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The effect of ploughing intensity on the carbon flux of temperate agricultural grasslands

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Summary

Models of landscape carbon sequestration focus primarily on changes in land use and give little indication of modifications to carbon flux due to differing land management practice within the same category. In the agricultural category, for example, reseeding and ploughing practices vary. Ploughing modifies flux rates in agricultural grasslands by disruption of soil and removal of photosynthetic material. There is limited literature on the effects of differing practices. We present data of flux rates based on deep and minimum tillage overseeding and controls. Using a randomised block design we measured flux from 20 plots using a Perspex chamber and portable infrared gas analyser (IRGA). Our data suggests that loss of photosynthetic material from destruction of the grass sward temporarily changes grasslands from sinks to sources. For example flux from deep ploughed treatments reduced from mean of 0.82 ±0.11 to -1.85±0.2 g CO₂ m⁻² hr⁻¹ while control plots ranged from -1.88±0.11 to -2.41±0.2 g CO₂ m⁻² hr⁻¹.

Key words: CO₂ flux, carbon, sink, source

Introduction

Models of land-based carbon sequestration account for land use type, i.e. differences between land use categories, but exclude variation of management practices within each category. For example, grasslands in temperate regions require periodic tillage and reseeding in order to maintain a healthy sward (Drewer et al., 2017), but there are a paucity of data on the effects of tillage and reseeding, and their frequency, on local carbon fluxes (Willems et al., 2011). Failure to account for potentially large variations in local carbon fluxes is likely to result in biased and inaccurate estimates of CO₂ emissions at the national level. For example, in the United Kingdom (UK), land-based carbon sequestration estimates are produced using ‘Land Use, Land Use Change and Forestry’ (LULUCF). Assessments which are modelled based on Intergovernmental Panel on Climate Change (IPCC), Tier 1 approaches at regional scales
Ploughing results in major disruptions to soil, leading to CO₂ loss (Palm et al., 2014; Soane et al., 2012; Powlson et al., 2011; Lal, 2004). Ploughing aerates soil and allows the incorporation of added nutrients to maintain high harvest yields (Drewer et al., 2017). In non-ploughed systems, soil structure is denser, soils have a higher moisture content (Sheehy et al., 2013), and carbon is protected from decomposition due to physical protection within soil aggregates (Ogle et al., 2012). Ploughing also results in a loss of photosynthetic material for a time, affecting Gross Primary Production (GPP). Re-establishment of a grass sward, after approx. 100 days, can return flux levels to pre-ploughed levels (Hadden & Grelle, 2017). There are varying management practices for grassland reseeding including: conventional ploughing, where soil is inverted from a depth of 20–30 cm, minimum tillage, which disrupts only topsoil (~5 cm depth) and overseeding, where new seed is sown into an existing sward (Schulz et al., 2014).

We performed a field experiment to compare post-ploughing Net Ecosystem Exchange (NEE) and Ecosystem Respiration (Re) time-series, measured using a portable infra-red gas analyser, between various management practices. We predicted that differing ploughing treatment blocks would exhibit significant differences in their carbon flux resulting from structural changes to soil; which, at cumulative large-scales, are likely to impact the accuracy of national carbon emission estimates.

**Materials and Methods**

**Study site**

The experiment was conducted at the Agri-Food and Biosciences Institute (AFBI), Hillsborough research farm in County Down, Northern Ireland (latitude, longitude: 54°27’N, -6°04’W). The site was in intensive grassland production using perennial Italian ryegrass (*Lolium perenne*) and had been used for sheep production in the previous year. The soil was a clay loam / silty clay loam formed over a Triassic red sandstone mixed till or SWG1 (Higgins et al., 2012). (UK soil inventory). The site had not been ploughed for approximately 15 years prior to the experiment.

**Experimental design**

A randomised block design was developed where each of four experimental treatments were replicated five times (20 plots in total); each plot was 2 m × 1 m. Treatments consisted of T1: Conventional ploughing (spraying off, ploughing to a depth of 20 cm), power harrowing, rotavated, sowing seed, and rolling), T2: Minimum tillage (spraying off, rotavated to a depth of 5 cm), power harrowing, sowing seed, and rolling), T3: overseeding (drilling-seed), and T4: Controls (unmanaged plots of existing sward). T1 and T2 sprayed with a glyphosate-based herbicide (160 mL of Roundup™ in 10 L water) three weeks before treatment application. All plots (except the controls) had applications of 29.62 g plot⁻¹ of Nitro chalk (27% N), 6.92 g plot⁻¹ of grass seed and 40 g plot⁻¹ of agricultural lime after initial treatment application.

**Measuring carbon flux**

Flux measurements were quantified using a large, 50 L, chamber made from transparent perplex. Sampled air from inside the chamber headspace passed through an attached infra-red gas analyser (EGM 4, PP-systems Hitchin UK) and flux determined as the difference between in and out flow concentrations (Welles et al., 2001). Internal air was mixed with a small fan to ensure equal distribution of CO₂ (Pumpanen et al., 2004). Net Ecosystem Exchange (NEE) was
measured with a transparent chamber allowing photosynthesis to occur in the chamber headspace. Ecosystem Respiration \((R_e)\) was measured using the same chamber with a dark cover blocking light suppressing drawdown by photosynthesis. \(R_e\) measurements were made immediately after \(NEE\) measurements; each measurement period was 120s. Flux readings were randomised between plots and taken between 10:00 and 14:00 on each measurement day, to minimize diurnal effects on flux in accordance with IPCC good practice guidelines. Measurements commenced on 15/09/2015 taken three times a week until 29/10/2015 after which frequency was weekly until 22/12/2015 when measurements ceased. Eight infrequent measurements were taken from 10/02/2016–22/04/2016 to investigate flux over a longer time frame.

**Environmental variation**

Time-series of air temperature and soil temperature (°C) at 10 cm and 30 cm depths and soil moisture (%) were obtained from an adjacent weather station, approx. 10 m from the study site, connected to the environmental change network (see http://www.ecn.ac.uk/ for details). Continuous variables were recorded hourly and daily averages obtained. Data was then compared based on days of flux measurement.

Soil core samples were collected using a hydraulic soil core to a depth of 10 cm. For each sample, carbon (C) and nitrogen (N) (%) was measured by dry combustion chamber (Leo Trumac, Stockport, UK). Phosphorus (P) using an automated continuous flow wet chemistry analyser (Skalar San plus, Holland), and potassium (K) content using Flame Photometer, (Sherwood Scientific model 410). Soil bulk density measurements were also taken for all plots but after flux measurements had been completed. A surface sample of undisturbed soil was taken to a depth of 5 cm. The sample was weighed, dried until constant mass and re-weighed to determine percentage (%) moisture content. The dry weight was then divided by the volume of the sample container to obtain a measure of the bulk density.

Grass canopy height was measured using a sward measure. Five random points within each plot were selected and height measured when a transparent platform made first contact with any grass structure. Measurements were averaged for each plot. Grass height was recorded on three occasions (26/05/2016, 22/07/2016 and 17/08/2016) to investigate any treatment effects.

**Statistical analysis**

Flux measurements of \(NEE\) and \(R_e\) were analysed as the dependent variables by treatment using restricted (residual or reduced) maximum likelihood (REML) using a power model due to the time-dependent nature and the non-regularity of the data. Variation in weather conditions were analysed using Principal Components Analysis (PCA) reducing air temperature, soil temperate (at both 10 cm plus, Holland), and soil moisture content to two axes. Block*Plot was fitted as a Random Factor, to the REML model, PC1, PC2 and Time as covariates. To test effects from loss of photosynthetic material the factor ‘Photosynthesis’ was created that split the dataset into two parts: 1) post-treatment up to 100 days and 2) after 100 days. Representing pre and post sward re-establishment. The interaction of this factor and treatment was also fitted as Photosynthesis*Treatment. Residual plots demonstrated the data to be normally distributed (Gaussian). Fisher’s Least Square Difference (LSD) was used to identify post-hoc differences between treatment means. Grass and soil metrics were compared between treatments using a one-way ANOVA. All statistics were performed using Genstat 16th Edition (VSN International Ltd.).
Results

REML analysis showed a significant difference in treatment and across time for NEE but not for Re (Table 1). Treatments T1 and T2 (were previous sward was destro yed) became net sources of CO₂ (mean flux T1 0.82±0.11 g CO₂ m⁻² hr⁻¹, T2 0.88±0.11 g CO₂ m⁻² hr⁻¹) for approx. 100 days post ploughing after which time both returned to being net sinks (mean flux T1 -1.85±0.2 g CO₂ m⁻² hr⁻¹, T2 -1.84±0.2 g CO₂ m⁻² hr⁻¹) (Fig.1). T3 and T4 were net CO₂ sinks for the duration of the study period (mean flux first 100 days T3 -1.61±0.2 g CO₂ m⁻² hr⁻¹, T4 -1.88±0.2 g CO₂ m⁻² hr⁻¹; mean flux after 100 days T3 -2.18±0.2 g CO₂ m⁻² hr⁻¹, T4 -2.41±0.2 g CO₂ m⁻² hr⁻¹). Treatments T1 and T2 did not differ from one another (Fisher’s LSD post-hoc *P* >0.05) and T3 and T4 did not differ from one another (*P* >0.05) but T1 and T2 did differ from both T3 and T4 (*P* <0.05) (Fig. 2). The differences observed were driven by post-treatment effects in the first 100 days with little difference observed throughout the rest of the study period. Environmental components (See supplementary mater ial) were significantly influential for both NEE and Re (Table 1). PCA suggested temperature (Air, and Soil, 30 cm and 10 cm) and soil moisture accounted for much variation (50%), with rainfall and solar radiation secondary components (26%). The loss of photosynthesis was not directly significant, however when crossed with treatment it was for NEE, this was not the case for Re (Table 1).

Experimental treatments did not influence soil carbon (*F*ₐdf=3=0.64, *P* =0.598), nitrogen (*F*ₐdf=3=0.32, *P* =0.812), phosphorus (*F*ₐdf=3=0.75, *P* =0.538) or potassium (*F*ₐdf=3=0.39, *P* =0.761) though variance was typically greater for most soil nutrients within ploughed treatments T1 and T2 than unploughed treatments T3 and T4 (Fig. 3a–d). Soil bulk density did vary significantly between treatments (*F*ₐdf=3=5.50, *P* =0.013) being significantly evaluated in the ploughed treatment T1 (Fisher’s LSD post-hoc *P* <0.05) whilst the unploughed T4 controls had the lowest values (Fig. 3e).

Mean grass canopy height did not differ between treatments (*F*ₐdf=3=0.38, *P* =0.767) nor did grass dry matter (*F*ₐdf=3=0.78, *P* =0.77). The longest grass lengths were recorded in the unploughed T4 control plots (Fig. 3f).

Discussion

Net Ecosystem Exchange (NEE) was strongly affected by tillage with ploughed treatments being a CO₂ source during the first 100 days post-ploughing (which occurred during autumn in the current study) before returning to being a net CO₂ sink similar to our unploughed and control treatments. These results appear to be driven by the loss of photosynthetic material (i.e. the sudden destruction of the standing grass crop) rather than differences in flux rates. CO₂ release has been observed after soil disruption at shallow (5 cm) and deep (20 cm) soil horizons at similar situations in Ireland and Scotland, with fluxes returning to pre-ploughed levels approximately 2 months (ca. 60 days) after ploughing (Willems et al., 2011; Helfter, 2015). A fourfold increase in CO₂ release has previously been observed due to post-ploughing (Merbold et al., 2014). Re-establishment of vegetative grass cover due to reseeding subsequently converts ploughed plots to CO₂ sinks several months after ploughing.

Ecosystem respiration (Re) was unaffected by ploughing. Fig. 1b suggests there is a decline in flux rates before rising again. This coincided with the winter period thus, Re decreases during winter before increasing the following spring (Hadden & Grelle, 2017; Flanagan & Johnson, 2005). When variation due to time was taken into consideration no significant difference was observed. Ploughing is recommended when environmental conditions are sub-optimal for soil microbial activity to reduce respiration and thus CO₂ release (Rutledge et al., 2014). Hadden & Grelle (2017) observed higher respiration rates in set-aside land when compared to cultivated
land during spring with differences ascribed to higher vegetation biomass adding organic matter to the soil increasing decomposition by microbial activity. Our results suggest, that in the short-term where ploughing occurs in autumn, subsequent low winter temperatures (and thus lower root and microbial activity) reduce CO2 release which resulted in no differences in Re between ploughed and unploughed treatments.

Failure to account for management practices i.e. the type of tillage and the frequency of its repeated use (for example, regular reseeding) on carbon fluxes within temperate grassland production systems may result in biased and inaccurate estimates of carbon sequestration during National-level inventories. Merbold et al. (2014) report that a 10-year rotation for grass was insufficient to restore half of the CO2 lost due to the just one ploughing event in Switzerland. Meta-analyses suggest carbon stocks accumulate in the upper layers of non-ploughed (no till) systems and whilst ploughing impacts upper layers it has little impact at lower depths (Powlson et al., 2011; Angers & Eriksen-Hamel, 2008). Below the ploughed layer, carbon is more recalcitrant (Rasse et al., 2006). Thus, the treatments applied in the current study are unlikely to have affected carbon storage deeper than the depth of the plough. It may be difficult to detect the impact of short-term perturbations on soil carbon pools if large background deposits of carbon are present; with impacts taking up to 10 years to detect depending on the magnitude of the perturbation (Smith, 2004).

Many studies have reported a reduction in soil bulk density with ploughing (Osunbitan et al., 2005), however, we report the opposite effect with ploughed treatment T1 Deep ploughing (spraying off, ploughing to a depth of 20 cm), power harrowing, rotavation and sowing seed) significantly increasing soil bulk density. T1 was the only treatment to affect soil below 5 cm (the measurement level of bulk density). Ploughed treatments were rolled, adding weight and compacting soil, after establishment, possibly accounting for the change in bulk density. Mahmoudi et al. (2015) observed an increase in bulk density with increased depth of tillage. The soils in the current study had a high clay component, which can show a higher bulk density after ploughing than non-ploughed soils or soils with a low or no clay component (Laine et al., 2017; Necpálová et al., 2014; Ji, 2013).

Soil nutrient content and subsequent grass canopy height was unaffected by tillage during the current experiment perhaps due to the application of agricultural lime and fertiliser during reseeding which may have masked any loss of nutrients. Ploughing soils allows for greater root penetration by reducing resistance (Mahmoudi et al., 2015). The small sampling time may also play a role. Grasslands are reseeded only rarely, approx. once every 10 years (Merbold et al., 2014) it is conceivable that the grass in treatment 4 would degrade over time showing less growth potential than the reseeded treatments. This hypothesis would need investigated further.

The duration of the experiment was short (<1 year) with data collection during autumn, winter and spring coinciding with low biological activity with few NEE and Re measurements taken during winter. As flux rates, particularly for NEE, were correlated with environmental variables it would be necessary to construct a longer time series (1 year) with measurements of soil temperature and moisture in plot as opposed to in an adjacent plot as here.

Nevertheless, we provide clear evidence supporting the hypothesised changes in flux post-ploughing of temperate grasslands where the system moved to being a carbon source for approximately 100 days before returning to being a carbon sink. These changes are likely attributed to the loss of photosynthetic material rather than effects of ploughing per se.

Acknowledgements

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References


Figures

a)  

b)  

Fig. 1 Time-series throughout the experiment for fluxes in a) Net ecosystem exchange (NEE) and b) ecosystem respiration ($R_e$) across treatment blocks. Straight dashed line represents 0 flux. The convention is positive figures represent a loss of $\text{CO}_2$ from the ecosystem and negative figures represent a sequestration of $\text{CO}_2$. 
**Fig. 2** Bar charts showing a) mean NEE pre and post canopy establishment and B) Mean $R_e$ pre and post canopy establishment. Error bars are standard error. White bars represent pre-100 days and grey bars post 100 days.
Fig. 3 Barcharts showing the mean for a) soil carbon (%), b) nitrogen (%), c) phosphorus (mg/l), d) potassium (mg/l) content, e) bulk density (with LSD scores) and f) grass canopy height (cm) after re-establishment of sward across four treatment blocks: T1: Deep ploughing (spraying off, ploughing to a depth of 20cm), power harrowing, rotavation, sowing seed, and rolling), T2: Minimum ploughing (spraying off, subsoiling to a depth of 5cm), power harrowing, sowing seed, and rolling), T3: overseeding (drilling-seed), and T4: Controls (unmanaged plots of existing sward). Error bars are Standard error.
Table 1 Restricted (or residual, or reduced) maximum likelihood (REML) model outputs for a) NEE and b) Re. Block*Plot was fitted as a Random Factor.

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<th>n.df</th>
<th>d.df</th>
<th>p</th>
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**Online Supplementary Materials**

**Fig. S1** Times-series showing environmental for a) air temperature, b) rainfall, c) soil temperature at 10 and 30cm depths and d) soil moisture content. Atmospheric variables were measured at adjacent weather station.

**Table S2.** Summary statistics for soil analysis

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