Reply to reviewer #1:

Reviewer #1: General comments:

Reviewer #1: The authors investigated how net ecosystem carbon (C) exchange (NEE), gross primary productivity (GPP), ecosystem respiration (R) differ between mountainous grassland ecosystems of different land-use as well as how these parameters are associated with leaf area index (LAI), plant biomass, and light use efficiency (LUE) in the different systems. Given the large changes mountainous ecosystems are currently facing in many European countries (ceasing of agricultural land use practices) this topic is of great relevance and studies such as this one can help to better understand the carbon (C) sink-source capacity of mountainous ecosystems. However, to make a contribution in that context, I suggest the authors to look at their data differently from how they currently do.

The main results presented in the current version of the manuscript are relationships between LAI, LUE, PFD and NEE, GPP, R etc (some questions remain though on the data presented eg. in Fig 1 ➔ see comment below). In my opinion, this is nothing really novel and has been published many times by various authors for grassland ecosystems, even at high elevations (Gu et al. 2003, Kato et al. 2004a,b).

Reply: While it is correct that relationships between LAI, LUE, PFD and NEE, GPP, R have been published in many studies, even for mountain grassland ecosystems, we look at these relationships from a land-use perspective. This is, as we believe, a prerequisite for understanding the CO_2 source/sink strength of these ecosystems and thus fully falls into the scope of our paper. We will try to better motivate our analysis in the introduction of the revised paper in order to make this point clear.

Reviewer #1: Given the large amount of data the authors have available from all their different grasslands on similar soils I would have expected them to much more use this data to show how land use affects the fluxes. In Figure 3 they do present differences between the land use types. However, when reading the captions they took data from May 2002 for the valley bottom meadow, August 2002 for mountain meadow, August 2002 for the pastures, August 2003 for the nutrient poor abandoned grassland, March 2002 for the nutrient rich abandoned grassland (according to 11443, line 22 "seasonal peak values"). To me it is not a feasible comparison as the environmental conditions etc

must have differed considerably, when measuring the fluxes. If the authors think that this is the only approach to show what they intended to show I think they have to provide some explanations for this.

Reply: It is correct that it is inappropriate to compare seasonal peak values from different years with each other. To make fluxes across the land-use gradient comparable in Figure 3, we expressed them on a common basis, i.e. at photon flux density (PFD) of 2000 μmolm^{-2} s^{-1} and temperature of 10°C. These values for PFD and temperature also occurred during the periods compared. In our comparison we used seasonal peak values from all available years. We realize that the actual years available were not made this sufficiently clear in the caption of Figure 3. The correct figure caption is:

Fig. 3. Mean peak season values of (A) gross primary productivity per unit ground area at photon flux density of 2000 μmolm^{-2} s^{-1} (GPP_{2000}), (B) ecosystem respiration at a reference temperature of 10°C (R_{10}), (C) GPP_{2000} per unit leaf area, (D) R_{10} per unit leaf area, (E) light use efficiency (LUE), (F) R_{10}/GPP_{2000} at optimum LAI based on all field campaigns across all study years. Sites are indicated as: M_v (valley bottom meadow), M_m (mountain meadow), P (pastures), $A_{n\text{-}r}$ (nutrient-rich abandoned grassland), $A_{n\text{-}p}$ (nutrient-poor abandoned grassland). Significantly different means are indicated by different letters (oneway ANOVA). Error bars represent standard errors, M_v n = 4 (May 2002 to 2005), M_m n = 7 (August 2002 to 2004 and 2006 to 2008), P n = 7 (August 2002 to 2004 and 2006 to 2008), $A_{n\text{-}p}$ n=6 (August 2003 to 2004 and 2006 to 2008), $A_{n\text{-}r}$ n=2 (March 2002 to 2003).

Reviewer #1: The next major comment concerns the methods: The authors state that they measured the fluxes in the different vegetation types "between 2002 and 2008 in episodic campaigns every three to four weeks". Did they measure all the vegetation types on the same day or in the same week or within the same months? If the week/month is true, I think they have to provide the environmental conditions during with the measurements were taken. Otherwise the fluxes obtained from one site are not comparable to the ones from the others. I know that it is difficult to hit all the sites on the same day with the chamber system, but since this likely was not possible, the results should somehow be adjusted to account for this disadvantage. Please also clarify how often and when exactly you took your measurements.

Reply: Throughout all campaigns we sampled the sites on the same day or within two to three days, where always stable weather conditions persisted. It was therefore not necessary to define a specific order between site sampling. Three frames were placed at each site and were alternately recorded once per hour with one chamber system. That means, we did about 30 to 50 single measurements per day. It was randomly chosen with which plot the sampling started. In order to document the diurnal course, from 2002 to 2005 the measurements began immediately before sunrise and ended about three hours after sunset. For 2006 to 2008 the measurements started in the night and ended at midday (mostly between 2:00 am and 12:00 am). Ecosystem respiration measurements reported in this paper were thus made during nighttime. To account for possible effects of differing environmental conditions between a few days we calculated daily mean NEE for all studied time frames across all sites, using the site specific environmental conditions and measured NEE response curves (Figure R1). Thus, daily mean NEE shown in Figure R1 is immediately comparable across sites. This Fig. will also be included and discussed in some detail in the revised manuscript.

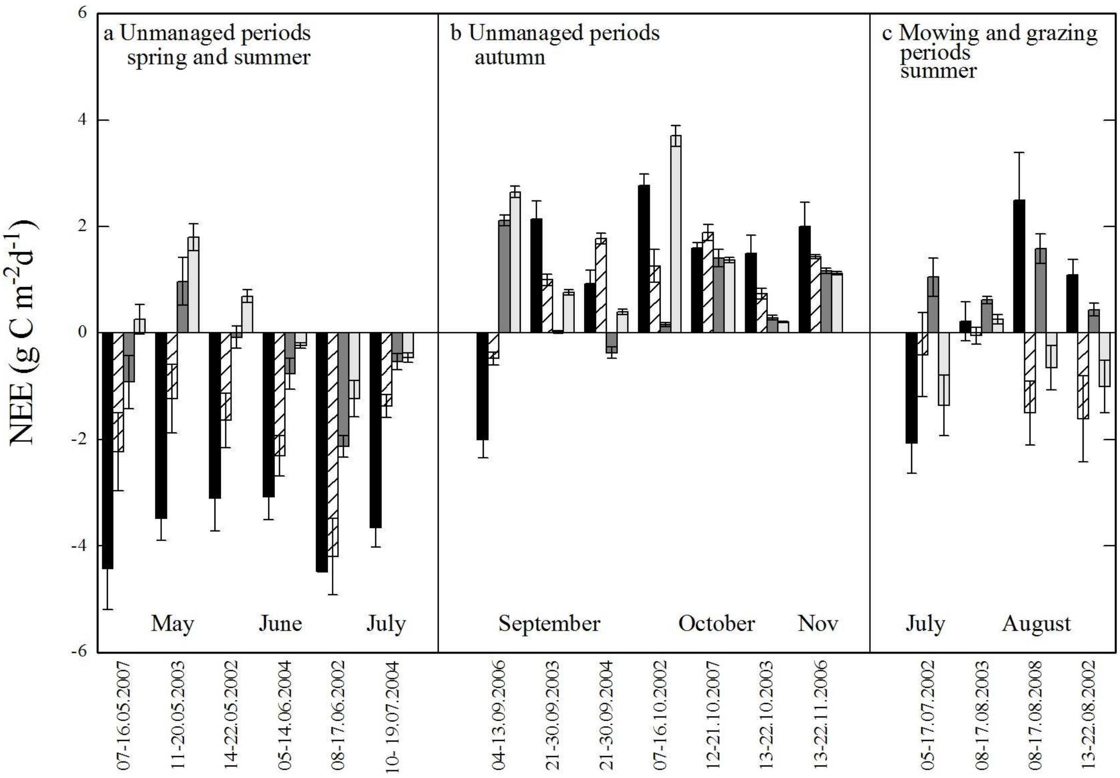


Figure R1: Daily integrated net ecosystem exchange of CO_2 (NEE) (g C $m^{-2}s^{-1}$) of (A, B) unmanaged, and (C) mowing and grazing periods from 2002 to 2008. Each time period refers to the same 10 days for all sites. NEE was calculated using a rectangular hyperbolic model, based on 10 day period during which 1-2 days of chamber measurements were available, and using the site-specific microclimatic conditions. Sites are indicated by black bars (valley bottom meadow), criss-cross bars (mountain meadow), dark grey bars (pastures) and light grey bars (abandoned). Error bars represent standard errors (n = 10).

Reviewer #1: The third major comment concerns Figure 1. First of all I wonder why the authors did not use all the data they have collected. They mention in the abstract and intro that they measured the fluxes between 2002 and 2008, but the figure contains only results from 2002-2004. Also, would it not be more meaningful to show NEE measured on a specific date over time (e.g., from 2002 to 2008) and then show when the pastures were mown/grazed and how the fluxes developed thereafter? Having said this: how did the authors assess the effect of grazing given that they mention that grazing took place from May to mid-September? Are all the filled symbols for the pastures presented in figure 1 from May to mid-September, the open ones for March/April and mid-September till November? If so, wouldn't the differences in fluxes be due to differences in temp, light etc., during the different seasons and not due to grazing? Please clarify this.

Reply: The aim of this Fig. was to provide an impression of the distribution and variability of the available data, and how they reflect changes in light availability, season and type of grassland. Presenting the data for all years would not add any substantial further information, while overloading the Fig. with information and making the depicted dataset less accessible. However, all aggregated data shown in Figures 2, 3 and 4 are based on the complete dataset including all years from 2002-2008. Closed symbols indicated NEE after mowing and grazing on the meadows, and pastures, respectively. As you could see on Figure 1 there were comparable light intensities for the plotted curves during and outside the mowing and grazing periods. In addition, both, air and soil temperatures were higher during the management periods (May to mid September) than before and after mowing and grazing.

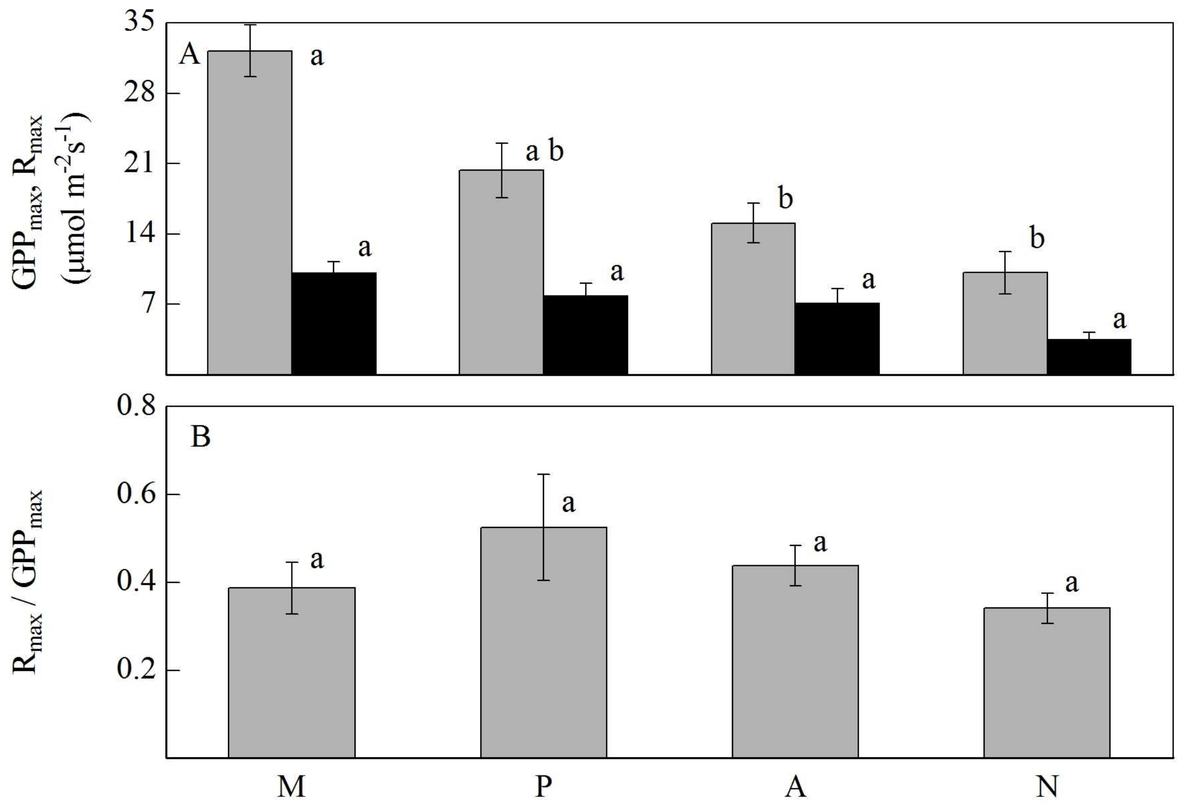
Reviewer #1: The last major comment concerns the discussion. I suggest that the authors revamp the discussion to put more emphasis on what is known from other studies on how land-use (moving, grazing, fertilizing) affects different fluxes, instead of

putting the main focus on how environmental parameters, LAI and biomass are affecting them.

Reply: We believe that we are already discussing land use effects a lot (e.g. p. 11444 l. 26 ff), and we are convinced that besides physiology and canopy structure exactly LAI, above-ground biomass and abiotic drivers mediate such effects of land-use. In any case, we will carefully consider this comment and try to improve our discussion by putting even more emphasis on land use effects.

Reviewer #1: They do provide Figure 5, which gives some general insight on potential overall patterns. However, from the figure it is not clear whether the differences in values are significant. Please add.

Reply: We have modified Fig. 5 (see below) – it now includes details on the significance of the differences between the land use types.



Reviewer #1: Why have natural grasslands lower fluxes than the managed ones?

Reply: We assume that the main reason for lower fluxes at unmanaged systems is the lower soil fertility in comparison to the managed systems, which are usually fertilised leading to higher flux rates of GPP and R. We will add this to the revised text.

Reviewer #1: Were these studies conducted with eddy covariance or chambers, which would affect the values measured as you mention in your methods? Could you clarify this too?

Reply: Most of these studies used micrometeorological methods (in particular the eddy covariance technique), a few chambers. While our compilation of studies thus bears the potential for systematic differences associated with the use of different methods, we believe that a detailed treatment of these error sources would go far beyond the scope of this paper. We will however explain this potential problem in the revised paper.

Reviewer #1: Wouldn't it be more meaningful to plot the values of all these studies eg. against elevation, air temp or precipitation, indicate which data points are M, P, A or N and then discuss how the systems differ along such gradients (maybe no difference at low elevation, but much more at higher ones?). With just the bars as in Figure 5 it is difficult to really assess what is going on in terms of land use change.

Reply: The referee correctly points out possible confounded effects between land use and climate on a regional and global scales. Such effects will be addressed by incorporating climate parameters in a larger statistical analysis, which will be included in the revised manuscript

Reviewer #1: Summarizing the points made above, I think the authors should much more address what they announce in the title within the manuscript, i.e., how land use affects ecosystem CO_2 fluxes.

Specific comments:

Reply: This will be done in the revised manuscript.

Reviewer #1: Abstract

Reviewer #1: Abstract: 11436, line 10: You mention physiology. To me it is not clear from the methods how you assessed this? Can you add this?

Reply: Changes in NEE, GPP and R between different managed grasslands could potentially be caused by differences in leaf area, its spatial arrangement and species physiology. We showed that NEE, GPP and R are closely related to leaf area index (LAI) (Fig. 2). Differences in GPP normalised with LAI are interpreted as being attributable to differences in physiology. We recognize that differences in canopy structure complicate such an assessment and will mention this in the revised manuscript.

Reviewer #1: Abstract: 11436, line 12: "parameters of light response curves were generally closely coupled" to what? One another? Please clarify

Reply: What we actually mean is that light response curve parameters are closely related to each other – will change the wording in the revised paper in order to make this point clear.

Reviewer #1: Introduction:

Reviewer #1: Introduction: 11438, line 9: you mention that you have flux measurements from 2002-08, but you never present all the data. Can you clarify?

Reply: The aim of this Fig. was to provide an impression of the distribution and variability of the available data, and how they reflect changes in light availability, season and type of grassland. Presenting the data for all years would not add any substantial further information, while overloading the Fig. with information and making the depicted dataset less accessible. However, all aggregated data shown in Figures 2, 3 and 4 are based on the complete dataset including all years from 2002-2008.

Reviewer #1: Introduction: 11438, line 14-19: the hypotheses do not represent anything really novel in my opinion. Could you refocus them so they deal much more with the effects of land use change you are trying to assess?

Reply: We will try to reformulate the hypotheses by putting more focus on the effects of land use, as follows: We tested the hypotheses that (1) differences in NEE and its component processes GPP and R between differently managed mountain grassland ecosystems are primarily driven by differences in the amount of photosynthetically active leaf area and its CO_2 assimilation potential, that (2) NEE and its component processes thus decrease as management intensity (in particular fertilisation) decreases (meadows>pastures>abandoned grasslands), and that (3) theses changes occur in a similar manner for all component processes, which results in conservative ratios between carbon uptake and release.

Reviewer #1: Methods:

Reviewer #1: Study sites: 11438, line 24: from table 1 it does not look as if you measured the fluxes at all the sites from 2002-2008 (see also comment above). Please clarify this in the text

Reply: This is correct, as has been clearly documented in table 1. The text will be modified as follows: Investigations were carried out during the growing seasons (May to November) on a meadow at the valley bottom (970ma.s.l.) in the years 2002-2005, a mountain meadow (1750–1820ma.s.l.) in the years 2002-2004 and 2005-2008, two pastures (1930 and 1950ma.s.l.) in the years 2002-2004 and 2005-2008, a nutrient-rich abandoned grassland (1960ma.s.l.) in the years 2002-2003, and a nutrient-poor abandoned grassland (2000ma.s.l.) in the years 2003-2004 and 2005-2008.

Reviewer #1: Assessment of the net ecosystem CO_2 exchange: 11439, line 14-15: did you sample all the sites at the same date of the year, or a week/month apart? Please clarify.
Reviewer #1: If not at the same day, how did you define the order of your measurements. Valley to top? Random? Please add the exact measurement schedule to the manuscript.

Reply: We sampled the sites on the same day or within two to three days, where normally stable weather conditions persistent. It was therefore not necessary to define a specific order between site samplings. To account for possible effects of differing environmental conditions between a few days we calculated daily mean NEE for all studied time frames across all sites, using the site specific environmental conditions and measured NEE response curves as shown in Figure R1. We will add this to the revised paper.

Reviewer #1: Assessment of the net ecosystem CO2 exchange: 11439, line 15-16: What do you mean by a "diurnal course" for each site? When did you start your measurements (time) and when did they usually end? Did you also measure throughout the night?

Reply: In order to document the diurnal course, from 2002 to 2005 the measurements began immediately before sunrise and ended about three hours after sunset. For 2006 to 2008 the measurements started in the night and ended at midday (mostly between 2:00 am and 12:00 am). This information will be added to the revised manuscript.

Reviewer #1: Did you measure your plots more than once at a site? If so, how often over the course of the day/night? Did you only have one chamber system so you measured your three plots one after another or did you have three chamber systems and measured all three plots at the same time? If only one chamber, did your randomly choose with which plot to begin etc. Please add this information for clarification!

Reply: Three frames were placed at each site and were alternately recorded once per hour with one chamber system. That means that we did approximately 30 to 50 single measurements per day. It was randomly chosen with which plot the sampling started. This information will be added to the revised paper.

Reviewer #1: Assessment of the net ecosystem CO2 exchange: 11439, line 23: since it is not clear what times of the day you measured the fluxes it is not clear why there should have been no light. Did you measure at night, or did you use shade cloths? Please clarify.

Reply: As described above we measured both during the night and day under the prevailing environmental conditions, i.e. no shade cloths were used.

Reviewer #1: Assessment of the net ecosystem CO2 exchange: 11440, line 19 – 11441, line 7: is this needed? The chamber method is a recognized method, so I don't think you have to list how they differ from the eddy flux tower measurements. Maybe it would be meaningful to mention this if the values they obtained from other papers to come up with figure 5 were adjusted.

Reply: A comparison with an independent method increases the confidence in the data and will thus presumably strengthen our paper. Therefore we have compared chamber and eddy covariance data directly. To take the comparison one step further, we tested for the valley bottom site how well mean daily NEE corresponded between eddy covariance-based and chamber-based data. For mean daily NEE based on chamber data, we calculated daily mean NEE for time frames of 7 days using the site specific environmental conditions and NEE response curves measured during the course of a single day. This was compared against aggregated NEE data from the eddy covariance station. As depicted in the Figure R2, the chamber method underestimated the NEE measured by eddy covariance at the valley bottom meadow on average by only 5%.

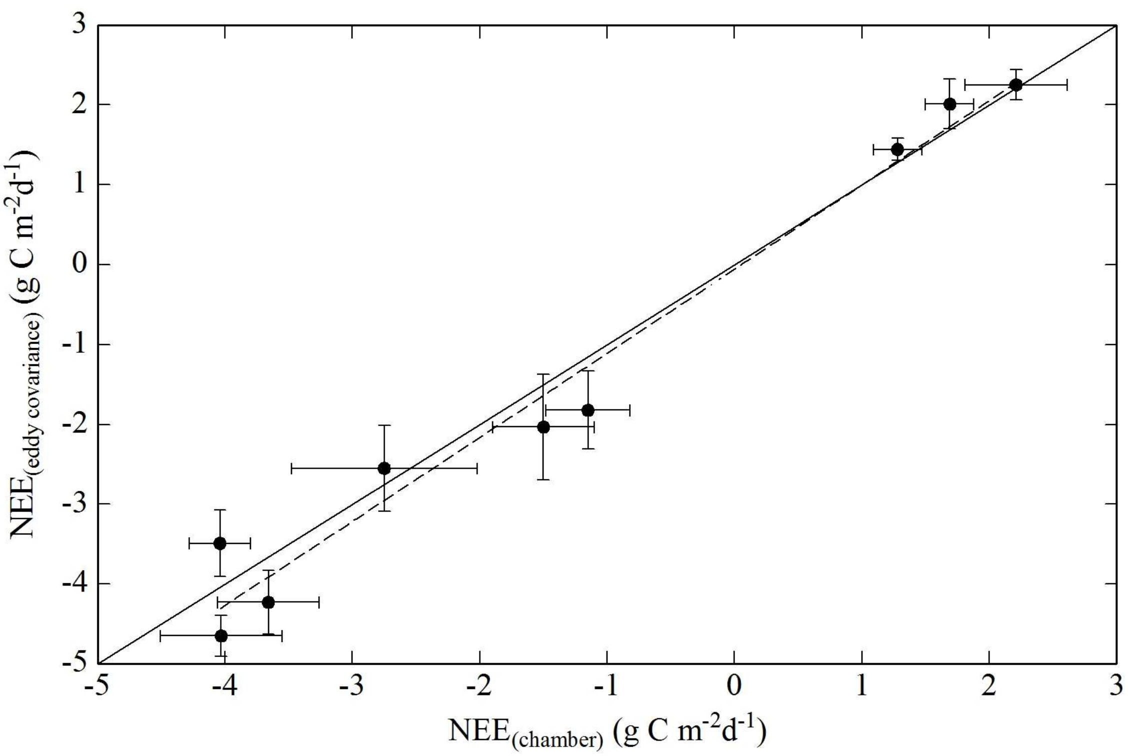


Fig. R2: Comparison between daily integrated net ecosystem exchange of CO_2 (NEE) (g C $m^{-2}s^{-1}$) obtained from chamber and eddy covariance based data at the valley bottom meadow. The solid line is the 1:1 line, the dotted line corresponds to a fitted linear regression. ($NEE_{(eddy\ covariance)} = 1{,}05NEE_{(chamber)} - 0{,}05$; R2=0.97). Error bars represent standard errors (n = 7).

Reviewer #1: Assessment of the net ecosystem CO2 exchange: 11441, line 22 – 24: could you add some information on how you calculated LUE exactly? This is not clear from the text provided. Could you also add at the end of the paragraph what negative and positive fluxes represent in your study?

Reply: LUE was calculated by a linear regression fitted to the light response curves at low incident light intensities - the slope of the linear regression corresponds to the LUE. In this study, negative fluxes represent a net CO_2 uptake by the ecosystem, positive ones to the reverse. This information will be added to the revised paper.

Reviewer #1: Results:

Reviewer #1: 11442, 15-16: You mention that after mowing or grazing the systems released CO_2 for approximately 6-10 days. I think this is a really interesting result and should be much more prominent in the manuscript since the authors want to address how land use affects the fluxes. Please see my suggestion of how to address that under "general comments". Please also explain how grazing can have an instantaneous effect on the fluxes when the systems are grazed from May – mid-September (also see general comments).

Reply: The question of how long it takes until the system changes after mowing from a net source of CO_2 to a net sink was already studied for the valley bottom meadow by Wohlfahrt et al., 2008a. Therefore we haven't put this question in the main focus of our manuscript. Effects of mowing and grazing can be clearly seen in the new figure showing daily average NEE of the various sites in a comparative fashion. We will elaborate on the effects of mowing and grazing when referring to this new figure.

Cattle were moved around within the pasture by the farmer in order to ensure relatively even grazing, which in total lasted from May to mid September, within the entire area. As a consequence, the frames where NEE measurements were made had time to recover (and regrow) between grazing periods. Once grazing started again, an immediate response to grazing was thus observed. We will clarify this issue in the revised paper.

Reviewer #1: 11442, 21-24: you mention that "the nutrient-rich abandoned grassland showed much higher values of NEE at any given temperature and light intensity, as compared to the nutrient-poor abandoned grassland". This is – given Fig 1 – probably true in 2003 when you measured the fluxes in both systems. However, that is the only year you have results for both grasslands. Given that 2003 was – as mentioned several times – an exception in terms of air temperatures, the statement above should probably be softened somehow.

Reply: It is correct, 2003 is the only year in that we measured both the nutrient-rich abandoned grassland and the nutrient-poor abandoned grassland. We will modify the corresponding sentence to: "In the year 2003, the nutrient-rich abandoned grassland showed much higher values of NEE at any given temperature and light intensity, as compared to the nutrient-poor abandoned grassland."
Differences due to climatic conditions in 2003 are minimized by normalizing NEE and GPP to a photon flux density of 2000 µmolm^{-2} s^{-1} (NEE_{2000}, GPP_{2000}) and R to a reference temperature of 10°C (R_{10}) (Fig. 2, 3 and 4).

Reviewer #1: 11443, line 7 – 10: you mention that 68% of NEE, 75% of GPP and 60% of R, respectively, were explained by PFD Air temp Soil temp Aboveground biomass LAI Grassland type Year of measurement Time of the season Given all these parameters were used in the model – what explains the remaining 25% to 40% variability in fluxes then? I think you should discuss this at least to some extent.

Reply: The unexplained variability could a.o. be related to a number of factors, including spatial variability in nutrient availability (typical for mountain grasslands) and related above-and belowground processes, as well as species composition. We will discuss these issues in more detail in the revised paper, and include some references to back up the notion.

Reviewer #1: 11443, line 22-11444, line5: I do not understand why you use seasonal peak values from different years for this comparison (see also general comments). To me this is as if you are comparing apples with oranges. Maybe this approach is valid but then it needs some explanation why this was done and why it is okay to do this. Also, what is optimum LAI and how was it determined?

Reply: It is correct that it is inappropriate to compare seasonal peak values from different years with each other. In our comparison we used, as mentioned, seasonal peak values from all years. As mentioned above, we made a mistake in the caption of figure 3.

We determined optimum LAI from relationships between NEE at photon flux density (PFD) of 2000 $\mu molm^{-2}\ s^{-1}$ (NEE_{2000}), gross primary productivity at PFD of 2000 $\mu molm^{-2}\ s^{-1}$ (GPP_{2000}), ecosystem respiration at a reference temperature of 10°C (R_{10}) and light use efficiency (LUE) in response to leaf area index (LAI). Therefore we accounted effects of different light and temperature intensities. LAI at highest flux rates were defined as optimum LAI.

Reviewer #1: 11443, line 29 – 11444, line 1: You mention that for the "ratio R/GPP there was no significant trend across the sites". However, looking at Figure 3f there are significant differences between the different land use types. E.g., the R/GPP of Mm is significantly lower than the one of An-p. Please clarify this in the revised manuscript.

Reply: That is correct, we will modify the text to:

For the ratio R/GPP there was no significant trend across sites, except between the mountain meadow and the nutrient poor abandoned grassland, the highest ratio occurring on the N-poor abandoned grassland (Fig. 3f). However, the conclusion (11446, line 7 – 9) that the ratio of R_{10} over GPP_{2000} is generally not affected by land management, has not changed, because the ratio was relatively constant across all types of ecosystems of our study.

Reviewer #1: Discussion:

Reviewer #1: It would be nice to incorporate what is known from other studies on how mowing, grazing, fertilization affects ecosystem CO2 fluxes into the discussion, which would allow to better assess whether these mountain systems react differently to different land use than other systems (see general comments). At present this is not really done.

Reviewer #1: 11444, line 26 ff: As mentioned before I suggest that you give the effects of mowing and grazing much more space in this manuscript and then also compared their findings with the ones of other studies.

Reply: Mowing and grazing are integral components of the land management, therefore we discussed the effect of mowing and grazing with regards to our findings and compared it with that of other studies: "Both, mowing and grazing, cause a substantial reduction of leaf area and thus GPP, turning the meadows and the pastures from sinks to short-term sources of CO_2 (Fig. 1). For the valley bottom meadow (three cuts per year) of our study it took on average 16 days after the first cut to become (on a daily basis) a net sink for CO_2 again (Wohlfahrt et al., 2008a). This pattern repeated itself after the second and third cut, whereas daily average rates of net CO_2 uptake and loss before and after cutting, respectively, decreased from the first to the third cut. Other studies in warm temperate grasslands showed that between 6 to 11 days are required before net carbon gain (on a daily basis) is resumed (Dugas et al., 1999; Novick et al., 2004)."

This point will be further reinforced by the addition of the new figure showing daily average NEE, as mentioned above, and will be discussed in more detail, including also further references on the topic.

Reviewer #1: Tables:

Reviewer #1: Table 1: - are your MAT and MAP values measured at a nearby weather station? If not, why are the values exactly the same for all the higher elevation plots? If measured within the ecosystems I would expect that there is a difference in MAT and MAP between 1850 and 2000 meters in elevation?

Reply: Yes these values were record from nearby weather station – will clarify in the revised paper.

Reviewer #1: - what are your aboveground biomass values for spring/summer/autum that you present? Are these ranges of your different plots or years? Please clarify.

Reply: This ranges refer to the minimum and maximum values in the given observation period.

Reviewer #1: Table 2: - maybe it would be meaningful to include the information from this table into figure 2. Also, please add what regression functions you used.

Reply: In our opinion is it better to show the regression statistics for this figure in a separate table. We think that figure 2 would be overloaded if we included this information. The type of regression function will be added to the table legend: "The following functions were used: for Reply: NEE_{2000} vs. LAI: cubic and linear, GPP_{2000} vs. LAI: cubic and linear, R10 vs. LAI exponential- and linear, LUE vs. LAI: cubic and linear."

Reviewer #1: Figures:
Reviewer #1: Figure 1: See suggestion in general comments

Reply: See reply above.

Reviewer #1: Figure 2: As mentioned above maybe it would be meaningful to include table 2 into this figure and also add the regression functions.

Reply: See reply above.

Reviewer #1: Figure 3: see suggestions in general comments
Reply: See reply above.

Reviewer #1: Figure 5: please provide information on whether the values are different or not.

Reply: Done – see reply above.

Reviewer #1: Minor comments:
Reviewer #1: 11436, line 11: Exchange "(GPP)" with "(PFD)"

Reply: Done.

Reviewer #1: 11460 Figure caption 3: change Pn to P (second last line)

Reply: Done.