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Response to comments by Hoffmann et al. on "Upland grasslands in Northern England were atmospheric carbon sinks regardless of management regime"

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Hoffmann et al. suspected a likely overestimation of carbon (C) sink reported in our paper (Eze et al., 2018) entitled "Upland grasslands in Northern England were atmospheric carbon sinks regardless of management regime". They attributed this to potential sources of error associated with the estimation of C fluxes from closed-chamber measurements.

Hoffmann et al. questioned the negative winter time gross primary productivity (GPP) values we calculated. It is true that GPP refers to the C gained by plants and GPP measurements are expected to yield positive values. However, GPP is not actually measured but calculated as a residual between measured net ecosystem exchange (NEE) and ecosystem respiration (ER). Negative GPP values are sometimes generated during winter months when low temperatures limit the activities of plants including photosynthesis. This was the case for the winter GPP calculated in our study. However, this is not a unique phenomenon to our study. In the literature, negative winter GPP values are sometimes reported as zero (see footnote to Table 1 in Kato et al., 2006 and paragraph 34 in Schaefer et al., 2012), whereas other authors report the negative values (e.g. Table 1 in Kato et al., 2006). We chose to report the negative GPP values as calculated (Figure 3 in Eze et al., 2018), although these were not significantly different from zero. These winter months' GPP values, calculated from measured NEE and ER values, could not have led to an over-estimation of annual GPP fluxes as they were estimated using a gap-filling saturation function based on mean daily photosynthetically active radiation (PAR) data (as described in section 2.4.1 in Eze et al., 2018).

Hoffmann et al. considered our statement that the grasslands were atmospheric C sinks as a misleading interpretation of NEE for net ecosystem C balance (NECB), as we did not include any estimate of C export from the sites in terms of cutting or removal through livestock grazing. As highlighted by Hoffmann et al. NECB accounts for all possible ecosystem C imports (e.g. supplementary livestock feed and organic manure) and exports (e.g. harvested plant biomass, C offtake in meat and milk, leaching and erosion C losses) and is therefore a better measure of C sink/source of an ecosystem than NEE. However, the focus of our study was on NEE. Very few studies account for the overall C balance of managed ecosystems. For example, five studies (Ammann et al., 2007; Soussana et al., 2007; Elsgaard et al., 2012; Chang et al., 2015; Jones et al., 2017) referenced in Eze et al. (2018) investigated the NECB in managed grasslands. Four out of these five studies did not account for C losses via leaching and erosion, and none of the studies estimated C export in milk and meat. Some of the studies (e.g. Ammann et al., 2007; Chang et al., 2015) had to rely on modelling in order to estimate some components of the C cycle. This shows that NECB is a common limitation in many C flux studies and is a gap in C cycle understanding that is challenging to address because: 1) researchers have to rely on good record-keeping by farmers for information on biomass harvest, meat and milk offtake; 2) internal cycling of C by animals is hard to quantify; and 3) accurately monitoring C loss via erosion and leaching is more challenging than measuring gaseous C fluxes.

Using the carbon use efficiency (CUE) values of between 0.35 and 0.65, which were values extracted by Amthor and Baldocchi (2001) from earlier studies (Andrew et al., 1974 and Risser et al. 1981) of Shortgrass Prairies of northeastern Colorado and Tallgrass Prairies of northeastern Oklahoma in the USA, Hoffmann et al. calculated the annual autotrophic respiration (R_a) at our sites and showed that the R_a of one of the sites was greater than the annual ER by 3 g C m^{-2} y^{-1} (see Table 1, Hoffman et al.). This led them to imply that: (i) the heterotrophic respiration (R_h) at our site was at best zero, which is unlikely; (ii) our reported annual ER and GPP were biased. A wider range of CUE values (0.2 to 0.7) has been reported for global grasslands (e.g. see Fig 2 in Yang et al., 2017; Iersel, 2003 and Amthor, 2000) than those used by Hoffman et al. in their calculations of NPP, R_a and R_h for our sites. In addition, a value for biomass production efficiency (a proxy for CUE) of 0.78 has been reported for alpine grasslands (see Supplementary Table 1 in Campioli et al., 2015).

CUE displays a wide range in values as it is influenced by climate, management, and other environmental factors, with higher values found in cooler regions (Yang et al., 2017). Alpine grasslands are much more similar to the upland grassland sites in our study in terms of shallow soil depth (Garcia-Pausas et al., 2017) than Prairie grasslands characterized by deep (often greater than 100 cm) weathered Mollisols (Kucharik, 2007). Hence, using a range of higher CUE values (0.7 and 0.78) we have reworked the calculations of Hoffmann et al. (Table 1), which shows that the R_h at our sites is neither negative nor zero, but is low as would be expected in these upland grasslands with shallow soil (<20 cm) and cool temperate climate.

Table 1: Cross-check of partitioned annual flux estimates (modified from Hoffmann et al.) using CUE of 0.7 and 0.78.

Reference	**Site**	**Modelling frequency**	**GPP**	**ER**	**NEE**	**NPP**	**Ra**	**Rh**	**CUE**
			g C m^{-2} y^{-1}						
Eze et al. (2018)	Nidderdale-hay meadow	daily	-1024	359	-665	717 799	307 225	52 134	0.70 0.78
	Nidderdale-silage pasture		-1053	366	-687	737 821	316 232	50 134	0.70 0.78
	Ribblesdale-hay meadow		-863	410	-453	604 673	259 190	151 220	0.70 0.78
	Ribblesdale-permanent pasture		-980	416	-564	686 764	294 216	122 200	0.70 0.78

Hoffmann et al. suggested three possible reasons for their suspected bias in our annual C fluxes: 1) low data coverage; 2) low frequency of flux measurements; and 3) the use of daily climate data in modelling. We acknowledge that these three factors could potentially lead to underestimation of ER, however, we could not account for them in our study for the following reasons:

1. We conducted flux measurements (NEE and ER) once every month for a period of one year using closed chambers. This resulted in a total of 12 measurements per plot over one year (n = 96 per site and year), which were used for modelling annual C fluxes. This methodology and frequency of sampling has been used by many others (e.g. Luo et al., 2007; Quin et al., 2015; Salimon et al., 2004; Zhou et al., 2006). The sites we studied were located in upland areas that were under normal farm operations. The difficulties in accessing these sites and not being able to make flux measurements at times when farm machinery was on-site limited our data coverage. These restrictions are not unique to our study alone but characterize studies in relatively remote upland sites under active land management.
2. We acknowledge the valid point made by Hoffmann et al. that our annual flux estimates may have been different if we had captured rapid changes resulting from management activities, such as cutting of grass and application of manure. As stated in point 1, the frequency of C flux measurement was limited by farm operations. Access to study sites was not allowed during periods of biomass harvest especially when machinery was on site. Transportation to the study site was also difficult. The frequency of measurements was therefore restricted to once every month.
3. To estimate annual C fluxes, we applied temperature- and PAR-dependent functions on daily PAR and mean daily soil temperature data. We only had access to daily PAR data, hence for consistency in time steps we had to use mean daily soil temperature data

to estimate annual ER. As indicated by Hoffmann et al., it may have been more accurate to model GPP and ER using hourly or half-hourly data, but these were not available to us, and is likely to be the case for many other studies attempting to quantify annual GHG fluxes from terrestrial ecosystems.

While our approach is consistent with many other studies, as mentioned above, we also acknowledge the potential for error due to unavoidable operational and data limitations. Hence in principle we support the call for campaign flux measurements at higher frequency made by Hoffman et al. However, more work is needed in a variety of managed ecosystems to determine the reduction in uncertainty that is achievable by more intensive campaigns, with or without gap-filling using eddy-covariance methods as suggested by Lucas-Moffat et al. (2018).

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