biogeochemical cycles. 2001 Dec;15(4):955-66.

De Groot, W.J., Pritchard, J.M. and Lynham, T.J., 2009. Forest floor fuel consumption and carbon emissions in Canadian boreal forest fires. Canadian Journal of Forest Research, 39(2), pp.367-382.

Potter, C., 2018. Ecosystem carbon emissions from 2015 forest fires in interior Alaska. Carbon balance and management, 13(1), pp.1-10.

Rogers, B.M., Veraverbeke, S., Azzari, G., Czimczik, C.I., Holden, S.R., Mouteva, G.O., Sedano, F.,

Treseder, K.K. and Randerson, J.T., 2014. Quantifying fire-wide carbon emissions in interior Alaska using field measurements and Landsat imagery. Journal of Geophysical Research: Biogeosciences, 119(8), pp.1608-1629.

(Response)

Great, these have all been read and incorporated where and if appropriate in the manuscript.

Page 3, line 75: Analysis intended to The goal of this study is to distinguish the effects of climate on fire induced changes in C and N stocks with direct, fine scale measurements and little loss of generality thereby providing insight into both local processes and valuable, globally comparable data from an under sampled region.

Not sure what is meant by "little loss of generality."

(Response)

It was meant that the methods weren't intended to be so specific that the results could be considered ad hoc.

suggested change:

"The goal of this study is to distinguish the effects of climate on fire induced changes in C and N stocks from an under sampled region with direct, fine scale measurements that both provide insight into local processes and allow for global comparison."

Page 3, Line 88: 50 burnt plots were selected from a pool of 325 fires identified during the summer 2018 period which were mapped from remotely sensed data and provided by the Swedish Forest Agency (Skogsstyrelsen).

And Page 4, Line 94: The first constraints on site selection were to avoid wetland or steeply sloping areas using prefire, topo-edaphic derived soil moisture data (TEM) provided by the Swedish Environmental Protection Agency (Naturvårdsverket) (Naturvårdsverket, 2018) and elevation and slope data provided within the ArcGIS software environment.

And Page 4, Line 110.

Is the reference referring to a location? Please clarify.

(Response)

These are the equivalent Swedish names for the agencies. We recognize the confusion and they will be removed.

Page 4, line 90: Remote sensed data was taken as the average pixel value within a 20 m diameter circle centered on the plot with GIS analysis utilizing QGIS (QGIS Development Team, 2019), ArcGIS (Esri Inc., 2019) and the pandas Python 3 package (Wes McKinney, 2010).

The authors describe their methodology for using remotely sensed data before describing exactly what that data is and where it is from. Suggest reorganizing this section.

(Response)

We have revised the text to first present the data and source, then the methodology: :

“50 burnt plots were selected from a pool of 325 fires identified during the summer 2018 period which were mapped from Sentinel-2 infrared data and provided by the Swedish Forest Agency. Each 20×20 m2plot was located within distinct burn scars (greater than 2 km separation) to reduce potential for pseudoreplication or spatial autocorrelation (Bataineh et al., 2006) and allow for increased spread across the climate gradients (Schweiger et al., 2016). Constraints were placed on plot selection using spatial data within the QGIS (QGIS Development Team, 2019) and ArcGIS (Esri Inc., 2019) software environments. Plot wide values for raster data were taken as the average pixel value within a 20 m diameter circle centered on the plot. The first constraints…:

Page 4, line 100: Sentinel-2 infrared imagery taken during the time of fire was used to delineate assisted in delineating the exact locations of burnt plots by determining placing them where there had been a strong and consistent infrared signal existed that was well within the mapped final fire perimeter boundaries.

(Response)

accepted

Page 4, line 121: The compartments included These were the four soil layers, of mineral, duff, moss/litter and char, as well as the two aboveground compartments, of the understory and overstory vegetation.

(Response)

accepted

Page 4, line 122: The organic layer was defined as the considered the grouping of the duff, moss/litter and char layers grouped together.

(Response)

accepted

Page 5, line 146: If a fallen tree was charred only on its lower (in standing orientation) portions, it was deemed standing during fire ignition and its measurements were included if its base was within plot boundaries.

(Response)

accepted

Page 5, line 153: Only bole diameters from the burnt plots were used to investigate When testing the influence of overstory vegetation on C and N loss, while bole diameters from adjacent control plots were ignored. bole diameters from the burnt plots were used and not the adjacent control. C and N stock estimates for overstory were not included in this analysis, and the measurements were only used to assess its role in controlling C and N stocks in all other compartments.

(Response)

accepted

Page 6, line 165: CCVs for these two layers were calculated as the sum of the formed by weights

of these coarse and fine fractions.

(Response)

Suggested change:

"The weights of the coarse and fine fractions formed a pair of CCVs for each of the layers."

Page 6, line 175: Data was stored in comma-separated value files with minimal redundancy. Calculations were performed with custom written Python 3 code using the pandas library. The measurable properties used in C and N stock calculations within soil compartments are the depth, bulk density and CR or NR.

I suggest deleting the first two sentences in this paragraph, as they are unnecessary. Throughout the manuscript, "stock calculations" need to be defined as C and/or N stocks. Otherwise, it is difficult to understand what is meant by "stock calculations."

(Response)

accepted

Page 7, line 187: These distributions were approximated as normal and unless otherwise noted,

and all confidence intervals were constructed at the 95% level using the formula

(Response)

Suggested change:

"These distributions were approximated as normal and all confidence intervals were constructed at the 95% level, unless otherwise noted, using the formula"

Page 7, line 204: C and N stock losses and rearrangement.

Suggest changing the word "rearrangement" to "redistribution" throughout the manuscript.

(Response)

We opt to use the word "restructured" since it can be defined specifically to refer to proportional distribution of total amounts across compartments as well as changing bulk density and weight concentrations. This can be made clear by splitting hypothesis 1 (Line 80) into two parts:

1. Fire significantly reduced C and N stocks across forest compartments

2. Fire restructured organic layer C and N stocks by increasing overall bulk density and adjusting their weight concentrations across residual compartments and a newly formed pyrogenic layer.

Page 10, line 315 The char layer was likely largely produced by fire interacting with the understory and moss/litter layer, however averaged char layer C and N stocks were greater than losses from the two layers combined suggesting there were also large contributions also from the duff layer.

(Response)

accepted

Page 11, line 318: Because the char layer was conglomerated and completely blackened, it is unlikely that material was incorporated postfire.

(Response)

accepted

Page 11, line 327: N losses in non-boreal forests have been related to fire fuel temperature during time of fire with lower intensity fires transferring a greater proportion of pools of organic N into soil ammonium and nitrate rather than removing N in gaseous forms (Neary et al., 1999).

(Response)

accepted

Page 11, line 331: Therefore, the N cycle in boreal systems may be highly dependent on active fire properties, fuel type and resulting fuel transformation, and the greater N losses in Alaska compared to Eurasia could be explained by its dissimilar fuel and the characteristically more intense crown fires across the North American boreal zone (de Groot et al., 2013a; Wooster and Zhang, 2004).

(Response)

accepted

Page 11, line 359: This direct effect was largely mediated by the incorporation of measures of fire-induced fuel transformation into the models, i.e. production of char layer C or N.

(Response)

addition of “the” accepted

(Comment)

GENERAL COMMENTS

This study assesses the effect of wildfires on the C & N stocks in boreal forests of Sweden. It uses a "space substitution for time" approach, where the authors choose "control" unburnt areas adjacent to the burnt sites and consider those to be comparable to the burnt sites before the fire. It is fully understandable to use this type of approach as, most of the times, it is the only one available when studying the impacts of wildfires. Having said that, this approach has its limitations because, many times, those "comparable" sites are not exactly the same to the burnt sites, and, actually, many times that is the reason why they did not get burn in the same place. The authors, therefore, need to: 1) demonstrate this is not the case in the selected sites (e.g. maybe using remote sensing indexes before the fire to check if they were comparable), 2) acknowledge and discuss this limitation in the manuscript.

For example, the authors state in L293: "TEM differences between paired burnt and control plots were observed to increase both with control and burnt TEM levels however not along gradients of MAT ". Unless I am misunderstanding this, it sounds like there were already differences in soil moisture between the burnt and the unburnt sites before the fire, therefore, they would have had different fire behaviours and impacts in the hypothetical case where all had been burn.

(Response)

Thanks very much for your detailed comments which we believe have substantially improved the manuscript.

We agree that the plot pair approach has both advantages and limitations, as do all experimental designs. With the appropriate precautions (listed below), we believe that we have done a more thorough job in plot pair matching than is typical in wildfire study by using several important, fine-spatial scale variables and by performing follow up analysis. We are confident that the approach still permits robust and useful conclusions to be made.

1. The plot pairs were matched with remotely sensed data as mentioned throughout the methods section (especially starting at line 104). We matched plots based on similar values of moisture (TEM, giving on an integer scale of 0 - 240, not broad moisture classes), dominant tree species, tree biomass and basal area, elevation and slope. We also used visual images to check apparent connectivity and confirm a minimum stand age of at least 30 years.
2. We feel the major limitations are clearly acknowledged in the first paragraph of section 4.3 (line 365). We state that burnt plots may be biased towards greater fire susceptibility and even hold more carbon and nitrogen. While random error in plot pair mismatch may be compensated for by high sample size (n=50), we state that systematic error may still be present due to this bias.

3. We also presented a short, follow up analysis of the control plot matching (mostly contained near line 290). We focused on moisture due to its documented effects on fuel build up and flammability (it was also the only plot-pair matching variable that apparently affected the plots across the entire gradient). Indeed, there were small differences in TEM, but that is because it was not feasible to match plots perfectly for all variables used. We demonstrated that this difference is negligibly small in several ways. First, TEM differences did not covary with our observed controls on C and N losses (i.e. C, N, MAT, MAP), and is therefore likely not involved in confounding. Second we used the organic layer C predictive model from our results using MAT, MAP and TEM to correct for TEM differences within plot pairs and this produced no significant change in the distribution of estimated C and N losses.

(Comment)

Along these same lines, more than referring to the observed differences as "losses" (which imply measurements before and after fire), it would be probably more accurate to talk simply about "differences". Also considering that the sampling was done already 1 year after the fire (what is a pretty short time for wildfire investigation for sure but you may be seeing indirect effects already).

(Response)

We will more clearly state the limitations of assuming plot pair differences are due actual prefire to postfire changes. We also add an explanation for the timing of sampling.

Line 104: In order to estimate the effects of fire, prefire properties of each burnt plot were approximated by measurements from a single identically sized adjacent control plot centered between approximately 15 and 150 m outside the fire boundaries (100 plots total, i.e. 50 plot pairs). A major limitation to this approximation is that observed differences within plot pairs may be skewed through inaccurate or imprecise representation of prefire burnt plot properties by control measurements. An attempt to reduce these errors was made by incorporating a large sample size (n = 50) and strict controls on the matching of important ecosystem variables. To reduce mismatch…

Line 120: Site visits occurred approximately 1 year postfire over the dates August 5 to August 20 in 2019. This 1 year delay intended to capture the more immediate effects of fire due to potential rapid spikes in nutrient losses and tree mortality, which generally occur within the first year, but avoid the accumulation of discrepancies in C and N stocks relative to control due to any longer term differences in rates of decomposition, leaching and litter addition (Granath et al., 2021; Certini, 2005; Sidoroff et al.,2007).

(Comment)

Another key issue that I am missing is why there is no information about the short-term climate variables in the discussion. Theses short-term variables are key drivers of fire behaviour and therefore impacts on C&N stocks.

(Response)

We agree these are potentially important variables and used gradients of SPEI and summer 2018 temperature and precipitation anomalies to represent short term weather. A discussion of all three of these are found in the paragraph starting at line 384.

We can improve this paragraph by explicitly reminding the reader of the connection of the analyzed variables (i.e. SPEI, TEM, MAT and MAP) to processes explained.

Line 390: By incorporating measures of long (TEM, MAT, MAP) and short term moisture balance (SPEI), …

(Comment)

I believe these issues need to be resolved before a decision upon acceptance of the manuscript can be made. In additions, I have other specific comments below and in the pdf attached.

(Response)

We believe the issues above are well addressed and handled with reasonable rigor within the scope of the paper. However, we plan to make minor adjustments to the text to more explicitly state assumptions and create a more clear linkage between analyzed variables and the processes they represent.

(Comment)

SPECIFIC COMMENTS

ABSTRACT: some rephrasing will improve readability, please see my detailed comments in the pdf attached.

(Response)

Great, these comments were incorporated.

Abstract

The boreal forest landscape covers approximately 11% of the earth's land area and accounts for almost 30% of the global annual terrestrial sink of carbon (C). Increased emissions due to climate change-amplified fire frequency, size and intensity threaten to remove elements such as C and nitrogen (N) from forest soil and vegetation at rates faster than they accumulate. This may result in large areas within the region becoming a net source of greenhouse gases creating a positive feedback loop with a changing climate. Meter-scale estimates of per area fire emissions are regionally limited and knowledge of their relation to climate and ecosystem properties is sparse. This study sampled 50 separate Swedish wildfires, which occurred during an extreme fire season in 2018, providing quantitative estimates of C and N loss due to fire along a climate gradient.Mean annual precipitation had strong positive effects on total fuel, which was the strongest driver for increasing C and N losses,while mean annual temperature (MAT) had greater influence on both pre- and postfire organic layer soil bulk density and C:N Ratio which had mixed effects on C and N losses. Significant fire-induced loss of C was estimated in the 50 plots comparable to estimates in similar Eurasian forests but approximately a quarter of those found in typically more intense North American boreal wildfires. N loss was insignificant though a large amount was conserved in a low C:N surface layer of char in proportion to increased MAT. These results reveal the large discrepancies of C and N losses between global regions and variability across local climate conditions. A need exists to better incorporate these factors into models to improve estimates of global emissions of C and N due to fire in future climate scenarios. Additionally, this study demonstrated a linkage between climate and the extent of charring of residual soil fuel and discusses its potential for altering C and N dynamics in postfire recovery.

(Comment)

INTRODUCTION:

-L30: please add more updated references.

(Response)

2020 and 2019 are very recent.

(Comment)

- L45: please describe a bit more the differences between Eurasian and North American fuels and fire regimes here, as it is key to understand the implications of this study's findings.

(Response)

This can be better addressed in

Line 45 : Composition of tree species, with their associated fire adaptation strategies, has also been shown to have a strong impact on fire severity and intensity and distinguishes the boreal wildfire regimes of the North American and Eurasian continents (Rogerset al., 2015).

And

Line 60: For example, the Eurasian boreal region is dominated by relatively fire resistant overstory vegetation that avoids excessive heating by promoting lower intensity ground and surface fires than that in boreal North America, which is more prone to spread rapid flaming combustion throughout the canopy (Rogers et al., 2015; de Groot et al., 2013a)

(Comment)

-L47: the explanation about fuel chemistry also needs expanding.

(Response)

We can clarify by emphasizing that the chemistry of the fuel is dictated by the initial chemical properties of the litter inputs and their decomposability.

Line 47: Furthermore, climate has been observed to have a conditioning effect on fuel chemical composition through its control over vegetation characteristics and the decomposition state of their detrital inputs, which are often represented by the C:N weight ratio in soils (Vanhala et al., 2008; Kohl et al., 2018).

(Comment)

- L50: please update these references, there are several reviews on the topic less than 15-20 years old.

(Response)

We now reference the recent field measurements of Santín et al 2016 supporting this knowledge.

(Comment)

- L55: this is only true for some types of emissions calculations and, right now, the most commonly used models using this type of approach (e.g. GFED) are changing. Please update this part and do provide references less than 17 years older, as this is a topic that is rapidly changing.

(Response)

We alter this paragraph by including information on alternative and more recent emission estimation methods but also emphasize that our goal is to provide ground validation and meter scale assessments of landscape heterogeneity on areal C and N losses that are absent from many methodologies that are designed for the regional scale.

Line 55: Boreal C emissions due to a single wildfire can be calculated by multiplying total area burned by estimates of C emissions per area (French et al., 2004). While total area burned may be evaluated directly through remote sensing (Ruiz et al., 2012), per area C emissions are generally derived from labor intensive field sampling which is extrapolated to the larger scale either directly or through weighting by remotely sensed data (e.g. topography, vegetation cover) or poorly constrained free parameters such as total fuel load (French et al., 2004; Soja et al., 2004; van der Werf et al., 2017; Veraverbeke et al., 2015; Kaiseret al., 2012). This field sampling has been regionally limited and biased towards a few high intensity burn complexes in North America which may in turn bias global emission estimates (van Leeuwen et al., 2014; Akagi et al., 2011). For example, the Eurasian boreal region is dominated by relatively fire resistant overstory vegetation that avoids excessive heating by promoting lower intensity ground and surface fires than that in boreal North America, which is more prone to spread rapid flaming com-65bustion throughout the canopy (Rogers et al., 2015; de Groot et al., 2013a). C loss in a group of Siberian boreal forest surface fires was found to be 0.88 kg C m^{-2}(Ivanova et al., 2011) which is about a quarter of what is typical in North America Wildfire (3.3 kg C m^{-2}) (Boby et al., 2010; Walker et al., 2020) and about one fifth of an extreme wildfire in Fennoscan-dia (4.5 kg C m^{-2}) Granath et al. (2021). Although Eurasia contains over 70% of the boreal global land area (de Groot et al.,2013a) and about 50% (20 Mha yr^{-1}) of its yearly burnt area (Rogers et al., 2015), methodologies for estimating global and regional C emissions are severely lacking ground validation and meter scale assessments of drivers of C loss variability from this region (van der Werf et al., 2017; Kaiser et al., 2012).

(Comment)

- L66-70: this paragraph needs references.

(Response)

- There is only one boreal wildfire study that we know of directly measuring immediate wildfire losses of N (by measuring, not assuming, N content of the soil in burnt plots).

- To support the claim that fires are typically studied within small groups we, rather than exhaustively list the numerous studies where the statement is true, present the few conglomerate studies that contain them in line 70.

(Comment)

- Please explain somewhere how the fire 2018 was one of the two (with 2014) most extreme over the recent years, and that it was associated to drought, as this is important context for this study.

(Response)

Thanks for this, it will surely provide better context.

Line: 74 This study sampled 50 separate fire complexes spanning broad gradients of mean annual temperature (MAT) and precipitation (MAP) which ignited in Sweden during summer 2018 (Fig. 1). This summer, along with that of 2014, were two of the most extreme fire seasons within Sweden in recent history, driven by severe drought conditions (Wilcke et al., 2020)

(Comment)

- Hypothesis 3 is very long and complex, not enough information has been given in the introduction to understand it completely. Please elaborate this part and consider dividing it in two.

(Response)

We agree this hypothesis can be made more easy to digest, and is suggested to be separated as shown below.

3. A direct relation between climate variables and fire induced C and N stock changes exists.

4. The relation between climate and fire driven C and N stock changes is mediated by long term ecosystem properties that affect the combustion level of forest fuel.

(Comment)

MATERIALS AND METHODS:

- L88: please explain a bit more how the fire scars were detected (beside “remote sensing data”).

(Response)

The Swedish Forest Agency manually added perimeters to apparent burn scars observed by Sentinel-2 infrared imagery.

Line 88: 50 burnt plots were selected from a pool of 325 fires identified during the summer 2018 period that had perimeters manually mapped by the Swedish Forest Agency from burn scars appearing in Sentinel-2 infrared data.

(Comment)

- L99: Sentinel-2 during the time of the fire? Were all fires long enough for them to be captured with sentinel infra-red? What if the main fire front had already passed? This does not sound like the best option for choosing the best plot.

(Response)

Good point. It is hard to determine when a forest transitions from what can be considered active fire to burn scar using infrared imagery. For many fires we could see the fire grow and were able to determine an approximate start point. We assumed, also, that after the main front had passed the ground may continue to smolder. But indeed, we can not confirm the signals were all from active fires and we can change the text to indicate this.

The most important plot selection criteria was good prefire plot-pair matching. The infrared signal was only used to avoid what appeared to be a fire’s periphery as determined by low pixel intensity but was not used to compare separate fires quantitatively.

Line 99: Sentinel-2 infrared imagery was used to locate planned burnt plots near pixels showing the highest intensity within the mapped final burn scar perimeter. This gave greater certainty the plots experienced a more developed fire effect rather than peripheral heating alone.

(Comment)

- L148: one year after the fire many of the needles, specially those affected by fire (i.e. brown or black) would have fallen already. This needs to be acknowledged as a limitation of this method.

(Response)

This is acknowledged in line 141. The char layer was conglomerated and the small amount of unburnt material was easily removable from its surface. This material was assumed to be postfire additions from the canopy and was discarded and therefore disregarded from stock calculations.

(Comment)

- L156: how the representativeness of the whole understory is proved using 4 patches per plot? How were these patches chosen in areas with a very heterogeneous understory distribution? Please explain.

(Response)

Replication of understory samples was limited because of (1) The very large number of other components to be recorded and the large number of plots and (2) the relatively small contribution of understory C to total forest C storage (though a large C turnover in Sweden). Which meant that we focused our time and resources on intensively sampling the largest and most variable ecosystem C components (the soil). We tested various different sampling methods including established methods of ‘random’ or stratified sampling but found the small sample size and area to often produce understory estimates that were clearly not representative of the whole plot. Our solution was to perform transects through the plot noting estimated percentage dominance and coverage of the plant functional groups and then placing the square cutting perimeter to represent this. We believe this method to be much more consistent at capturing functional group dominance across plots than attempts at random or stratified sampling with such a small portion of the total plot area.

We more clearly outline this method and our reasons for its favor within the manuscript

Line 156: Understory samples were taken from control plots by cutting all non-moss, non-tree plant material at the surface of the soil from within four 40×40 cm2 patches. To reduce sampling error due to small areal coverage of the plot the sample patches were chosen by performing transects through the entire plot noting visual estimates of coverage and proportions of plant functional groups (i.e. graminoids, forbs, shrubs, and pteridophytes) and selecting representative patches for the portion of the plot that was vegetated, which was always all non bare rock surface. These values were applied to a visual estimate of non bare rock surface area of the burnt plots as an approximation of its prefire understory coverage. CCVs for understory were determined by sorting the sampled understory plant material and measuring dried weights of the functional groups graminoid, forb, shrub, and pteridophyte.

(Comment)

- For the methods used no references are given, are these new methods? If so, how do you ensure the representativeness of your measurements?

(Response)

The central methodology is the calculation of soil carbon and nitrogen by multiplying soil depth by bulk density by elemental ratio which is confirmed by dimensional analysis. Soil profiles were separated mainly due to their obvious differences in density that also followed the cited Canadian Soil Classification System that is used in many fire prediction methods. References are added for motivating separate analysis of the pyrogenic layer. Tree mortality estimation reference is added. Support for our 20 times replication of soil depth measurement per plot is now referenced. Our choice of sampling 1 year post fire is elaborated upon (in the immediately following text) and referenced.

Line 120: Site visits occurred approximately 1 year postfire over the dates August 5 to August 20 in 2019. This 1 year delay intended to capture the more immediate effects of fire due to potential rapid spikes in nutrient losses and tree mortality, which generally occur within the first year, but avoid the accumulation of discrepancies in C and N stocks relative to control due to any longer term differences in rates of decomposition, leaching and litter addition (Granath et al., 2021; Certini, 2005; Sidoroff et al.,2007).

(Comment)

- L166: “visual estimates for percentage volume of needles, broad leaves, woody material, moss and lichen were multiplied by total weight to form CCVs”: does not this assume densities of these different materials are similar, what it is obviously not true?

(Response)

The aim was to broadly test for an effect of litter composition as clarified in the following suggested change.

Line 166: Dry moss/litter samples were weighed and visual estimates for percentage volume of needles, broad leaves, woody material, moss and lichen were multiplied by total weight to form CCVs. This broadly categorized, visual estimation, along with the assumption of equal category density, is meant to test for general effects of variation in proportions of surface fuel types on total soil fuel build up and fire severity.

(Comment)

RESULTS

- L208: “transferred large amounts of C and N from lower soil layers to the highly nitrogenous surface layer of char.” This was not a “transfer” but a conversion. Please rephrase.

(Response)

We have rephrased as suggested.

(Comment)

- In several places the authors talk about C and N “lost” from the different soil layers and now “found” in the char layer. This assumes that all char is coming from soil, what may be the case in some places but not in others where the understory and canopy led to charred inputs to the ground (as discussed in L315). Even if these inputs may not be too substantial in some places they can be in others. Please rephrase.

(Response)

We agree these words are ambiguous and will be reworded throughout. The purpose of comparing estimated disappearances of C&N from the various compartments to char layer C&N is because we *do not* assume where char C&N is coming from. Char C&N can come from any of the soil compartments, the understory, the overstory or even be deposited from material above. We do show across all plots that the understory cannot be a substantial contribution due to it’s low overall C. We can also show that canopy blackening is rare and the amount is not correlated to char layer mass.

Based also on comments from Reviewer #1, we will include more information on canopy and its damage in an added section to the Results:

Line 204: 3.1 Survey of burnt plot vegetation

The 50 burn plot overstories were largely pine dominant with a percentage of spruce stems between 25-50% in 5 plots, between 50-75% in 3 plots and 2 plots with greater than 75%. Birch stems were less than 25% in 44 plots and between 25-50% in 6 plots, of which only 1 of the 6 was spruce dominant. All plots showed visible charring of tree boles though only 3 plots had greater than 1% plot wide canopy blackening. These plots were pine dominant with 2 having less than 1% spruce while the other had 6 spruce of the 27 stems within the sampled area. Prefire aboveground overstory C and N were estimated as4.46±0.738 kg m−2and 0.0385±0.00621 kg m−2, respectively, with 5.31% of C (0.237±0.0321 kg m−2) and 12.3%8of N (0.00474±0.000641 kg m−2) coming from pine and spruce needles. The 50 burnt plots had a large percentage tree mortality (45.0±8.76%) compared to control (4.21±1.63%). Total C and N loss, as well as char layer mass, was not correlated to canopy browning, blackening nor increased mortality in burnt plots relative to control.

Understory coverage was reduced to 10.2±5.15% of its estimated prefire values. This laid bare the surface layer of charred material present in all plots. This layer was conglomerated and easily separable from lower layers and new litter additions which were mostly needles. Upon breaking apart the layer, it was found to be completely blackened throughout.

(Comment)

- Also, when talking about “increases” of C/N in the mineral soil layers: did any of the fires really affect the mineral soils? If not, then a direct effect is not possible and the variability observed may be due to differences between control and burnt sites. Please clarify and discuss.

(Response)

The comparisons were made to highlight the small differences on top of their statistical insignificance to emphasize that likely little change to total C&N occurred in mineral layers due to fire. We agree this is easy to misinterpret and so have removed comparison of these insignificant values to C&N stocks in other layers.

(Comment)

DISCUSSION

- L313: “highly nitrogenous char layer”, this is not correct because, as explained several times in the Results Section, the char layer has a lower N content than the unburnt soil components.

(Response)

We used it to imply a high concentration of nitrogen, i.e. high weight of N per sample weight. We have changed this to reduce any semantic confusion.

Line 313: ...within the high N_R char layer...

(Comment)

- L314: “The char layer was likely largely produced by fire interacting with the understory and moss/litter layer”: what data are supporting this statement? There was a substantial difference between the duff layer in the burnt vs unburnt sites too, so it is expected fire did burn through this layer considerably too (as explained in the second half of the sentence). So the current wording is misleading, please rephrase.

(Response)

The assumption was that the surface char layer always had some contribution from the understory and moss/litter due to their proximity to the surface. Evidence for the duff layer being included in the char layer was given by the fact that char layer C&N was often greater than these two layers combined. It has been rephrased to the following:

Line 314: Proximity to the soil surface suggest a portion of the char layer was likely always derived from fire interacting with the understory and moss/litter layer, however averaged char layer C and N stocks were greater than losses from the two layers combined suggesting there were large contributions also from the duff.

(Comment)

- L324: please add data to support the statement of “low level of overstory damage”… for example, the charring heigh or the fraction of the canopy scorched/burnt.

(Response)

This is addressed in an additional results section

Line 204: 3.1 Survey of burnt plot vegetation

The 50 burn plot overstories were largely pine dominant with a percentage of spruce stems between 25-50% in 5 plots, between 50-75% in 3 plots and 2 plots with greater than 75%. Birch stems were less than 25% in 44 plots and between 25-50% in 6 plots, of which only 1 of the 6 was spruce dominant. All plots showed visible charring of tree boles though only 3 plots had greater than 1% plot wide canopy blackening. These plots were pine dominant with 2 having less than 1% spruce while the other had 6 spruce of the 27 stems within the sampled area. Prefire aboveground overstory C and N were estimated as4.46±0.738 kg m−2and 0.0385±0.00621 kg m−2, respectively, with 5.31% of C (0.237±0.0321 kg m−2) and 12.3%8of N (0.00474±0.000641 kg m−2) coming from pine and spruce needles. The 50 burnt plots had a large percentage tree mortality (45.0±8.76%) compared to control (4.21±1.63%). Total C and N loss, as well as char layer mass, was not correlated to canopy browning, blackening nor increased mortality in burnt plots relative to control.

Understory coverage was reduced to 10.2±5.15% of its estimated prefire values. This laid bare the surface layer of charred material present in all plots. This layer was conglomerated and easily separable from lower layers and new litter additions which were mostly needles. Upon breaking apart the layer, it was found to be completely blackened throughout.

(Comment)

- L340-345: the comparison of the char layer with the charcoal in Hart and Luckai is not appropriate. Those authors selected individual pieces of charcoal within the soil, with a high proportion very probably coming from wood and therefore displaying very specific characteristics. The char layer in this study is a mix of charred organic materials with inorganic charred materials (also called “wildland fire ash”, see Bodi et al. 2014). In addition, there will be also some unburnt components even after cleaning the samples (as the mix is not easy to separate, specially one year after fire). A better comparison would be the charred layer in Santin et al. Geoderma 264 (2016) 71–80, and other similar studies.

(Response)

We agree comparisons with studies measuring similar pyrogenic layers are more valuable and we have now adjusted the text to this.

Line 340: The strong alteration of char layer C:N relative to prefire fuel is comparable to results from studies that have incorporated similar pyrogenic layers that are observed to be a mixture of organic or inorganic material types across broad ranges of combustion completeness (Bodí et al., 2014). For example, the C:N ratio in a pyrogenic layer 1 year after a low intensity Siberian Larch forest surface fire in Russia was 31.4 (prefire 49.1), which is much lower than the 43.8 C:N ratio (prefire 39.4) observed the day after an experimental, high intensity jack spruce crown fire in Canada (Santín et al., 2016; Dymov et al., 2021), further suggesting general differences in thermolability of soil C and N under regionally varied heating regimes.

(Comment)

L346-350: along the same lines than previous comment, it may be that the inorganic N is adsorbed to char but, also, that the inorganic components of the “ash” layer are still present in your “char layer”.

(Response)

This is also a good point. We have revised the text to account for it:

Line 346: The high N_R of the char layer may therefore be due to adsorption of fire mineralized N or preserved, prefire mineral N and act as a steady source of bioavailable nutrients to plant and microbial communities during succession. Alternatively, N may be stored in this layer in partially combusted organic forms (Certini, 2005).

(Comment)

- Section 4.2: why the immediate weather parameters are not discussed here (e.g. SPEI)? These will be the ones more closely related to fire characteristics and therefore differences between burnt and unburnt plots.

(Response)

This section, and the manuscript overall, was meant to highlight the climatic control pathways on C&N loss. SPEI and anomalies (as well TEM) were used as exogenous variables to test the isolation of these effects and were more of a supplement to the main message. Therefore they were reserved for the following section to better focus on these distinct aspects.

(Comment)

- L365: “ignition probability” does not relate to fuel but to ignition opportunities such as human causes (e.g. accidental) and lighting. please rephrase.

(Response)

It was left unclear whether ignition probability here considers a time aspect (concerning the chance of receiving an ignition source) or if it implies probability of ignition of a stand under receiving a given source. We can try to reduce this uncertainty by modifying the text.

Line 365: A caveat of the pair plot matching methodology is that burnt plots may have had a greater tendency to ignite due to specific properties that heighten their fire susceptibility relative to controls. As a result, the comparably low C and N losses may be due to underestimation via burnt plots being biased to a greater prefire fuel load than their paired controls (systematic error) rather than these differences being approximately random (random error).

(Comment)

- L367: What info/references support this statement? This does not necessarily has to be the case, actually, very dense forest plots may have a higher moisture and, therefore, may be less susceptible to burn (as explained in Section 4.3 actually).

(Response)

The support is given directly after, in line 368, where N was observed to have no significant difference due to fire. If there is a bias in the control plot matching method it is not likely that it results in a significant increase in control plot N stocks relative to the actual (yet unmeasured) prefire N stocks in burnt plots. This would require an unlikely fire induced increase in total N to compensate and bring the differences to 0 postfire. Therefore, any present systematic error is either likely negligible or due to *increased* prefire burnt plot stocks relative to control.

The paragraph then goes on to argue why this systematic error is not detectable within the data used in this study, suggesting either N losses are indeed minimal and/or more detailed analysis of pair plot biases are needed to explain them.

Indeed, higher moisture has been related to increased fuel loading (Walker et al. 2018 in the manuscript). But failure of the SPEI index to improve our models led us to conclude instantaneous levels of moisture did not substantially restrict the percentage availability of fuel under the extreme drought conditions of 2018. However, we did not make assumptions of typically wetter fuels being more or less flammable than typically drier ones, when both are thoroughly dried. That we left to test through CCVs, bulk density, C:N ratio etc. Also, we were not in the position to suggest flammability, in terms of C lost relative to C loading, is indeed related to fire's ability to propagate into and through a given stand, and only had done so to hypothetically introduce a discussion of a possible source of plot-pair mismatch (which is now removed from the manuscript).

(Comment)

- L370: I don´t understand this statement, was TEM not the same in the control plots than in their burnt counterparts?

(Response)

Not exactly, but they were close. It is important that we state in the methods section that TEM is made of integer values ranging from 0-240 and not based on only a few broader moisture classes as is common. This might be a source of confusion. See comment above for explanation on the TEM mismatch.

(Comment)

FIGURES

It would be very useful to have a figure with pictures showing burnt and unburnt sites.

(Response)

We agree a visual could aid in getting a feeling for the plots. There are 100 plots that all look quite different, but a few photos can be added as supplementary information if valuable.

(Comment)

TECHNICAL COMMENTS

Please see attached pdf with minor suggestions directly on the manuscript.
Citation: https://doi.org/10.5194/bg-2021-178-RC2

(Response)

Thank you, these comments were helpful and all addressed within revisions.