Effect of land management on grassland carbon dioxide fluxes

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Abstract.

Grassland soils can act as both a source and sink for atmospheric carbon dioxide (CO_2). Implementing grassland management practices that increase the rates of soil CO_2 sequestration are urgently sought to offset Ireland's agricultural greenhouse gas emissions. However, land management of Irish grasslands is not yet accounted for in the national inventories simultaneously posing a limitation and opportunity for refining modelled estimates of carbon sequestration. In this study, eddy covariance flux towers were established to monitor net ecosystem CO_2 exchange (NEE), gross primary productivity (GPP) and ecosystem respiration (Re) in three grassland types (intensive dairy grazing, drystock grazing and zero-grazing) in geographically distinct agricultural catchments in Ireland. The initial results show larger magnitude of NEE, GPP and Re in intensively grazed and zero-grazed grasslands that are subject to frequent grazing/defoliation followed by recovery of photosynthetic potential. The continuously grazed drystock grassland exhibited lower NEE and GPP rates but smaller seasonal fluctuations in daily fluxes which may reflect the reduction in nutrient availability to support higher GPP. However, the drystock grazed grassland had significantly higher soil water content which may stimulate higher soil CO_2 respiration resulting in lower NEE over time. Management practices involving defoliation and nutrient supply influenced affected season CO_2 exchange but longer-term flux monitoring is required to assess the net ecosystem carbon budgets of each grassland system.

Introduction

Grassland ecosystems account for 61% of the total land use in Ireland and vary in their management intensity, soil type and climate (Haughey et al. 2021). Grasslands are considered sinks for atmospheric carbon dioxide (CO_2) i.e., they absorb more CO_2 via photosynthesis than is released by respiration. Ireland's grasslands are primarily utilized by ruminant livestock (dairy, beef and sheep) for grazing and/ or harvesting for winter forage. However, there is a paucity of information on how management of these grasslands influences seasonal CO_2 exchange and subsequently, the rate of soil carbon sequestration over time. In particular, understanding how CO_2 exchange is affected by grazing intensity (dairy vs. beef grazing systems) or whether the pasture is grazed or cut will greatly improve our ability to account for different grassland production systems in our national inventories. We present results of CO_2 fluxes for three differently managed grassland sites (intensive grazing by dairy cows, a drystock grazing system with beef cattle and sheep, and zero-grazing which is the mechanical harvesting and feeding of fresh grass) located in three agricultural catchments in Ireland. We hypothesized that management will have a larger influence on daily seasonal net ecosystem exchange (NEE) rates than climate.

Methods

The experimental sites were located on privately owned farms in three agricultural catchments in Ireland characterized by varying land uses, soil drainage and geology. The sites studied here were an intensive dairy grazing system (DG) in Timoleague (GPS: 51.63 N, 8.79 W), a drystock grazing system (DRY) in Cregduff (GPS; 53.61 N, 9.12 W) and a dairy zero-grazing system (ZG) in Castledockrell (GPS: 52.57 N, 6.61 W). The DG site is situated within a multi-paddock grazing system with Holstein Friesian dairy cows at a mean stocking rate of 2.9 LU ha^{-1}. The sward composition was perennial ryegrass with some white clover. Recently grazed/cut pasture is fertilized with a mixture of urea and protected urea and dairy cow slurry (20 m^3 ha^{-1}) with a total annual N input >270 kg N ha^{-1}. The DRY site is a mixed beef and sheep continuously grazed system with a mean stocking rate of 1.3 LU ha^{-1}. Slurry is applied twice annually at a rate of 20 m^3 ha^{-1} giving a total N input *ca*. 50 kg N ha^{-1}. The ZG system is a perennial ryegrass-white clover sward (80%:20%) reseeded in 2019. The pasture is cut to 4 cm typically five times per year including two silage cuts. The pasture receives approximately 25 kg N ha^{-1} (NPK; 22:05:05), 20 kg N ha^{-1} dairy cow slurry (19 m^3 ha^{-1}) and SulfaCAN fertilizer (100 kg ha^{-1} 26%N and 5%S) applied evenly after each defoliation event with an annual N input ranging between 225-315 kg N ha^{-1}. Eddy covariance flux towers were established at these three field sites (Table 1). Fluxes of CO_2 and water vapour were monitored using an enclosed path infrared gas analyzer (LI-7200RS, LiCor Inc., Lincoln, NE, USA) and 3D sonic anemometer (Gill WMP). Meteorological variables also accompanied flux measurements including air temperature and relative humidity (Vaisala, HMP55, Finland), incoming/outgoing shortwave and longwave radiation (CNR4, Kipp and Zonen, Delft, Netherlands), volumetric soil moisture and temperature (Stevens® Water Monitoring Systems, Inc., Oregan, USA) and soil heat flux (Hukseflux, Delft, Netherlands). Half-hourly fluxes were computed using EddyPro software (v7.0.9) and post-processing of fluxes (gap-filling, variable averaging and flux footprint allocation) was completed using TOVI software (LiCor Inc., Lincoln, NE, USA). The night-time flux partitioning approach was used to partition net ecosystem CO_2 exchange (NEE) into gross primary productivity (GPP) and ecosystem respiration (Re).

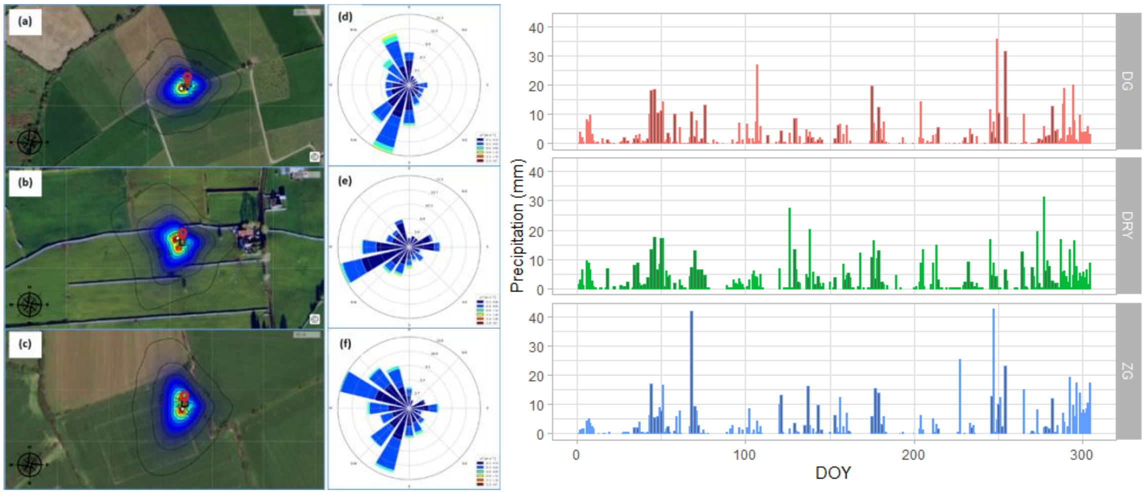

Figure 1. Contour maps (a-c) illustrating the flux footprint (ranging from 10-80%) and wind roses (d-f) (left), and daily precipitation (right) obtained from the catchment meteorological station. Cumulative precipitation from 1st January to 31st October 2022 was 748, 860 and 724 mm at the DG, DRY and ZG catchments.

Result and Discussion

Temporal variation in CO_2 flux dynamics was evident across each experimental site. In the DG grassland, daily NEE gradually increased until summer and decreased towards the autumn period. The NEE fluxes in the DRY grassland fluctuated frequently with *ca*. 59% of days showing net photosynthesis (C uptake). The temporal pattern of NEE in the DRY grassland during this summer and autumn period shows similar consistency to the early spring period in the DG grassland. Although with the least complete data set, ZG displayed similar temporal variation to DG in terms of the magnitude of the fluxes and flux fluctuations, characteristic of defoliation and recovery in managed grasslands.

Maximum NEE was recorded at the ZG grassland (-11.3 and -13.2 g C m^{-} d^{-1}) between 10 and 27 days after the first cut (DOY=111) and around 33 days after the second cut (-11.7 and -12.6 g C m^{-2} d^{-1}) (Fig. 2a). Maximum NEE at the DG grassland was recorded 16 days and the day prior to the first cut (-10.5 and -10.6 g C m^{-2} d^{-1}) (Fig. 2a). Defoliation by rotational grazing and cutting causes a reduction in leaf area and carbon assimilation rates (Rogiers et al. 2005). Kirschbaum et al. (2020) found that GPP recovered after two weeks following defoliation in a temperate dairy grassland. Puche et al. (2019) observed more abrupt reductions in GPP from mowed plots compared to progressive removal of biomass by dairy cows in two managed grassland sites. The magnitude of the GPP and NEE at the DG and ZG sites is also attributed to the fertilizer N supply which stimulates GPP and faster C turnover post-defoliation.

A comparison of GPP and Re show that the DG pasture had the highest GPP and Re (-21.9 and 12.4 g C m^{-2} d^{-1}) and the ZG pasture had the lowest recorded GPP and Re (-13.1 and 6.7 g C m^{-2} d^{-1}). Maximum NEE of the DRY grassland (-5.1 g C m^{-2} d^{-1}) was less than half that of the intensively grazed and cut sites. Additionally, for the DRY site, the maximum GPP and Re were 26.1% and 4.8% lower, respectively, than the DG pasture. Allard et al. (2007) observed lower GPP in extensively compared to intensively grazed grasslands owing to higher proportions of stems that have lower photosynthetic rates relative to leaves. The combined lower net photosynthetic rates and relatively high respiratory CO_2 losses partly explains the lower NEE in the continuously grazed DRY pasture. Moreover, the DRY pasture receives nutrients in the form of dung and urine that are deposited heterogeneously across the paddocks in contrast to the evenly applied slurry and synthetic fertilizer at the DG and ZG sites.

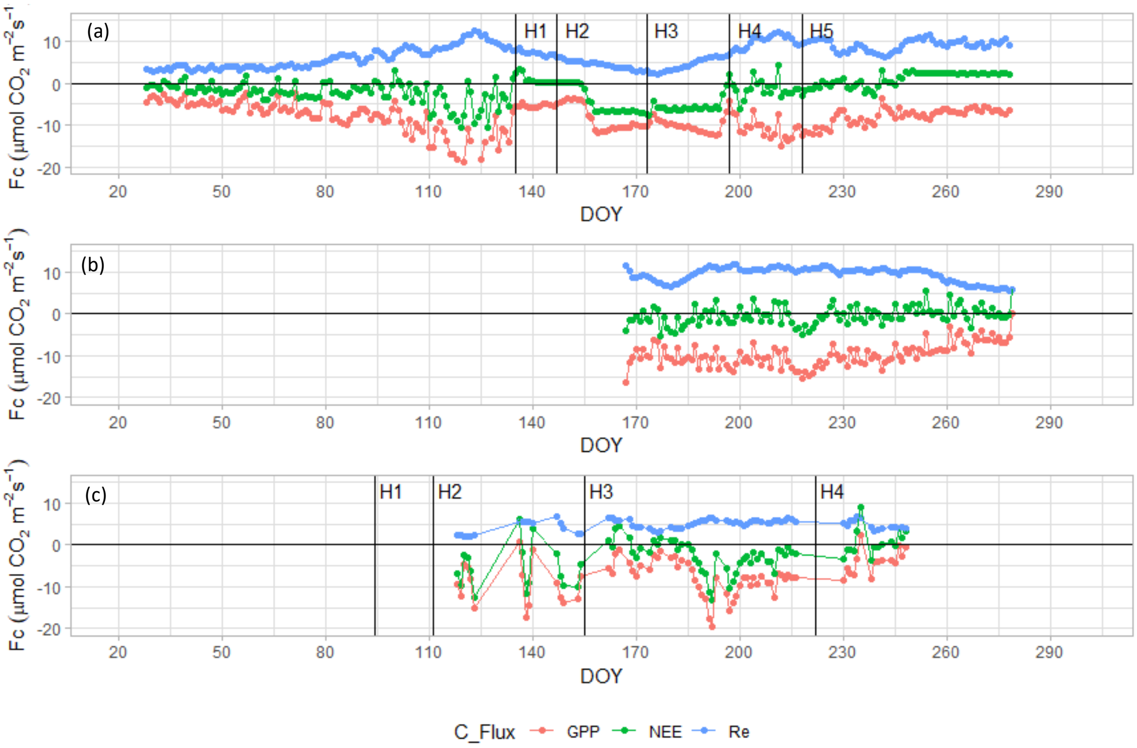

Figure 2. The CO_2 flux (Fc) in the (a) DG, (b) DRY and (c) ZG grassland ecosystems. Mean daily fluxes are represented as net ecosystem CO_2 exchange (NEE; Green) and partitioned into gross primary production (GPP; Red) and ecosystem respiration (Re; Blue). Vertical black lines denote harvest events recorded at the DG and ZG sites.

Analysis of the site-specific meteorology (Figure 3a-d) suggests the value ranges for incoming shortwave radiation (SW_IN) and soil temperature follow similar temporal trends across the different geographical regions. Daily NEE showed a strong dependency to SW_IN at both the DG and DRY grassland (Figure 2a, 2b and 3b), notably up to the first harvest and later in the season (between DOY~200 and 240). Mean albedo (ratio of incoming to outgoing shortwave radiation) values ranged from 0.23 to 0.25 (Figure 3a) consistent with previously reported mean value of 0.25 for grasslands (Jones 2013) despite the within season variation observed. The volumetric water content (VWC) of the soils showed large variation across sites (Figure 3c). The DG and ZG grasslands displayed similar temporal trends and magnitudes despite large gaps in the data. However, the mean VWC for DRY (29.7%) was over twice that of the ZG (11.3%) pasture over the same seasonal period (DOY 167-248). The DRY site is characterized by a freely draining brown earth overlying a karst limestone bedrock with a water table closer to the surface than the freely draining DG and ZG grassland soils. The higher VWC with similar soil temperatures are likely the main drivers for the higher heterotrophic CO_2 emissions explaining the relatively large Re flux at the DRY grassland. However, the dense vegetation cover, lower stocking rate and higher soil water availability may imbue the DRY grassland with greater climate resilience under warmer, drier atmospheric conditions.

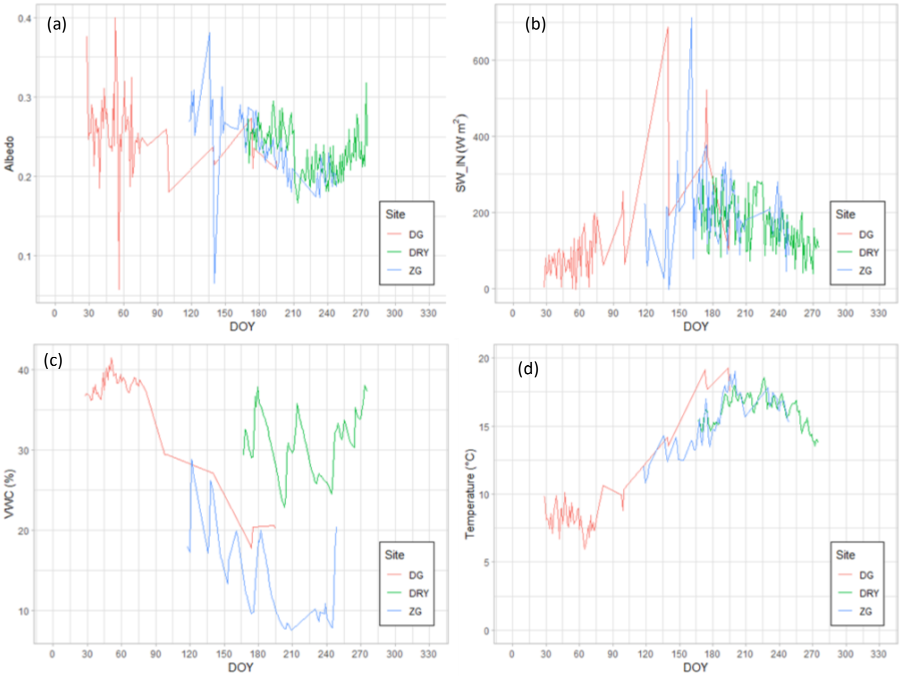

Figure 3. Temporal variation in (a) albedo (%), (b) incoming shortwave radiation ($W\ m^{-2}$), (c) soil volumetric water content (%) and (d) soil temperature (ºC) at the DG (red), DRY (green) and ZG (blue) sites.

In this study, fluxes of CO_2 were measured on farms which were representative of the dominant grassland management system of the agricultural catchment. One limitation of our study relates to spatial replication and determining the true level of uncertainty with the flux measurements (Hill et al. 2017). Spatial replication could be improved by increasing the number of eddy covariance systems: (i) within the flux footprint on the same field or (ii) on similar farms in the same catchment. This can be difficult to achieve on non-research farms where field sizes are small and site selection is ultimately determined by the farmer's willingness to host infrastructure for research purposes. A replicated experimental design would also limited by high equipment costs and logistics involved with site maintenance. In the absence of spatial replication, inter-annual variation in CO_2 exchange can be assessed for individual contrasting grassland ecosystems to determine whether changes in C sink potential are attributed to land management or meteorological effects.

Conclusions

Our C flux measurements from an intensive dairy grazing, drystock grazing and zero-grazing grassland (<1 year) suggest management influences seasonal CO_2 exchange through its effect on GPP and Re. The intensively managed pastures (DG and ZG) achieved their maxima and minima NEE before and after defoliation reflecting rapid changes in vegetation cover and the ecosystems photosynthetic capacity. Ecosystem CO_2 fluxes at the DRY grassland were lower in magnitude and less sporadic, however, GPP and thus C uptake potential, could be impeded by the denser vegetation cover and lower nitrogen inputs. The net effect of the higher soil water content at the DRY site may not only stimulate higher respiratory CO_2 losses but also enhance the ecosystems resilience to short-term weather variability (e.g. higher air temperatures, drought). Long-term monitoring will be required to assess the cumulative C exchange and net C budgets for each managed grassland system.

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