Author Comment

We are grateful to the three anonymous referees for their insightful and constructive feedback on our discussion paper. We have expressed our thanks in the acknowledgements section of our revised manuscript. Below we address each of the referees' comments in turn, explaining our response and detailing relevant changes that we have made to a revised version of our paper. Our responses below are shown in red text, and changes made during revision of the manuscript have been highlighted using the 'track changes' function.

Anonymous Referee #1

The study of Speed et al. investigates how carbon stocks in different vegetation and soil pools vary across a ca. 300m altitudinal gradient in southern Norway. They find little effect of grazing intensity, twelve years after grazing levels were manipulated. Their main conclusion is that there is continuous variation in soil organic matter stocks, with soil stocks increasing linearly with altitude, while there is a clear 'breakpoint' at the treeline for vegetation carbon stocks. The implications of these contrasting patterns are discussed in the context of ecosystem carbon stocks.

This is an interesting paper, but I do not find the conclusion that soil organic matter stocks are linearly related to altitude to be convincing. It appears that there is the same change as has been observed in previous studies (Sjögersten Wookey 2009; Hartley et al. 2012), albeit slightly less pronounced. The tundra system investigated in the current study is more grass-dominated than in these previous studies, which may help explain some of the differences. However, the key issue is that the data presented in Figure 3 does appear to show a change in organic matter contents and C stocks in the organic horizon at the treeline. All the organic horizon C contents are lower in the forest. There is one thick organic horizon within the forest zone (Fig A4), but the organic horizon C stocks in all other forest sites are substantially lower than the mean for the tundra. The analysis does not find a significant relationship between organic matter carbon stocks and altitude within the forest or tundra zones, and therefore it appears that the overall relationship with altitude is driven, in large part, by a change between the two ecosystem types.

In the supplementary methods of the study of Hartley et al. 2012, data were presented comparing tundra-heath and birch forest at the same altitude within the ecotone, ob-serving the same pattern of changes in soil carbon storage as when comparing sites above and below the treeline. Again, it may be that the more grass-dominated tundra in the current study explains the reduced magnitude of the differences in organic horizon C stocks above and below the treeline, but the data do not appear to support the conclusion that there is continuous variation in soil stocks with altitude, or that there is no threshold change around the treeline.

There is still very valuable information in this paper, especially in terms of how ecosystem C stocks change with altitude, with the relative importance of changes in above versus below ground stocks being presented clearly. I would suggest the study not claim there is no threshold change in soil carbon stocks around the treeline, but rather place the relatively small threshold change in soil stocks observed for this ecotone into the context of substantial increases in tree biomass. It would also be worth emphasising the differences between the vegetation communities (grass versus shrub-dominated tundra) being investigated in the current study versus those in much of the literature which has been cited.

Response: Referee 1 states that the observed linear increase in organic horizon C stock (Figure 4c) is driven by differences between the forest and alpine ecosystems rather than elevation *per se*. The evidence for this is that the organic horizon C stock is lower in the forest than alpine zone (when averaged across the elevational gradient within each system, P15446 L9-10 in the Discussion Paper) and that there is no elevational trend within either the forest or alpine zone (P15446 L11-13). The referee's interpretation here is correct. As we detailed in Section 3.2.2, there was no breakpoint in the linear relationship between organic soil C stock and elevation. As the referee states, the increase in organic soil C stock can thus be viewed as a response to the changing ecosystem, rather than a relationship with elevation *per se*.

Our main conclusion from this study is that C stocks do not linearly change with elevation across the treeline ecotone (15449, L21-24). We discuss that vegetation state explicitly needs to be addressed. So we completely agree with Referee 1 regarding this point.

In our revision we have revised both the discussion section and the abstract to avoid giving a mixed message. We now explicitly address the differences between the ecosystems in organic horizon C stocks in the discussion. We have also revised the discussion to further emphasise the need to account for vegetation state in addition to elevation when predicting C stocks around the treeline ecotone.

We have also highlighted the different vegetation type utilized in our study (see the following point for a more specific response to this point).

Specific comments:
Page 15441 line 5: This is the first time that the type of tundra being studied is really described. It would be useful to include more details in the introduction regarding the type of ecotone being studied and how it differs from some of the previous studies which have been cited.
Response: The referee raises a good point, although we note that the vegetation composition in our study is closer to that studied by Kammer et al., than the Abisko studies of Sjøgersten & Wookey and Hartley et al.

In our revision we have provided more detailed description of the tundra vegetation in the Introduction section, and have highlighted how we study a different tundra vegetation type to some of the previous studies (Sjøgersten & Wookey, Hartley et al.), but more closely related to others (Kammer et al.).

Page 15443 line 3: A fuller justification of the number of points required to detect breakpoints would be useful. There are only nine forest plots and since the hypotheses are about continuous versus discontinuous changes, is this really enough to be able to detect relatively small magnitude threshold effects?
Response: There are indeed only 9 plots within the forest. However, we do not test for breakpoints within the forest or within the alpine zones, only within the entire elevational gradient (where n=36). Sample sizes of around 40 have been shown to give acceptable estimates of breakpoint positions (Ryan, S. E., and Porth, L. S.: A tutorial on the piecewise regression approach applied to bedload transport data, U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, 41, 2007.)
In our revision we have given fuller justification for the sample size.

Page 15445 line 14: I am slightly confused about the definition of the organic horizon. With some of the soils having carbon contents as low as 10

Response: The reviewer raises a valid point here. According to IIUSS WRG, 2006 organic material should contain 20% SOC. The reason that some of the plots sampled in the birch forest have values as low as 10% is due to mixing of organic material (Oiea) with the underlaying mineral layer due to turbation. This turbation is assumed to be due to wind exposure on the trees and resultant below-ground perturbation. This turbation will lead to reduced estimates of C in the organic horizon, increased estimates of C in the mineral horizon, but will have no effect on the overall ecosystem C stock estimates.

In our revision we have clarified this by adding: "Due to difficulties separating the pure O-horizon from the underlying mineral horizon in the birch forest, as caused by arboturbation, the O-horizon represented OE or OA-horizons. Mixing of organic and mineral material will reduce the soil organic carbon content (SOC) and increase the bulk density of the soil (Martinsen et al. 2011). However, estimates of the ecosystem C stock will not be affected." (line 19, pg 15441).

Page 15448 lines 9-13: There seems to be an argument here that increases in carbon storage in plant biomass takes place more slowly than losses of carbon from soils. This is an interesting suggestion and perhaps one that could be discussed in more detail, in terms of trajectories of change in ecosystem carbon storage as the treeline shifts.

Response: This is indeed the argument we make here, and we agree that it should be discussed in more detail as the referee suggests.

In our revision we have further elucidated this argument.

Anonymous Referee #2

Speed et al measure soil and vegetation C stocks across an altitudinal gradient which includes a treeline ecotone. Within the alpine zone, they also assess the effects of grazing on ecosystem C stocks. The main question driving this research is whether there is continuous or discontinuous variation in ecosystem C stocks across the treeline ecotone. The authors report a minimum in ecosystem C stock at the treeline, with gradually increasing C stocks at both lower and higher elevations. They also report no significant effects of grazing on ecosystem C stocks.

The results are well presented and the manuscript is clearly written. The data shows the complexity of C storage across a mountain birch treeline, with relatively high productivity and stimulated decomposition at lower altitudes and low productivity and de-composition at higher altitudes. However, I think that the authors should move the focus to the influence of different vegetation on C stocks, rather than interpret the treeline as a 'discontinuum' within an elevational gradient (see. p. 15447, l. 15-17). The fact that vegetation C stock decreases as one goes up to a treeline is trivial, and somewhat implicit in the definition of treeline. What I find relevant in this study is that increased C stored in the soils can outweigh this decrease in vegetation C, with its implications on changing C storage patterns in regions where treelines are moving upwards.

Response: That birch C stock decreases up to the treeline is of course implicit in the treeline definition. However, we do believe that it is important to quantify the magnitude of the gradient in vegetation C stock, and particularly the degree to which the birch C stock is partially balanced by the field-layer vegetation C stock (higher in the alpine zone than in the forest). The patterns of ecosystem C stocks, comprising vegetation and soil C stocks are of great relevance (note that Referee 1 makes a similar point from the 'other side of the coin'). We do find clear evidence that there is a discontinuum in some C stocks at the treeline within the overall elevational gradient, and as the referee points out, this has implications for C stocks along elevational gradients in regions with dynamic treelines.

In our revision we have increased the emphasis on the influence of different vegetation types on C stocks in addition to discontinuous changes at the treeline.

Moreover, I think that changes in vegetation type across the treeline and the elevational gradient itself (obviously) overlap, and that it is difficult to separate the effects of both factors. Data in figs 3-5 show both, an elevational gradient and a change in vegetation and this is well illustrated by the segmented regressions in figs 3 and 5. However, I think that fig. 4 also shows a discontinuity in organic C content. Maybe the authors could also consider to study the effect of elevation on C content and soil depth within the alpine zone (Fig. 4), not with a segmented regression but with a regression excluding the forest data. Would the current relationships still hold? This could be easily added to the current figure. Also in Fig A4, excluding the forest data points, maybe a negative relationship between organic horizon depth and elevation becomes significant? This would probably explain why the increase in organic horizon C stock does not increase at the rate of organic C content (Fig. 4C 4a).
Response: The analyses that Referee 2 suggests have already been carried out, and these were reported in the original version of our paper. These are reported in text in the results. E.g. elevation and organic horizon C content within the alpine zone: P15445 L18. We have not added these relationships to the Figures, as in our opinion this makes them overcrowded and hard to read.

In our revision we have also added the statistics to the results section of our test of the difference in horizon depths between the forest and alpine zones – the organic horizon was on average 1 cm deeper in the alpine zone than in the forest zone.

Overall, I think that the focus of the paper could be changed from a rather descriptive treatment of the elevational gradient effect to a discussion of the different mechanisms driving the observed effects (vegetation changes, microclimatic effects on decomposition, etc.).
Response: Unfortunately we do not have data available to partition the influence of the different mechanisms on carbon stocks. However, in our revision we have added further discussion (3 new paragraphs, see the comments of Referee 3 and our responses) of these different mechanisms that may drive the patterns that we have observed.

Specific comments
p. 15438, l. 1-3. Are the reported elevational patterns in SOC largely vegetation mediated? What is the contribution of temperature/moisture effects on SOC?
Response: The authors of this review link elevational patterns to both abiotic controls on decomposition, and changes in vegetation with elevation.
We have revised this section to include this information.

Fig 2. Wouldn't a classification based on functional groups (i.e. shrubs, grasses, sedges...) be more useful?
Response: Referee 1 suggested that the difference in vegetation between our study and other related studies be given greater emphasis. Therefore we believe that retaining the species based vegetation description is preferable as it provides greater information as to the field-layer vegetation.

Fig. 5 caption: 'Field vegetation'? Birch is vegetation as well...
Response: Thank you for pointing out this error
In our revision this has been corrected

Referee 3

Speed et al. present a clearly structured paper documenting changes in ecosystem carbon stocks with elevation across a treeline ecotone. The major findings of this paper are: (1) vegetation C stocks decrease with elevation until the treeline, after which the vegetation C stocks are constant, (2) organic soil C stocks increase with elevation across the all vegetation zones, (3) total ecosystem C stocks increase with elevation above the treeline but decrease with elevation below the forest line, such that there is a minimum between the forest line and treeline (Fig. 5), and (4) there was no effect of short-term grazing on elevational patterns in ecosystem C stocks. This manuscript is appropriate for the scope of the journal Biogeosciences.

General Comments:

The authors establish clear predictions and then test these using appropriate methods, statistical techniques and interpretation. The results are well presented and the findings and interpretation are interesting. The paper is well written and the figures appropriately formatted and clear for the most part (see technical corrections below). The references to the literature are appropriate. However, I agree with reviewer #2 that the focus on the treeline as being static with a decrease in vegetation C with elevation is somewhat trivial and does not highlight the greatest contributions of the study.
Response: As we also replied to Referee 2, although it may be obvious that birch C stocks decrease towards the treeline, it remains important to quantify this in order to compare it to the C stocks in the rest of the vegetation and the soil. In our revision we have also added discussion relating to the dynamic nature of the treeline. This is further detailed in response to another of Referee 3's comments below.

This study will contribute to our understanding of forest ecotone carbon storage, particularly under global change. In fact, relating the findings to global change and addressing the dynamic nature of this treeline ecotone is where the paper could be strengthened (see below). There are three issues that could be better addressed: (1) the paper could have a stronger focus on climate and climate change, (2) the dynamic nature of the treeline could be better incorporated into the interpretation of the data, and (3) the implications of reduced recruitment due to herbivory could be better discussed.
Response: We are grateful for this insight from the Referee. We have addressed all these issues in our revision. Details of the changes made are given below in response to the Referee's specific comments regarding these points.

As Referee #2 discusses, the paper could have a stronger focus on the separate contributing effects of vegetation versus climate along the elevational gradient. And these findings could be put in the context of on-going climate change in the region in the discussion. Right now the links of the findings to climate are weak. What are the differences in climate along the elevational gradient? How do these differences relate to projected temperature changes in the region? How might ecosystem C stocks change with climate warming?
Response: The growing season soil temperature (5cm) decreases by around 1.4°C per 100m elevation within the alpine zone (1120 to 1260m). We unfortunately do not have equivalent data for within the forest. However, the climatic warming scenarios suggest a mean annual temperature increase of 2.3 to 4.6°C by 2100 in Norway (2.5 to 3.5°C in study region). Thus we can expect decreases in high alpine ecosystem C stocks, and increases in low alpine ecosystem C stocks dependent on rise of the treeline

In our revision we have added discussion of this, and combined this discussion with that of the timescales of different stock responses as suggested by Referee 1.

The ecosystem C stocks are put in the context of the vegetation gradient, but the dy-namic nature of the treeline that is suggested by the age structure (Fig. 3b) is not ad-equately discussed. How will ecosystem C stocks change with an advancing treeline. The study may not be able to answer this question, but it could be better addressed in the discussion section of the paper. Perhaps some sort of modelling exercise could shed further light on this issue.
Response: The reviewer makes a very good point here.
In our revision we have added discussion relating to the dynamic nature of the treeline in general, and with respect to herbivory (see following comment). The idea of a modelling exercise to explore this further is particularly interesting and something that has already begun, however, we feel that it is beyond the scope of the current study.

Though the authors do discuss herbivory, the implications of changing herbivory on treeline carbon storage is not as well fleshed out in the paper as it could be. The authors did not observe an effect of short-term grazing on the ecosystem C storage, however, they have previously found an impact of grazing on tree recruitment in this region. However, the impacts of grazing on future reduced recruitment could potentially be worked into a model estimate of the impact of grazing on future ecosystem C stocks.
Response: In our revision we have developed the discussion of the implications of changing herbivory on C storage across the treeline ecotone. To include estimates of the impact of grazing on C storage would require a detailed simulation model to be developed. We feel that this is outside the scope of the current study. However, it is certainly a worthy avenue to pursue in future.

As mentioned above, it would improve the paper if the difference in response rates between soil, vegetation and herbivory contributions to ecosystem C were explicitly addressed. Since both soil and vegetation C are driven by climate, how quickly would change occur to ecosystem C storage in this system with treeline advance? This dynamism also ties in with discussion of grazing, since the authors recognized already that the experiment may not have been running for long enough to have a meaningful impact on C stocks during this study. Perhaps it would be possible to gain further information from analysis of the grazing plots regarding response times in this system (as per review 1).
Response: This is a good point.
In our revision we have added discussion of the response rates of the different components of the ecosystem, discussing the direct impacts of climatic warming (e.g. temperature on

decomposition rate), followed by vegetation change (which may be buffered by herbivory, or accelerated by decreases in grazing) and then the indirect impacts on soil stocks mediated through vegetation change.

In order to address these issues, I would recommend the inclusion of three new para-graphs in the discussion and perhaps the addition or qualitative or quantitative modelled estimates of the influence of changing climate, treeline dynamics and herbivory in the region and the impacts of these changes on ecosystem C storage.
Response: In our revision we have added discussion of these three factors (herbivory, climate and response rates). Modelling of the impact of changing climate and herbivory through treeline dynamics is a very good idea, but beyond the scope of the current study.

Specific Comments and Technical Corrections:
1. The term field-layer vegetation should be changed to ground vegetation or some-thing similar as it is confusing. (And, the hyphenation should be used consistently if the term or a similar one is retained)
Response: Ground layer vegetation is often used to refer to bryophytes and lichens. We have therefore retained the term field-layer.
In our revision we have defined field-layer at first mention, and have ensured consistent use of the hyphen.

2. There are some minor phrasing issues that might benefit from a re-read e.g. p15437, line 2-5: 'biomass contribute', 'stock are' – singular or plural? P 15440, line 3 'soils were stored dark and cold' could be 'soils were stored in dark and cold conditions
Response: Thank you for pointing out these errors.
In our revision these have all been corrected.

3. P 15437 line 16: Should treeline advance and shrub expansion be considered an environmental 'challenge'?
Response: We agree that this was poorly phrased. The challenges are caused by the treeline advance (e.g. through driving further climatic change) as described later in this paragraph.
In our revision we have changed 'environmental challenges' to 'environmental changes'

4. P15448 line 26-27: Discussion between Hallinger et al (New Phytologist (2010) 186: 890–899), Buntgen & Schweingruber (New Phytologist (2010) 188: 646–651) and Hallinger & Wilmking (New Phytologist (2011) 189: 902–908) – could be useful for context on treeline advance and age structure.
Response: We are aware of this discussion and agree it gives important context.
In our revision we have cited the original Hallinger et al. paper (2010).

5. The grey and black dots in the figures are very hard to distinguish and should be changed to be larger or different symbols so that they can be told apart from each other.
Response: In our revision we have increased the size of the circular points and have also lightened the shade of the grey points to increase the contrast from the black points (This applies to Figures 3, 4, 5, A2, A3, A4).

6. Figure A2 is very difficult to read. Perhaps it could be turned into a multi-panel figure of the different components of the ordination to improve the communication of the data/analysis.
Response: We agree that this figure is difficult to read.

In our revision we have edited this Figure to improve its legibility within a single panel since we found it difficult to interpret when split between multiple panels.