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Interactive comment on "Impact of nitrogen fertilization on carbon and water fluxes in a chronosequence of three Douglas-fir stands in the Pacific Northwest" *by* X. Dou et al.

X. Dou et al.

baozhang.chen0808@gmail.com

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Dear Reviewer #2, We greatly appreciate your constructive review, which has been very helpful in improving our manuscript. Please find our point by point responses to your questions and suggestions below.

Comment #1: The Dou et al. study uses a artificial neural network (ANN) to estimate the 'control' treatment CO2 and water fluxes of a nitrogen (N) addition experiment in a Douglas Fir chronosequence in the Pacific Northwest. The experiment was conducted in the footprint of three eddy-covariance (EC) towers meaning the scale of the experiment was much larger than most N addition experiments, and also that the use of a

traditional control treatment was impractical. Overall I think this is an interesting study and important for assessing the impact of N addition on C and water fluxes in semi-natural forest systems. I think that the ANN approach is a nice way to address the impracticalities (cost and landscape heterogeneity) of using a traditional control in manipulations at the scale of EC measurements. However, I have one major concern with the ANN method and that is that the effect of stand development is not accounted for. Considering the data from both the HDF00 and HDF88 sites together, Figure 3 shows that there is a near linear relationship between GPP (or NEP) and stand age. The ANN does not consider stand age, which when accounted for could dramatically reduce the calculated N fertilization response of GPP and NEP. Stand age must be accounted for and I discuss this further below. The manuscript will benefit from restructuring, focusing around the broader question on the effects of N addition on C and water fluxes. The abstract is focused on the broader questions and the introduction mostly deals with them but then concludes that the primary goal of this study is to "resolve the slightly different findings ..." of Jassal et al. (2010) and Chen et al. (2011). Response: We address the issue of taking into account the effect of stand age at HDF00 and HDF88 in Comment #10 below.

Comment #2: Introduction I found some of the introduction to be lacking in structure and detail. Additional quantitative detail should be added to the discussion of the effect of N deposition given the widely different estimates between the Magnani paper and for example Sutton et al. (2008). Response: We thank the reviewer for this suggestion. We have added quantitative detail on the different estimates of N effects in Section 1 in the revised manuscript (see line 21 page 4 to line 4 page 5).

Comment #3: The introduction to the Jassal and Chen studies comes out of nowhere. There needs to be some introduction to the site and the experiment. Please develop the hypotheses/goals to be broader than just the resolution of differences between the Jassal and Chen studies. Response: We appreciate the suggestion. We have provided more background to the site and fertilization experiment (see lines 12-16 page 6 and lines 6-8 page 7).

Comment #4: Methods As pointed out by M. Wallenstein, why was such a high N addition rate used? This is way above anything that may occur via N deposition. There needs to be some justification based on the goals of the study. Chen et al. (2009) is referred to for the GPP and R partitioning method but some description should be added. NUE, WUE and LUE need defining in the methods. Especially NUE and LUE. Is LUE GPP over absorbed PAR or just PAR? Is NUE the sum of additional NEP over the four years, or is it the annual mean over the N addition? In fact NUE is a specific term, usually used to refer to NPP over N uptake. The term used by Sutton et al. 2008 is C:N response, please change NUE to something more in line with the literature. Response: Following the reviewer's suggestion, we have added the description about partitioning NEE into GPP and R in Section 2.3 in the revised manuscript (see lines 1-8, page 9). In the Pacific North West, N fertilizer application is typically 200 kg N ha-1 on Douglas-fir forest land. It is unlikely to have more than three applications over the stand rotation (typically 60 years). Regarding light use efficiency (LUE), it was the ratio of GPP to absorbed photosynthetically active radiation (APAR). N use efficiency (NUE) has been changed as C:N response. C:N response should be calculated from cumulative carbon gains over the entire post-fertilization period, we have now defined cumulative C:N response as the total increase in the net C sequestration over the four years following fertilization (i.e., ïĄĎNEP) per unit N applied. The 4-yr cumulative C:N response was 53, 97 and 51 kg C (kg N)-1 for DF49, HDF88 and HDF00, respectively. Detailed discussion of C:N response can also be found in our response to Comment #11 below.

Comment #5: Section 2.5 heading – I wouldn't describe the modeling as an experiment, it's a comparison of methods. Response: According to the reviewer's suggestion, we have modified the heading of Section 2.5 in the revised manuscript (line 20 page 10).

Comment #6: Results: The results section is disorganized and should be restructured

to improve the flow and readability in the manuscript. The comparison between the MLR model and the ANN model is interlaced with discussion of the N effects. The results should be organized to: 1) Start with the observed C fluxes (Figure 2 & section 3.2), 2) present the ANN model validation and comparison to the MLR model (Figure 1, then Fig 4 & 5, sections 3.1, section 3.4 to ln 10 p 2015), 3) present the effect of N addition (Fig 3, Fig 8, Fig 9, section 3.3, 3.4 from ln 10 p 2015, 3.5). Response: We have re-organized Section 3 (Results). We have combined the original five parts into three parts in the revised manuscript. Section 2 includes: 3.1. Comparisons of observed C ïňĆuxes and ET before and after fertilization in the chronosequence; 3.2. ANN model validation and its comparison to MLR model; and 3.3. Effects of N addition on C exchange ïňĆuxes, WUE and LUE in the chronosequence. Comment #7: Fig 6 & 7 can be added to Fig 4 & 5. Response: We have done this.

Comment #8: Why are GPP, R and NEP not presented in the same way as Figure 8? Please add another figure. Response: We have now presented them as in Figure.

Comment #9: Fig 3. All the pre-fertilization points should be open shapes and all post-fertilization should be filled shapes. Response: Following this suggestion, we have re-drawn Figure 3 in the revised manuscript.

Comment #10: Discussion: There are several issues with the discussion. 1) Figure 3 really suggest to me that there is a strong effect of stand development that has not been discussed at all. Fig 3a shows a near linear trend of GPP and NEP to stand age through the two sites HDF00 and HDF88. Does the ANN account for this? I'm assuming not. This needs discussing and further analysis to try to tease out the effects of stand development from the effect of fertilization. I don't think the ANN is able to do this. Without considering stand development it's impossible to support your second conclusion that N fertilization was the cause of the increase in GPP measured by the EC towers at HDF00 and HDF88. Response: We agree with referee that there is a significant effect of stand development as we demonstrated in Figure 3. Because of the differences of stand age among these three stands, the model was applied to each site individually, which we have now made clear in the revised manuscript (see lines 7 - 21 page 25). However, Jassal et al. (2010) found that adding age as another variable to describe C fluxes in the two growing stands (i.e., HDF88 and HDF00) did not improve the model fits. We further verified that, regardless of stand age, the ANN model for the calibration period in this study was still able to captured the relationship between environmental variables and C and water fluxes during the pre-fertilization period in the three stands with R2 close to 1. So ANN simulations for the model calibration period explained approximately 99% of the variance in monthly C fluxes and ET. On the other hand, although we didn't consider stand age as an input variable in ANN model, we believe that the ANN model considers the information on stand development in responses to C and water fluxes by the variations of C fluxes and ET in a chronosequence in an implicit way. Because we used C fluxes and ET as the output values of the ANN model to train the network during the period of pre-fertilization. It is worthy to note that the C fluxes varied with the stand development in a chronosequence, especially in two younger stands, which was different from environmental variables. Therefore, we may deduce that the trained ANN model had captured the information of stand development. This has been added to the revised manuscript in Section 4.5 (see lines 7-21 page 25). Further discussion of the effects of stand age can also be found in our response to Comment #12 below.

Comment #11: 2) The discussion in the context of N deposition is poor. There is limited discussion of the difference between the large N addition rates in this experiment and how this might be different to the lower rates of N addition via deposition. It is surprising that the C:N response (what the authors term NUE) is the same order of magnitude as previous studies (e.g. Sutton et al. 2008) as one would expect the large N addition rate to be used much less efficiently that the N added via atmospheric deposition. Furthermore, it is difficult to know if the comparisons are like-with-like as the C:N response shown by Sutton et al. 2008 and others are based on annual rates, and N arrives continually via deposition as opposed to a single fertilization event. There is no discussion that N would be expected to be used more efficiently by the forest subjected to the 60

kg N ha-1 addition, 200 kg N ha-1 is huge and more N under this treatment would likely be lost via leaching, volatization and denitrification. Response: We appreciate the comment. First, the three different-aged stands we investigated in this study belong to Pacific Northwest coastal forests of the United States and Canada. Pacific Northwest coastal forests between Oregon and Alaska cover approximately 105 km2 and play an important role in the global C cycle. In this region, due to their remote location, there is very little atmosphere N deposition. As a result, the standard forest fertilization application rate in West Coast forests is 200 kg N ha-1 from prilled urea (Hanley et al. 1996). While fertilization of stands of mid-rotation trees (i.e., of commercial thinning size, 20–40 years old) can result in additional merchantable timber volumes, fertilization late in the rotation may be the most attractive alternative economically. Similarly, to boost growth of seedlings/saplings while avoiding competition from prolific brush on N-deficient soils, fertilization is done on the drip line of saplings at a lower rate of 50-60 kg N ha-1. Therefore, high N fertilization level (200 kg N ha -1) in one single dose used in this study is a common forest management activity in N-limited forests (Chen et al., 2011), which is different from N deposition by the experiments of long-term low-dose N addition studied by Hyvönen et al. (2008). In conclusion, it is also important to investigate the responses of net C sequestration to this common N fertilization activity. Second, C:N response [kg C (sequestered) kg -1 (N added)], defined as the increase in the net C sequestration (i.e., NEP) per unit of N application, has been widely used to estimate the response of C sequestration to N addition (Magnani et al., 2007; Sutton et al., 2008). In this study, the 4-yr cumulative C:N response was 53, 97 and 171 kg C (kg N)-1 for DF49, HDF88 and HDF00, respectively. The values above from our study and Jassal et al (2010) are similar to those obtained by Sutton et al. (2008), which are significantly smaller than the assessment by Magnani et al. (2007), with an extremely high C:N response (approximately 725 kg C (kg N) -1) in wet deposition. Furthermore, for the youngest stand (HDF00), it seems that the 60 kg N ha -1 application to individual trees was more efficient with respect to C sequestration than the larger application (200 kg N ha -1) for the two older stands, which resulted from more GPP stimulated from N application to younger stand. We have incorporated these points into Section 4.3 of the revised manuscript (see line 8 Page 21 to line 9 page 22).

Comment #12: 3) There is limited uncertainty quantification. Both in the comparison of the Chen and Jassal work to this study and the effects of N fertilization using the ANN. Estimates of uncertainty should be added to Fig 8 and the data in Tables 2 and 3 in order to statistically asses the effect of N addition on C and water fluxes. However, this still would not be sufficient to account for the effect of stand age as discussed above. Response: We agree with the referee that there remains significant uncertainties in estimating the effects of fertilization on C and water fluxes, as shown in Fig. 8. We have added the results from Jassal et al. (2010), Chen et al. (2011) to Tables 2 and 3 to better present the differences among them in the revised manuscript. With respect to the effects of stand age, Magnani et al. (2007) found that 92% of the total variability in NEP resulted from age-related dynamics in five chronosequences analysed from boreal coniferous to temperate broadleaf forests. However, they also indicated that NEP was overwhelmingly controlled by N addition by human activities in many temperate forests and there was a strong relationship (R2=0.97) between average C sequestration and wet N deposition, although it was largely obscured when taking the effect of stand age into consideration. Krishnan et al. (2009) found that the same environmental variables that we used had a strong effect on C fluxes at half hourly to daily and even monthly timescales. Jassal et al.(2010) found that environmental variables explained about 95% of the variance of monthly GPP, R and ET in 61 yr-old DF49. Both Krishnan et al. (2009) and Jassal et al. (2010) used a multiple linear regression (MLR) analysis with a monthly step. It was impressive that an ANN model with its powerful advantage in investigating the complicated non-linear processes determined the relationship between environmental variables and C and water fluxes during the pre-fertilization period in the three stands, with an R2 close to 1, as shown in Table 1 and Fig. 5 (mentioned above). According to the fitted ANN model, it was more effective to simulate the C and water fluxes during the post-fertilization period, due to its strong generalization ability in extrapolating the implied and captured law between environmental variables and C

and water fluxes from the period of pre-fertilization to post-fertilization. Therefore, in this study, we focused on removing the inter-annual climatic variability impacts on C fluxes and ET in the three stands during the pre-fertilization period to estimate the effects of N fertilization on carbon and water fluxes during the post-fertilization four years. We have included the above discussion in Section 4.5 of the revised manuscript (see line 21 page 24 to line 4 page 27).

Comment #13: Section 4.5 is necessary but could be more focused and precise. What does the “and limitation” in the section title refer to, limitation to what? Ln 7/8 what does “modeling experimental methods” mean? Response: As suggested by the reviewer, we have now strengthened and somewhat sharpened this section to make it more focused. According to our understanding, "modeling experimental methods" refers to using some methods as modeling for conducting an experiment to address the scientific issue. In the case of our study, it can be considered that we used ANN and MLR methods as modeling the relationship between environmental variables and C and water fluxes to investigate the effects of N fertilization to C and water fluxes, respectively. To understand clearly, we have changed the statement "modeling experimental methods" to " modeling methods of our experiment " in the revised manuscript (line 20 page 10). The limitations in our study mainly include the uncertainties in EC-measured data, the selection of key input variables in our data-driven model regardless of the effect of stand development , the defects in model performance and the chosen time steps. These limitations could lead to some uncertainties in the estimates of the N fertilization effects in this study. Nevertheless, we believe this study helps to quantify the effects of N fertilization on C and water fluxes and reduce the uncertainty in model simulations. We have revised this part (Section 4.5) of the paper according following the reviewer’s suggestions in the revised manuscript (see line 21 page 24 to line 4 page 27).

Comment #14: I like the discussion of the reduction of ecosystem respiration in response to N fertilization, this is an effect that is unlikely to be affected by stand development and is a major conclusion of interest to the ecosystem C cycling community and it would be good to see this discussed in greater depth. Response: We appreciate these positive comments, and have now further strengthened the discussion in Section 4.2 of the revised manuscript (see lines 18 to 23 page 19).

Comment #15: Minor points: As noted by the previous reviews there are some acronym explanations missing, i.e. EC, PAR . I also found the site labeling difficult to follow, why not label the stands just with 61yr, 22yr, 10yr or at least add the age to the site identifier. Response: As stated in responses to earlier comments, all acronyms have been duly explained and defined in the revised manuscript. As suggested by the reviewer, we have also changed the stand labeling in the entire revised manuscript.

Comment #16: Section 3.3 heading – “variations” what do you mean by variations? Be more descriptive. Response: We thank the referee for this suggestion. ’Variations’ refers to the interannual variation of EC-measured C ïňĆuxes, ET, WUE and LUE. However, according to the reviewer’s suggestion, we have deleted the heading of the previous Section 3.3 in the revised manuscript.

Comment #17: Section 3.5 ln 14-19 should be part of the model validation/comparison section. Response: We have moved this part has into Section 3.2 of the revised manuscript.

Comment #18: There are several misleading/unnecessary conjunctives, e.g. “However” ln 24 p 2016 (one would expect WUE to increase WUE with no change in ET and an increase in GPP); “Moreover” ln 2 p 2017. Response: Good point. This has been corrected.

Comment #19: ln 27 “due to that it caused ...” change to “due to” Response: The change has been made.

Comment #20: P 2003 ln 3 “ecosystems mainly” needs to be corrected. There are a number of examples of this. Response: We have corrected this and made similar corrections elsewhere in the paper.

References

Chen, B., Coops, N. C., Andy Black, T., Jassal, R. S., Chen, J. M., and Johnson, M.: Modeling to discern nitrogen fertilization impacts on carbon sequestration in a Pacific Northwest Douglas-fir forest in the first-postfertilization year, Glob. Change Biol., 17, 1442-1460, 2011. Hanley, D. P., Chappell H. N., and Nadelhoffer E.H.: Fertilizing coastal Douglas-fir forests, Bull. 1800, Wash. State Univ. Ext., Pullman, Wash, 1996. Hyvönen, R., Persson, T., Andersson, S., Olsson, B., Ågren, G.I., and Linder, S.: Impact of long-term nitrogen addition on carbon stocks in trees and soils in northern Europe, Biogeochemistry, 89, 121-137, 2008. Jassal, R. S., Black, T. A., Cai, T., Ethier, G., Pepin, S., Brümmer, C., Nesic, Z., Spittlehouse, D. L., and Trofymow, J.A.: Impact of nitrogen fertilization on carbon and water balances in a chronosequence of three Douglas-fir stands in the Pacific Northwest, Agr. For. Meteorol., 150, 208-218, 2010. Krishnan, P., Black, T. A., Jassal, R. S., Chen, B., and Nesic, Z.: Interannual variability of the carbon balance of three different-aged Douglas-fir stands in the Pacific Northwest, J. Geophys. Res.-Biogeo., 114, G04011, doi:10.1029/2008JG000912, 2009. Magnani, F., Mencuccini, M., and Borghetti, M.: The human footprint in the carbon cycle of temperate and boreal forests, Nature, 447, 848-50, 2007. Sutton, M. A., Simpson, D., Levy, P. E., Smith, R. I., Reis, S., Van Oijen, M., De Vries, and W. I. M.: Uncertainties in the relationship between atmospheric nitrogen deposition and forest carbon sequestration, Glob. Change Biol., 14, 2057-2063, 2008.

Please also note the supplement to this comment:
http://www.biogeosciences-discuss.net/11/C3143/2014/bgd-11-C3143-2014-supplement.pdf

Interactive comment on Biogeosciences Discuss., 11, 2001, 2014.