Environment and Rural Affairs Monitoring & Modelling Programme

ERAMMP Year 1 Report 21:
GMEP Outstanding Analysis Part 2 - Revisiting Trends in Topsoil Carbon from CS2007 to GMEP 2013-2016

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Contents

Abbreviations and some of the technical terms used in this report are expanded in the project glossary: https://erammp.wales/en/glossary (English) and https://erammp.cymru/geirfa (Welsh)

1 Summary

New analysis was carried out to explore the reported loss of topsoil-C between 2007 and 2016 in the ‘Habitat’ category in the final GMEP report. This ‘Habitat’ category is defined as all habitats except woodlands, arable and improved grassland.

The GMEP survey squares were selected using Countryside Survey protocols stratified according to Land Classes. The final GMEP survey sample from 2012-2016 consists of 7% previously surveyed Countryside Survey squares. Further analysis was needed to explore, and account for, unintended shifts in environmental variables which could have contributed to the reported topsoil carbon decline.

The results indicate:

1. The reported change in the ‘Habitat’ category is driven by trends in upland habitats (median elevation of 400m).
2. In upland habitats, soil carbon is positively associated with dwarf shrub cover (particularly ericoid e.g. heather cover), *Sphagnum*, presence of peat, elevation and moisture conditions.
3. The coverage of dwarf shrubs was lower in GMEP than in Countryside Survey 2007, mostly due to lower cover of ericoids i.e. heather. This is consistent with decreasing soil carbon in upland habitats. Other variables (i.e. potential drivers) did not differ between surveys, or direction of change was inconsistent with reported C trends.
4. Re-analysis of Countryside Survey data (1978-2007) provides evidence that shifts over time from dwarf shrub to grass-dominated habitats are associated with a decline in topsoil carbon.
5. Overall, this suggest a potential role of ongoing vegetation change in upland habitats (i.e. conversion of dwarf shrub to grass-dominated) contributing to topsoil carbon loss.

Further work is needed to:

- Confirm recent vegetation change in upland habitats using independent data e.g. satellite data;
- Explore relationships between specific plant species and topsoil carbon in Countryside Survey where we have a high number of true repeat samples;

This work highlights the importance of the findings of the next ERAMMP survey, which will be more powerful than the combined CS-GMEP approach reported here.

2 Introduction

Soil organic carbon (SOC) is fundamental for plant nutrition and productivity, and is a key contributor to soil structure. Furthermore, soils play a critical role in production and sequestration of greenhouse gasses (GHGs) such as CO_2 and CH_4[1]. Because SOC underpins both food production and climate change mitigation, it is considered a highly valuable natural resource.

Policy structures in Wales[2,3] set out powers and responsibilities for public bodies to:

- 'Decarbonise' and combat climate change
- Ensure natural resources are managed in a sustainable way

Action cannot be taken on these points without clear evidence on the current state, and recent trends, of SOC in Wales. This is reflected in the inclusion of SOC as one of the 46 Well Being of Future Generations National Indicators (Number 13).The Glastir Monitoring and Evaluation Programme (GMEP) provided a representative snapshot of SOC levels across all common land uses in Wales from 2013-2016[4]. Crucially, GMEP SOC measurements can be put into the context of compatible data from the Welsh component of the Countryside Survey[5] (CS).

2.1 Soil C trends from GMEP

GMEP had two components, each with 150 1km survey squares:

1) **Wider Wales:** Representative of the Welsh countryside. Stratified-random across land classes. **Consistent with CS.**

2) **Targeted:** Targeted towards land under Glastir. Squares selected based on a dynamic set of criteria as outlined in GMEP reports.

Discussion and analysis in this chapter focusses entirely on the Wider Wales component for the purposes of representation and consistency with CS.

Although GMEP set out to establish a baseline for future environmental monitoring in Wales[4], it also allowed investigation of trends in soil properties since 1978. This was possible because SOC measurements from CS were collected and processed using a methodology that is consistent with GMEP; loss on ignition (LOI) measurements were taken from a stratified random sample of the Welsh countryside. LOI can be converted to SOC using a standard formula. Trends in topsoil C between CS and GMEP were explored across three major land use types, defined based on broad habitat classifications made by field surveyors at the time of sampling:

- **Woodland**: Comprises "Broadleaved mixed and yew woodland" and "Coniferous woodland"
- **Improved land**: Comprises "Arable and horticultural" and "Improved grassland"
- **Habitat**: Comprises all non-woodland and unimproved broad habitats

The resulting trends indicated non-significant increases in topsoil C in woodland and improved land, but a significant negative trend on habitat land[4] (Figure.1). This result is of great concern, because CS and GMEP data also demonstrate that habitat land represents a much larger pool of topsoil C than either woodland or improved land.

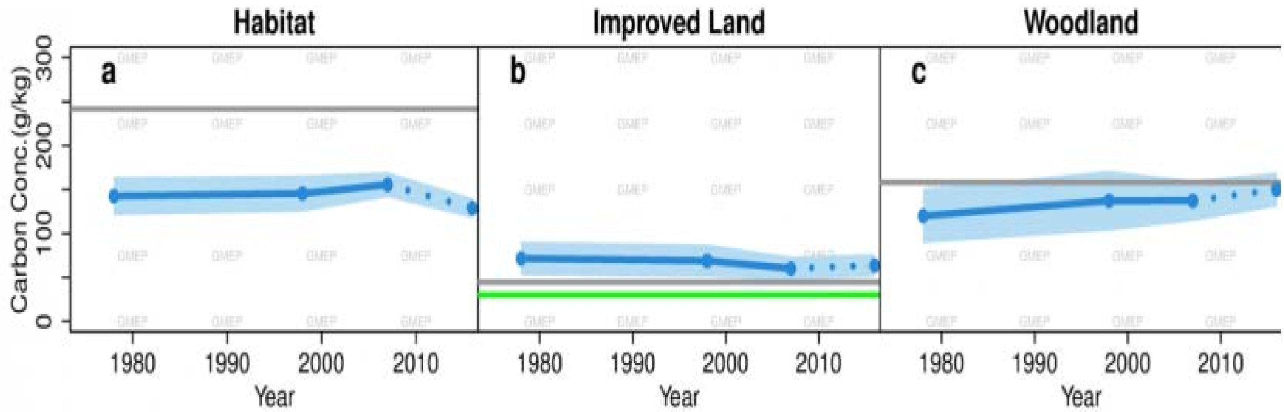

Figure 1. Trends in carbon concentration reported under GMEP4 across Wales in three land use types: “Habitat”, “Improved land” and “Woodland” (see section 1.1 for details). The three points towards the left of each graph are derived from CS squares surveyed in Wales in 1978, 1998 and 2007. The point on the right of each graph is derived from 150 GMEP wider Wales squares surveyed in 2013-2016. Grey lines are GB averages for that land use type from CS data. Green lines are thresholds that blue lines should not fall below.

2.1.1 Key limitations of CS-GMEP trends

Throughout this chapter it is important to recognise the limitations of trends comparing soil data between CS and GMEP surveys:

Trends are derived from distinct samples of the same statistical population

107 CS 2007 squares, and 150 “wider Wales” GMEP squares, were selected to sample the same population. That population is all 1km squares in the Welsh countryside, stratified for proportional representation of all land classes by area[5]. However, between the two surveys only 21 squares coincide exactly. There is inherent variability associated with trends derived from two distinct random samples, as opposed to one sample recorded consistently across time points. For this reason results of the ERAMMP field survey will be of great interest.

Plots may have transitioned in land use between surveys

The land use types used for GMEP reporting – “habitat land”, “improved land” and “woodland” – are defined based on broad habitat information recorded by field surveyors at the time of sampling. It may be reasonable to assume that surveyors recorded broad habitat in a consistent manner between CS 2007 and GMEP as they were trained by the same CEH staff. However, a given plot may have transitioned in broad habitat type between the two surveys, which has implications for soil C trends. Habitat transitions and their implications are discussed in greater detail in section 4.

2.2 Aims and scope

We further investigate trends in topsoil C observed under GMEP, especially on habitat land. Making use of soils data from CS 2007 and GMEP, as well as independent environmental datasets, we address the following key questions:

Section 3 – Uplands or lowlands: Are declines in topsoil C more severe at higher elevations?

Section 4 – Effects of climate and vegetation: Which environmental variables are associated with topsoil C in upland habitats?

Section 5 – Drivers of soil C trends: Could trends in environmental variables underpin change in topsoil C in upland habitats?

Section 6 – Land use transitions: Is there any evidence of land use transitions between CS 2007 and GMEP which could explain trends observed?

3 Locating habitat carbon declines: Uplands or lowlands?

3.1 Why consider elevation?

High resolution (5m) information on elevation is available under ERAMMP through the NextMap Digital Terrain Model[6] (DTM). This information is useful to pinpoint trends in soil C for the following reasons:

Elevation is a powerful proxy for other environmental variables

A huge variety of factors affect the concentration of carbon in the topsoil. These factors include, but are not limited to, parent material of the soil, temperature, precipitation, acid deposition, land use, agriculture & drainage[7]. These factors tend to exhibit some form of correlation with elevation across Wales (e.g. Figure. 2 shows correlation between elevation and land use). Stratifying trends between the uplands and lowlands will cultivate more sophisticated hypotheses about the drivers of change in soil C between CS and GMEP.

Controlling for elevation is statistically useful

Survey squares in CS and GMEP are mostly not in the same locations. As such there could be random variation in elevation of squares across the two surveys, with potential consequences for soil C although a consistent approach using ITE Land Classes was used to ensure compatibility. Elevation is fairly consistent within upland and lowland habitats between the two surveys (Figure. 2). However, lowland habitats have a slightly higher representation in GMEP than in CS (see numbers above box plots, Figure. 2). By including elevation in statistical models, we can be confident that the trend between the two surveys is not underpinned by a random trend in elevation.

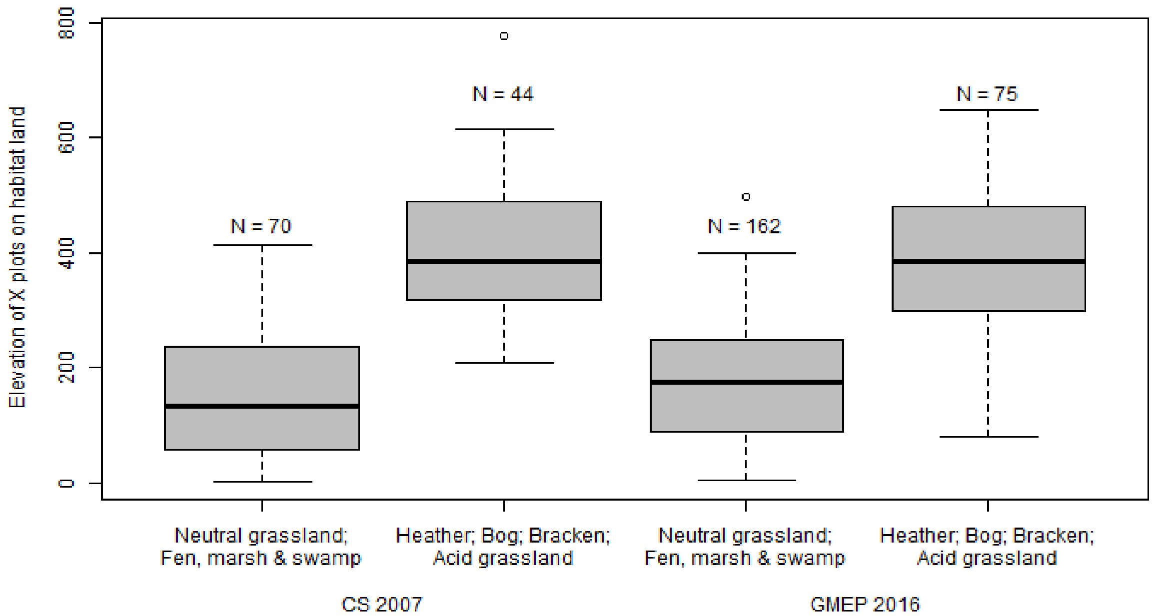

Figure 2. Elevation may differ between broad habitats and years. Elevation (metres) of “X plots” (randomly placed plots where vegetation and soils were sampled) as distributed between two subsets of “habitat land” across the two surveys. Thick black lines show the median, grey boxes show the interquartile range and N represents the number of plots in each category. While the average elevation of the two sets of broad habitats does not differ between surveys, Neutral grassland and Fen, marsh and swamp have a higher proportional representation in GMEP than they do in CS.

3.2 Methods

As in the GMEP final report[4], we used generalised linear mixed-effects models (GLMMs) to analyse change in topsoil C between CS and GMEP. We allowed trends to differ between broad land use groupings (habitat land, improved land and woodland) based on broad habitat classifications made by field surveyors. We also accounted for the spatial structure of the surveys using random effects.

We improve upon previous analysis by allowing soil C trends to vary not only between land uses, but also with elevation. We focussed only on the data from CS 2007 and GMEP, as this is the time period relevant to the C decline on habitat land. Elevation data from the NextMap DTM[6] (5m resolution) were extracted to soil sample locations using ArcMap 10.6[8]. For consistency with previous analyses, we fitted GLMMs with Gaussian error structures in *R 3.5.2.*[9] using the package *lme4*[10]. We constructed 3 models:

- **Model 1: A model analogous to the GMEP model** allowing soil C trends to vary between land use types.
- **Model 2:** A model that also allows trends to vary with elevation. Elevation effects on soil C trend are **the same** across land use types.
- **Model 3:** A model equivalent to model 2, except elevation effects on soil C trend are **different** between land use types (e.g. elevation affects trends in habitat land, but not woodland).

We scored the three models based on "Akaike's Information Criterion" (AIC)[11]. The model with the lowest AIC has the best fit to the data, while not being overly complex.

3.3 Results

The best model according to AIC was Model 3. This shows that elevation affects the slope of the soil C trend, but only on "habitat land" (Figure. 3). Topsoil C on habitat land is largely stable at low elevation. However, for every 100m increase in elevation, the trend between the two surveys steepens by -11.4 g/kg. AIC of Model 3 was 35.26 lower than the next best model, suggesting substantially improved fit to the data (see Appendix 1 for details) and clarifies that the trend in SOC is confirmed for habitat land but was only recent at higher elevations.

3.4 Next steps

By including elevation in analysis of soil C trends, we have:

Ensured that the trend in topsoil C was not underpinned by subtle differences in elevation between CS 2007 and GMEP samples.
Tracked topsoil C declines to habitat land in upland regions of Wales.
Fostered more sophisticated hypotheses about the drivers of changes in topsoil C.

Upland regions are colder, wetter and possibly more sensitive to changes in climatic conditions than lowland regions. Trends in topsoil C could be driven by climatic changes that are either more pronounced, or more impactful, at high elevation. Section 3 will include national datasets on temperature, precipitation and evapotranspiration to understand whether this is the case.

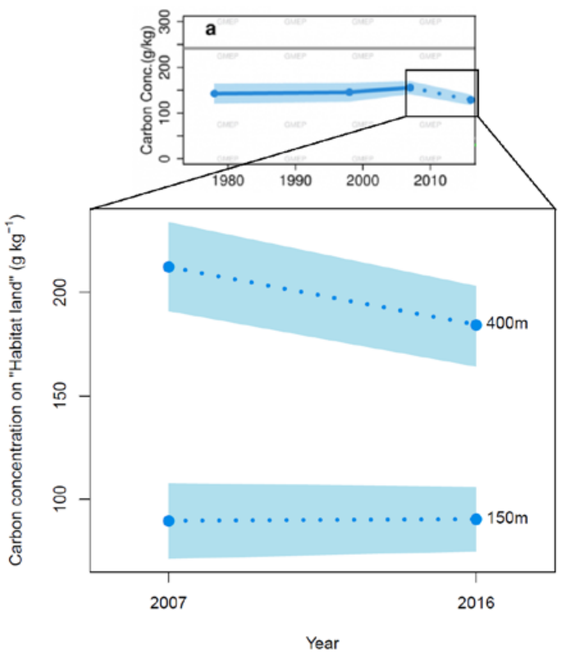

Figure 3. Carbon trends between CS 2007 and GMEP are more negative in the uplands. The top panel shows the original trend in topsoil C on habitat land from CS 1978, 1998 and 2007 through to GMEP 2016. The solid blue line represents modelled averages throughout CS. The dotted blue line shows change between CS 2007 and GMEP. The grey line shows the CS Great Britain average from 1978 – 2007, to provide context. The light blue area represents the 95% confidence interval for modelled averages.

The bottom panel shows modelled averages of topsoil C on habitat land between CS 2007 and GMEP at two elevations, based on the improved model. These elevations roughly correspond to the median values for the different broad habitat groupings shown in Figure. 2. While the trend between CS 2007 and GMEP appears to hold at 400m, there is no significant decline at 150m.

Furthermore, upland habitats comprise very different characteristic vegetation as compared with lowland habitats (Figure. 2). Neutral grassland makes up ~50% of "habitat land" and ~25% of the Welsh countryside (Figure. 4), but mostly occurs below 200m (Figure. 2). As such, soil trends might be linked to trends in upland vegetation including bracken, heather and *Sphagnum* bog (Figure. 4). Section 3 will make use of high-quality vegetation data collected under CS and GMEP to see (1) whether characteristic dominant vegetation changed between the two surveys, and (2) whether these changes could underpin trends in topsoil C.

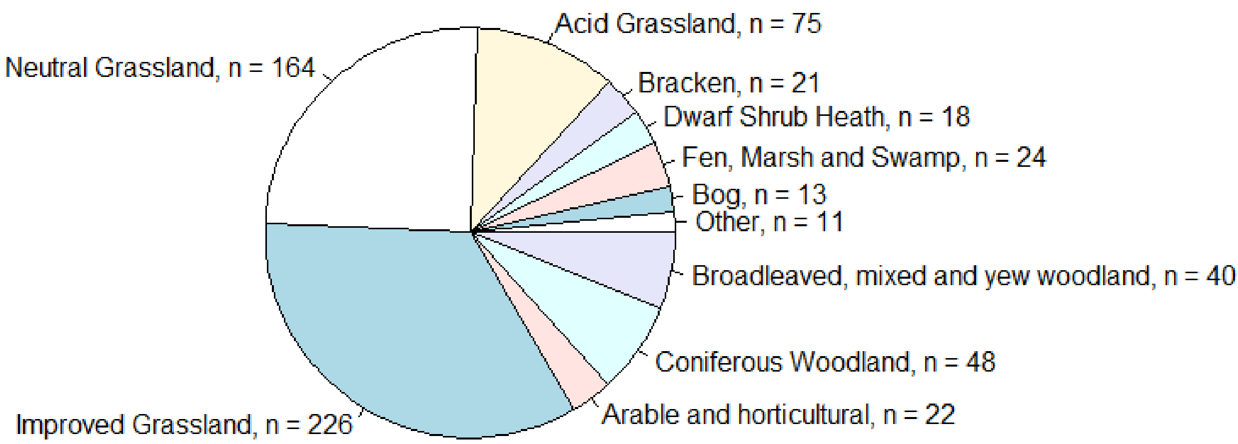

Figure 4. The distribution of soil samples across broad habitats in the GMEP field survey**. The top half of the pie chart comprises "habitat land", while the bottom half comprises "improved land" (improved grassland; arable and horticultural) and "woodland" (broadleaved, mixed and yew woodland; coniferous woodland).** With the exclusion of "fen, marsh and swamp", the current analysis suggests that broad habitats in the top-right of the pie are underpinning the trend in soil C between CS and GMEP.

4 Carbon declines in upland habitats: Links to vegetation and climate

4.1 Why consider vegetation and climate?

In this section we test more sophisticated hypotheses about the drivers of patterns and trends in soil C in upland habitats. We test effects of a variety of variables on soil C (see Table 1), allowing some effects to be different in slope or direction between surveys.

Table 1. Primary variables used to model topsoil C, and justifications for including each variable. We also allowed the direction of the effect of some variables to differ between CS 2007 and GMEP 2016. For example, the species composition of shrubs might have changed between CS and GMEP. If this were the case, we might expect the slope of the relationship between shrub cover and topsoil C to differ between surveys.

Variable used to model topsoil C	Justification	Test for change in direction of effect between surveys?
Climatic moisture –mean annual precipitation – mean potential evapotranspiration (MAP-PET, mm)	Moisture, and corresponding oxygen limitation, is thought to be a key driver of soil pH and C dynamics.	Yes – it is informative to know whether a carbon-moisture relationship was disrupted between surveys.
Temperature – mean annual temperature (°C)	Temperature limits plant productivity, potentially affecting accumulation of soil C e.g. from dead plant material.	No.
Acid deposition – non-marine sulphur, (kiloequivalents h^{-1} $year^{-1}$)	Positive relationship between acidity and soil C is established. Acid deposition known to have declined in recent years.	No.
Shrub cover – total cover of heather Ericoideae; gorse *Ulex*; bilberry *Vaccinium* (%)	Shrubs affect soil moisture and the depth profile of soil organic carbon.[12] They are responsive to land management.	Yes – species composition of shrub cover could differ between surveys, affecting relationship between soil C and shrub cover.
Bracken cover – *Pteridium aquilinum* (%)	Considered an invasive weed. Bracken control measures have been shown to affect soil properties.[13]	No.
***Sphagnum* cover** (%)	Associated with peat formation and soil C accumulation.[14]	No.
Deep peat – presence of underlying peat >0.4m	Soil dynamics are expected to differ between deep peat and organo-mineral soils.	Yes – areas without underlying deep peat may be more vulnerable to declines in topsoil C.
Moisture & deep peat interaction	Due to high drainage, precipitation and moisture might be critical on organo-mineral soils with no underlying peat.	No.

Variable used to model topsoil C	Justification	Test for change in direction of effect between surveys?
Elevation	Shown in section 2 to be a good predictor of patterns and trends in soil C.	No.
Survey trend – soil C change attributable to other drivers	Any trends not explained by the above factors are still represented in the model.	-

For the environmental variables in Table 1, we ask:

1) What is the relationship (if any) between each variable and topsoil C concentration?
2) For a subset of relevant variables, does the slope or direction of the relationship with topsoil C vary between CS 2007 and GMEP?
3) Given the above relationships, what is the expected contribution of each variable to the soil C trend in upland habitats in Wales?

4.2 Methods

4.2.1 Extracting soil C data from upland habitats

We extracted soil C data for upland habitats as defined by remote sensing data from the Land Cover Map 2015[15] (LCM). When habitat information from two separate time periods is used to produce a C trend, interpretation of that trend is complicated (see section 1.1.1 for details). Thus, we used independent, temporally consistent information to extract upland habitat soil samples; this ensured that C trends were not obscured by broad habitat transitions. However, see section 4 for an investigation on C trends in following observed habitat transitions in a small number of true repeat squares.

We selected all soil C records from CS 2007 and GMEP that were “acid grassland”, “bog”, “heather” or “heather grassland” according to the LCM. Figure 5 shows the distribution of these habitats; they occupy the majority of land above 250m elevation in Wales, and rarely exist below 250m. While the LCM allowed us to extract data consistently across the two surveys, in further analyses we used vegetation cover within 2m of the soil sample to understand the impact of habitat types on topsoil C.

4.2.2 Climate, vegetation, peat and acid deposition data

Temperature, precipitation and potential evapotranspiration data from 2003-2015 at 1km resolution were downloaded from the CHESS database[16,17]. For each soil sample, we extracted the mean annual temperature (°C), mean precipitation (mm) and mean potential evapotranspiration (mm) for 5 years up to and including the year that the sample was taken. Thus, for a soil sample taken in CS 2007 we used climate averages from 2003-2007 inclusive. However, for GMEP samples taken in 2016, we used climate averages from 2011-2015 inclusive (CHESS data were not available for 2016).

Vegetation cover data were extracted from the CS and GMEP databases and related to each soil sample based on unique plot identifiers. For each soil sample we extracted the cover of three vegetation groups; (1) a subset of characteristic shrub taxa (all of subfamily Ericoideae, *Ulex* and *Vaccinium*), (2) bracken *Pteridium aquilinum* and (3) all *Sphagnum* moss species.

Soil samples were classified as lying on deep peat (>0.4m) if they fell within the unified peat map produced during GMEP[4]. The unified peat map polygons bring together information on deep peat coverage from the British Geological Society, the Forestry Commission and Natural Resources Wales.

Finally, acid deposition data were downloaded at 5km resolution for two time periods, 2005-2007 and 2012-2014, from the Concentration Based Estimated Deposition database[18] (CBED).

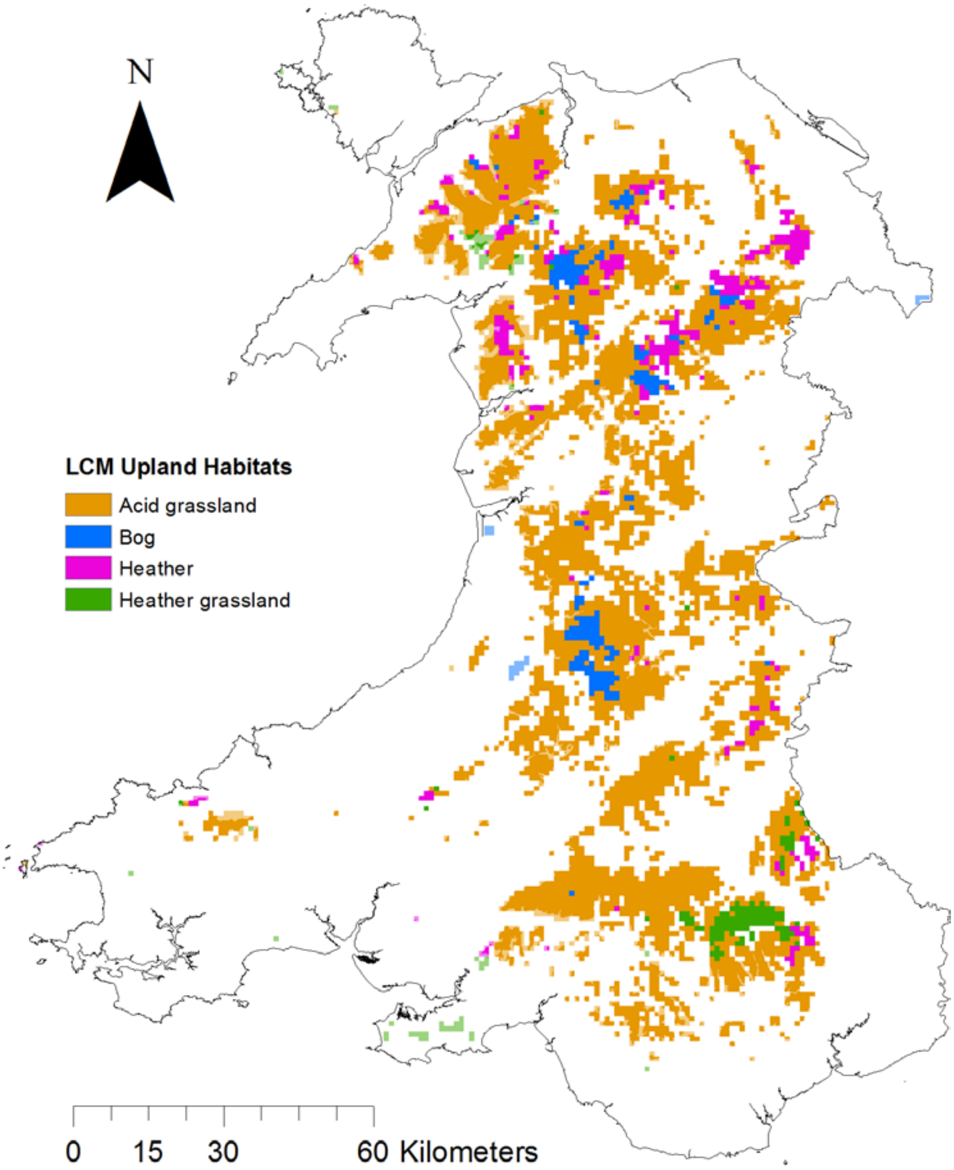

Figure 5. The distribution of upland habitats (acid grassland, bog, heather and heather grassland) in Wales according to the Land Cover Map 2015 (LCM). In the very few areas where habitats fall below 250m elevation, colours are shown as faded (e.g. heather grassland on the Gower peninsula, peripheral acid and heather grasslands in Snowdonia). LCM data are shown at 1km resolution.

4.2.3 Model fitting and model selection

As in section 2, we used generalised linear mixed-effects models (GLMMs) to analyse change in topsoil C using data from CS 2007 and GMEP. As outlined in section 3.2.1, we focussed on locations that fell into upland habitat categories in the LCM 2015. Again, we accounted for the spatial structure of the surveys using random effects.

In this analysis we test for effects of all drivers listed in Table 1. Environmental variables were extracted to soil sample locations using ArcMap 10.6[8]. Topsoil SOC concentration is derived from loss on ignition (LOI), which is a consistent proportion of LOI. As such, we improved our modelling approach by fitting GLMMs with beta error structures in *R 3.5.2.*[9] using the package *glmmADMB*[19].

For this analysis we fitted one model for every possible combination of environmental predictors outlined in Table 1. As in section 2, these models were scored and compared based on AIC. The effect of an environmental predictor was considered significant if it was included in both the best model (the lowest AIC model) and all models within 2 AIC units of the best model. This is a conservative method to determine significance. Incidentally, in this analysis inference would have been identical if we used standard significance tests for parameters that were included in the best model.

4.3 Results

There was no clear best model according to AIC, possibly as a result of correlation between some of the environmental variables considered. 12 models were within 6 AIC units of the best model, and had lower AIC than any simpler nested version (Appendix 2). Of these, 3 were within 2 AIC units of the best model. Six environmental variables showed consistent relationships with topsoil C, all appearing in the best model as well as models within 2 AIC units of the best model. These variables have up or down arrows in Table 2 under “Positive or negative relationship with C?”.

4.3.1 Shrub cover

Topsoil C in upland habitats was positively associated with total % cover of a set of shrub species (Table 2), specifically heather/crowberry (subfamily Ericoideae: genera *Calluna, Erica and Empetrum*), bilberry (*Vaccinium*) and gorse (*Ulex*). However, the relationship between shrub cover and topsoil C was diminished in GMEP. One explanation for this is that the difference in composition of shrubs between CS and GMEP; the reduction in upland shrub cover between CS and GMEP was mainly attributable to a reduction in Ericoideae (specifically *Calluna*; Figure. 6). Therefore, differences in both cover and species composition of shrubs between the two surveys could be a key factor contributing to C declines in upland habitats between CS and GMEP.

4.3.2 Underlying deep peat

The presence of underlying deep peat (>0.4m) was positively associated with topsoil C. A likely explanation is that the carbon-rich organic horizon of the soil would consistently make up the entire length of the 15cm soil core. The tendency for high topsoil C to be recorded on deep peat was stronger under GMEP than CS. This could be related to the increase in overall quality of blanket bog habitats recorded between CS and GMEP[4]. The above effects would be expected to positively impact the trend in topsoil C on habitat land. However, that positive impact was counterbalanced by a reduction in the proportional representation of deep peat in GMEP as compared with CS 2007.

4.3.3 Climatic moisture

Climatic moisture was positively related to topsoil C. Climatic moisture is likely to impact soil moisture as it is the net flux of water from precipitation into the soil after removing water transpired back to the atmosphere by evapotranspiration which is a key driver of accumulation of soil organic carbon. High soil moisture can result in reduced oxygen availability, hindering microbial decomposition and mineralisation of C[20]. High soil moisture can also impact the plant community, which affects the quality and quantity of plant litter entering the soil. Climatic moisture was not positively related to topsoil C where there was underlying deep peat. This is likely to be due to soil moisture on deep peat being related to drainage characteristics as much as precipitation, while soil moisture of e.g. organo-mineral soils is more governed by precipitation and temperature. Climatic moisture increased across most of Wales between the two surveys (Figure. 7). This would be expected to positively impact the topsoil C trend on habitat land, particularly at lower latitudes and elevations.

4.3.4 Other effects

We found that *Sphagnum* cover was positively associated with topsoil C in upland habitats. This makes sense given the role of *Sphagnum* in peat formation and soil C accumulation. As in section 2, we found that elevation was positively associated with topsoil C. We explicitly considered moisture and vegetation in this analysis, so elevation could be acting as a proxy for other variables such as land use history. There was no clear signal of a relationship between bracken cover, temperature or acid deposition and topsoil C and therefore is unlikely to have contributed to the trend reported.

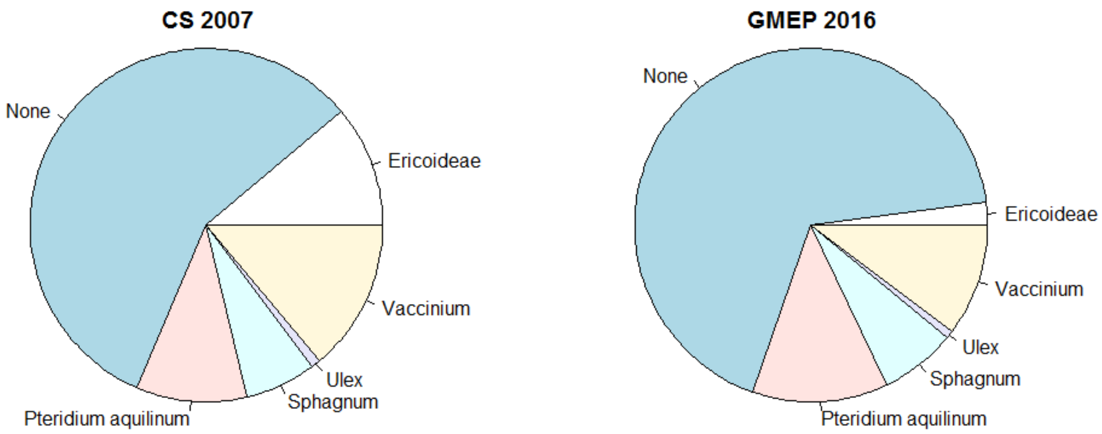

Figure 6. Pie charts indicating dominance (>20% cover) of a few characteristic vegetation types within 2m of upland habitat soil C samples. “Shrub cover” as analysed throughout this section comprises Ericoideae (white), Vaccinium (yellow) and Ulex (purple).

Table 2. Differences in environmental variables between CS and GMEP and the direction of significant relationships between environmental variables and topsoil C concentration. Non-significant relationships are not included here. Where two arrows are shown under "Positive or negative relationship with C", the steepness of the relationship differed between the two surveys. "The expected impact on C trend" is derived by putting these relationships in the context of changes in environmental variables between the two surveys;

Environmental variable	Change in environmental variable between CS and GMEP	Positive or negative relationship with C?		Expected impact on C trend	Explanation
		CS	GMEP		
Shrub cover	↓	↑	↔	↓	Shrub cover was positively related to topsoil C in CS. In GMEP, shrub cover was lower than in CS (Figure. 6) and the relationship between shrubs and topsoil C was diminished.
Deep peat	↓	↑	↑	↔	Deep peat was associated with increased topsoil C – especially in GMEP. However, the GMEP sample had lower representation of deep peat than CS 2007; the effect on the C trend is balanced.
Climatic moisture	↑	↑		↑	Moisture was positively related to topsoil C. Across most of Wales, the period running up to GMEP was wetter than the period leading up to CS 2007 – particularly at lower elevations (Figure. 7). On deep peat the effect of climatic moisture was diminished.
***Sphagnum* cover**	↔	↑		↔	*Sphagnum* moss cover was positively related to topsoil C, but did not vary between the two surveys across upland habitats. (Note: *Sphagnum* did increase in blanket bog habitat).
Elevation	↔	↑		↔	Elevation was positively associated with topsoil C. However, in upland habitats elevation was stable across the two surveys (Figure. 2).
Change not accounted for by variables considered	-	↓		↓	There remains an overall slight negative trend between surveys that was not driven by the environmental variables considered in this section.

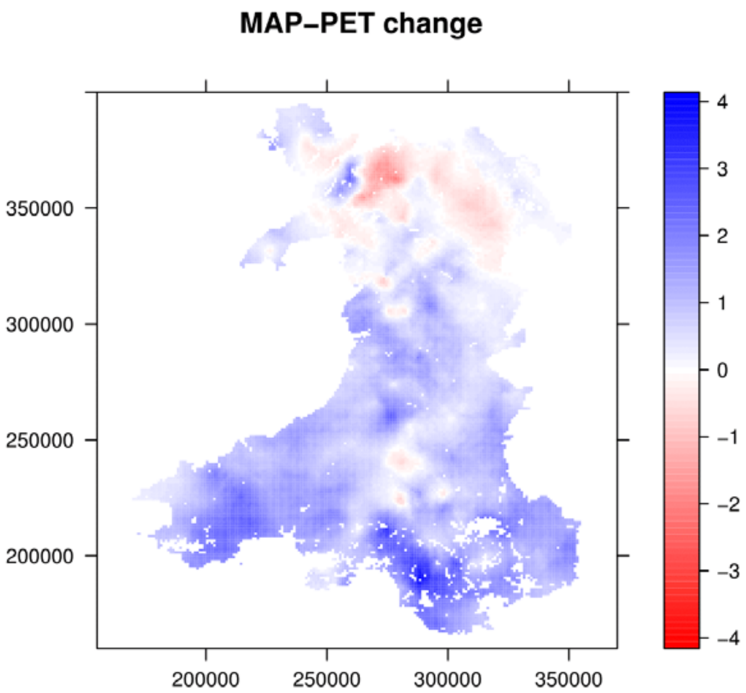

Figure 7. Trend in net water flux into the surface (mean annual precipitation minus mean potential evapotranspiration, measured in hundreds of mm) between 2003-2007 and 2011-2015 across Wales. Aside from a few areas in North Wales, climatic moisture has increased between the two surveys

These results suggest the environmental variable most consistent with the decline in SOC reported in GMEP is the link to lower shrub cover in the sample.

4.4 Evidence of the role of vegetation change on topsoil carbon from Countryside Survey transition sites

Eight of 50 (16%) GMEP plots which were a repeat sampling of CS 2007 plots were observed to undergo a transition between the land use types presented in GMEP. This provides proof-of-concept that habitat transitions would have occurred quite frequently between CS 2007 and GMEP as has been reported between before for CS. However, the repeat plot sample is too small to generate a robust analysis of change in topsoil C between the two surveys.

Instead we explored the much larger sample size from Countryside Survey where a large number of transitions has been tracked over time between 1978 and 2007. An extract of this work which was funded through aligned CEH funding is presented here to illustrate the likely link between loss or gain of dwarf shrub and grass and topsoil carbon (Figure 8). The results show consistently that a shift towards dwarf shrub or bog vegetation is associated with an increase in topsoil carbon whilst a shift towards grass-dominated vegetation is associated with a decrease.

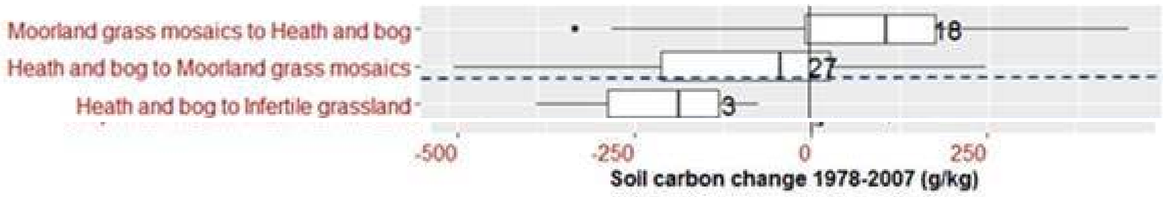

Figure 8 Positive (+) or negative (-) change in topsoil carbon (g/kg) in repeat Countryside Survey plots where a transition in vegetation has been reported between 1978 and 2007. Numbers indicate the number of plots which contribute to the results presented.

4.5 Next steps

The observed relationship between topsoil C and shrub cover (specifically Ericoideae, mainly comprising heather *Calluna vulgaris*) is of great interest. Excluding *Sphagnum* dominated plots, Ericoideae-dominated plots were the most carbon-rich of the vegetation types considered. Critically, there was a decline in the representation of Ericoideae in upland habitats under GMEP as compared with CS. This decline in Ericoideae could be a contributing factor to observed declines in topsoil C in upland habitats.

However, it is important to remember that CS 2007 and the GMEP wider-Wales component are largely independent samples of 1km squares in Wales. While the GMEP wider-Wales sample was drawn according to the same statistical processes as the CS 2007 sample; random fluctuations in representation of different types of plots may have occurred. Further work could determine whether the decline in heather-dominated plots between the two surveys was underpinned by real vegetation change or random fluctuations.

One way to quantify real change in cover of heather would be to use national-scale satellite imagery from the relevant time periods. Using field survey data on point coverage of Ericoideae, it may be possible to map heather across Wales at the time of each survey. This in turn would allow us to predict change in heather cover across the two surveys. The result could provide (1) independent evidence of declines in heather within GMEP survey squares, or (2) evidence that representation of heather has declined due to random sampling. Either way, mapping change in heather coverage would provide a useful indicator of vegetation change in upland Wales. This would also develop a workflow for use of field data to inform earth observation analyses.

To test the causal relationship between change in heather cover and topsoil carbon, repeat plots CS have been demonstrated to be a very valuable data resource. Further exploration of CS data could explore specific relationships for particular change in individual species such as heather, topsoil carbon change and whether the direction and magnitude of change is consistent with the GMEP reported topsoil carbon loss in upland habitats.

Finally, the next round of ERAMMP surveys will be vital in providing hundreds of repeat measurements from GMEP, massively increasing analytical power as well as providing critical information on habitat transitions. The new rolling soil monitoring programme, building on all past CS sampling locations by CEH across the whole of GB including Wales, will also provide additional evidence for trends in topsoil carbon.

5 Conclusions and Recommendations

In section 2 we advanced our understanding of topsoil C trends from GMEP by including the effects of elevation. Topsoil C declines were traced to upland habitats such as acid grassland, dwarf shrub heath, bracken and bog. However, trends on lowland habitats such as neutral grasslands, fen, marsh and swamp were stable. By including elevation in statistical models, we ensured that the topsoil C trend on habitat land was not underpinned by random changes in elevation between survey samples.

In section 3 we showed that climatic moisture, underlying deep peat and *Sphagnum* cover were positively associated with topsoil C. Interestingly, climatic moisture did not positively affect topsoil C if there was underlying deep peat. One explanation is that soils with underlying deep peat stay moist, and thus carbon-rich, even when rainfall decreases. On the other hand, freely draining organo-mineral soils would be more responsive to climatic moisture. For the most part, climatic moisture increased between CS 2007 and GMEP, especially in the lowlands (Figure. 7). As such, it is more likely to have driven a slight increase in topsoil C in the lowlands than a decrease in soil C in the uplands.

Shrub cover had a positive relationship with soil C. However, this relationship was diminished in GMEP – a fact probably driven by a difference in shrub composition between the surveys (Figure. 6). Fewer plots were dominated by shrubs in GMEP than CS 2007, a difference caused by reduced representation of Ericoideae (mostly comprising heather *Calluna vulgaris*). This reduction in heather may have contributed to the decline in topsoil C between surveys. However, it is unclear whether the reduction reflects a national decline in heather, or random fluctuation in the vegetation captured by the two survey samples. Future work on the relationship between shrub cover and topsoil C declines should:

1) **Determine the relative contribution of shrub cover and composition to the trend in topsoil C in upland habitats**. The trend in shrub cover and the relationship between shrubs and topsoil C are clear, but we haven't fully quantified how shrub trends affect the steepness of the topsoil C trend.
2) **Combine the field data on vegetation cover with satellite imagery from the same time periods**. For most of the 1km squares investigated here, we only have data from either CS 2007 or GMEP 2013-2016. However, satellite imagery is available for all squares across all time periods. By mapping heather across Wales between 2007 and 2016, we could determine the extent to which vegetative changes in field data are driven by sampling effects.

This chapter has discussed the limitations of the CS-GMEP trends (section 1.1.1). Nonetheless, the gold standard of soils trends within GMEP squares is on the immediate horizon; the aim of GMEP was to assess impacts of Glastir, and establish a robust baseline for future environmental monitoring[4]. Repeat visits to GMEP squares are planned under the Environment and Rural Affairs Modelling and Monitoring Programme (ERAMMP). Importantly, GMEP-ERAMMP trends will not carry the same limitations as CS-GMEP trends. Future soils surveys in GMEP squares will play a critical and cost-effective role in illuminating the drivers topsoil C trends in the Welsh countryside.

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7 Appendices

Appendix 1

Table of all models fitted in section 2. Shown are number of parameters, the AICc (corrected Akaike's Information Criterion) values and log likelihood of each model. We also indicate which parameters were included in those models. For continuous predictors the actual parameter is shown; for categorical predictors a "+" indicates inclusion of that variable. Elevation was rescaled by dividing by 100 prior to analysis and then centred on the mean. Models were fitted with beta error structures. Models were fitted with Gaussian error structures.

	Parameters	AICc	Log likelihood	Survey period	Land use category	Survey period: Land use category	Elevation	Elevation: Survey period	Elevation: Land use category	Elevation: Survey period: Land use category
Model 1	8	13305.52	-6663.7	+	+	+				
Model 2	10	13164.98	-6595.4	+	+	+	42.98	+		
Model 3	14	13129.72	-6585.6	+	+	+	49.07	+	+	+

Appendix 2

Table of all models fitted in section 3 which had AICc (corrected Akaike's Information Criterion) values within 6 units of the best model. Models are greyed out if there exists a simpler, nested model with a lower AIC – such models should be disregarded according to previous studies[21]. For continuous predictors the actual parameter is shown; for categorical predictors a "+" indicates inclusion of that variable. ELEV = elevation; MAP_PET = precipitation minus potential evapotranspiration (climatic moisture); PEAT = underlying deep peat; SO = sulphur (acid) deposition; Sphagnum = Sphagnum cover; Shrubs = shrub cover; YR = survey period; ":" denotes an interaction term; npar = number of parameters; logLik = log likelihood; AICc = second order Akaike Information Criterion for small sample sizes; delta = difference in AIC compared to the top model; weight = Akaike weights for each model based on AICc. ELEV and MAP_PET were rescaled by dividing by 100 prior to analysis. Furthermore, ELEV, SO and MAP_PET were centred on the mean. Models were fitted with beta error structures.

(Intercept)	ELEV	MAP_PET	PEAT	Pteridium aquilinum	SO	Sphagnum	Shrubs	YR	MAP_PET: PEAT	MAP_PET: YR	PEAT: YR	Shrubs: YR	npar	logLik	AICc	delta	weight
-1.10	0.22	0.11	0.90	NA	-2.06	0.03	0.01	+	-0.10	+	+	+	14.00	87.74	-145.71	0.00	0.13
-1.06	0.22	0.07	0.99	NA	-1.69	0.03	0.01	+	-0.10	NA	+	+	13.00	86.26	-144.99	0.71	0.09
-1.26	0.21	0.05	0.98	NA	NA	0.03	0.01	+	-0.10	NA	+	+	12.00	85.06	-144.82	0.89	0.08
-1.07	0.21	0.10	0.89	0.00	-1.92	0.03	0.01	+	-0.10	+	+	+	15.00	88.31	-144.59	1.12	0.07
-1.33	0.21	0.08	0.91	NA	NA	0.03	0.01	+	-0.10	+	+	+	13.00	85.96	-144.40	1.30	0.07
-1.28	0.20	0.08	0.91	0.00	NA	0.03	0.01	+	-0.10	+	+	+	14.00	86.75	-143.73	1.98	0.05
-1.21	0.20	0.05	0.99	0.00	NA	0.03	0.01	+	-0.10	NA	+	+	13.00	85.61	-143.70	2.00	0.05
-1.03	0.21	0.07	0.99	0.00	-1.56	0.03	0.01	+	-0.10	NA	+	+	14.00	86.63	-143.50	2.21	0.04
-0.96	0.25	0.11	0.86	NA	-2.41	0.03	NA	+	-0.10	+	+	NA	12.00	84.01	-142.73	2.98	0.03
-1.10	0.22	0.07	1.65	NA	-1.74	0.03	0.01	+	-0.13	NA	NA	+	12.00	83.93	-142.57	3.14	0.03
-1.01	0.22	0.11	0.87	NA	-2.21	0.03	0.00	+	-0.10	+	+	NA	13.00	84.97	-142.41	3.30	0.02
-1.14	0.22	0.10	1.62	NA	-2.04	0.03	0.01	+	-0.13	+	NA	+	13.00	84.91	-142.31	3.40	0.02
-1.31	0.20	0.05	1.66	NA	NA	0.03	0.01	+	-0.13	NA	NA	+	11.00	82.63	-142.16	3.54	0.02
-0.93	0.23	0.11	0.87	0.00	-2.25	0.03	NA	+	-0.10	+	+	NA	13.00	84.66	-141.81	3.90	0.02
-1.11	0.20	0.10	1.60	0.00	-1.90	0.03	0.01	+	-0.13	+	NA	+	14.00	85.55	-141.34	4.36	0.01
-1.26	0.19	0.05	1.64	0.00	NA	0.03	0.01	+	-0.13	NA	NA	+	12.00	83.29	-141.28	4.43	0.01
-1.07	0.20	0.07	1.63	0.00	-1.60	0.03	0.01	+	-0.13	NA	NA	+	13.00	84.39	-141.25	4.46	0.01
-0.97	0.21	0.11	0.88	0.00	-2.07	0.03	0.00	+	-0.10	+	+	NA	14.00	85.49	-141.21	4.49	0.01
-1.37	0.20	0.07	1.64	NA	NA	0.03	0.01	+	-0.13	+	NA	+	12.00	83.15	-141.00	4.71	0.01
-0.90	0.24	0.07	0.98	NA	-1.98	0.03	NA	+	-0.10	NA	+	NA	11.00	81.88	-140.67	5.04	0.01
-1.25	0.21	0.08	0.89	NA	NA	0.03	0.00	+	-0.10	+	+	NA	12.00	82.92	-140.54	5.16	0.01
-0.95	0.22	0.07	0.99	NA	-1.78	0.03	0.00	+	-0.10	NA	+	NA	12.00	82.92	-140.53	5.17	0.01
-1.31	0.19	0.07	1.62	0.00	NA	0.03	0.01	+	-0.13	+	NA	+	13.00	84.01	-140.49	5.22	0.01
-1.16	0.21	0.05	0.98	NA	NA	0.03	0.00	+	-0.10	NA	+	NA	11.00	81.59	-140.08	5.63	0.01
-1.22	0.24	0.08	0.87	NA	NA	0.03	NA	+	-0.10	+	+	NA	11.00	81.56	-140.02	5.68	0.01
-1.19	0.19	0.08	0.89	0.00	NA	0.03	0.00	+	-0.10	+	+	NA	13.00	83.66	-139.79	5.92	0.01

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