Answers to reviewer comments BGD:

Anonymous Referee #1

This manuscript describes a comparative experiment on soil organic carbon stocks. They compare automatic and soil sampling results in order to know if they are equivalent to define the small spatial and temporal variation. The concept and results are novel. This study is interesting and must have involved a great deal of work. While the results merit publication, with respect, I think the paper requires major revision. This study pointed the need to more information about the different type/technic of soil C storage in order to standardize the results and pointed the advantage and inconvenient of them. Nevertheless, added a table will be a good idea to underline these differences and the need to more advances, and the necessity of this study.

Please see answer to comment 1.

The methods and statistical analyses seem not totally appropriate.

Please see answers to comments regarding the method section below. No comment regarding our statistical analysis was raised, wherefore we do not exactly know to which statistical analyses this comment refers.

With respect, your discussion need more attention in order to forward your innovative results. Currently, your paper tend to look like a technical report but without enough "technical information", and I think that it is more than that.

Please see answers to comments and made changes in the MS regarding the Result and Discussion section below.

General comments:

1. Firstly, more information are needed in order to see the real advantage of your methodology. Presently, we are quite lost and the benefit of AC-based C budgets is not enough forward.

We rewrote parts of the Abstract to more directly address the advantages of using the AC-based approach (mainly the small-scale spatio-temporal resolution of gained ΔSOC values).

"Tendencies and magnitude of ΔSOC values derived by AC-measurements and repeated soil inventories corresponded well. The period of maximum plant growth was identified as being most important for the development of spatial differences in annual ΔSOC. Hence, we were able to confirm that AC-based C budgets are able to reveal small-scale spatial differences and short-term temporal dynamics of ΔSOC. "

In addition we now describe the benefits of the AC-based approach within the Introduction in more detail by directly comparing it to:

1. soil sampling based approaches
2. other measurement systems used for estimating the gaseous C exchange

"Compared to mentioned approaches for detecting ΔSOC by either repeated soil sampling or observations of the gaseous C exchange, automatic chamber (AC) systems combine several advantages. On the one hand flux measurements of the same spatial entity avoid the mixing of spatial and temporal variability, as done in case of point measurements by repeated soil inventories. On the other hand, AC measurements combine advantages of EC and manual chamber systems because they not only increase

the temporal resolution compared to manual chambers but also allow for the detection of small-scale spatial differences and treatment comparisons regarding the gaseous C exchange (Koskinen et al., 2014).”

2. Need more details on the soil information and their effects on the soil C storage process: different soil layers taking into account; what about the roots, which are the main C input in the soil.

We agree that process studies are needed, however, they are not within the scope of the presented MS, which compares two methods to show the accuracy and precision of AC derived ΔSOC values for on an exemplary field site. Hence, we discuss soil related processes and soil C storage processes with respect to the plausibility of observed ΔSOC using both methods (see section 4.2).

None of both methods are usually able to differentiate observed ΔSOC between soil layers. As stated, most repeated soil inventories are based on topsoil soil sampling, which disables a distinct investigation and interpretation of different soil layers (except if samples are taken for the different layers). Opposing to that, the presented AC-based approach, integrates ΔSOC over the entire soil column (thus including processes in all soil layers), which however in return hampers a soil layer specific investigation.

In case we misunderstood this comment, and it refers to more details about soil sampling given in section 2.3; we want to refer to changes made in section 2.3.

“After soil manipulation, a 5-m raster sampling of topsoils (Ap horizons) was performed during April 2011. Each Ap horizon was separated into an upper (0-15 cm) and lower segment (15-25 cm), which were analyzed separately for bulk density, SOC, Nt and

coarse fraction (< 2 mm) (data not shown). From these data, SOC and Nt mass densities were calculated separately for each segment and finally summed up for the entire Ap-horizon (0-25 cm). The mean SOC and Nt content for the Ap horizon of each raster point was calculated by dividing SOC or Nt mass densities (0-25 cm) through the fine-earth mass (0-25 cm). In December 2014, composite soil samples of the Ap horizon were collected. The composite samples consist of samples from four sampling points in a close proximity around each chamber."

Concerning the root issue, we refer to a statement in the MS *"Usually, coarse organic material is discarded prior to analysis (Schlichting et al., 1995) and therefore, total SOC is not assessed (e.g., roots, harvest residues, etc.)."*. This is in line with standardized routines of sample preparation in soil sciences. To better address this issue, we added this information to section 2.3 as well.

"Prior to laboratory analysis coarse organic material was discarded from collected soil samples (Schlichting et al. 1995)."

3. Why do you clearly underestimate the deep soil in your C budget?

It is not stated in the MS, that we underestimate deep soil layers in our C budget. As mentioned above, AC-measurement derived C budgets account for the entire soil column underneath the chamber, since the observed net flux is a result of the soil and crops components underneath the chamber. This is not the case when detecting ΔSOC by repeated soil inventories which only sample the upper soil horizon. However, since we show that both methods are able to detect almost the same ΔSOC over the study period, C allocation to deeper soil layers is most likely not relevant in this study over the turn of the presented study period (please see answer to comment 24).

"In contrast to the soil resampling method, we postulate a higher accuracy and a lower precision in the case of the AC-based C budget method. The reasons for this include a number of potential errors affecting especially the measurement precision of the AC system, whereas over a constant area and maximum soil depth, integrated AC measurements increase measurement accuracy."

4. Did you have more information about the seasonal variation of the soil chemistry, soil density in link or not with the different plant species?

As a comparison of two different methods to detect ΔSOC, the seasonal course of soil chemistry and density was not within the focus of this MS. Repeated soil inventories are usually based on soil samples taken at a frequency of one to five years (e.g. Van Wesemael et al., 2011), and studies investigating the seasonal course are scares (as stated in L 79-84 within the Introduction). However, seasonal variations of different soil chemistry parameters were measured throughout the entire study period at two profiles of the depression (details are given in Rieckh et al. 2013).

5. In the abstract, line 43 page 2, you talk about soil properties but nothing after.

We agree and changed the sentences.

“The measurement site is characterized by a variable groundwater level (GWL) and pronounced small-scale spatial heterogeneity regarding SOC and nitrogen (Nt) stocks.

6. The temporal variation were nicely represented with 4 years of measurement, but concerning the spatial variation, I think that there are some overestimation because of you are only one chamber by topographic step, so no replication by topographic step; and on the other hand, this topographic gradient seems to be too little, with only “difference in altitude 1m within in a distance of approx. 5 m of each other. Page 7 line 140. So for me there are not enough difference to “called” spatial variation.

We agree on this and fact that the topographic gradient is rather small. Therefore we changed *“spatial variation”* into *“spatial differences”* throughout the entire MS. As mentioned in the title and abstract, and specified in the introduction, we aimed at showing that AC-measurements are in principle suitable to detect small-scale or in-field spatial differences (10-30 m), since their ΔSOC values fit well to those derived by repeated soil inventories. This is a prerequisite to detect spatial heterogeneity, which is not only common for the study area but also wider areas of the northern hemisphere. Whether or not these differences are too small depends however on the precision of the approach used to detect these differences.

We added results of Wilcoxon rank sum tests (regarding spatial (chamber-related) differences between measured R_{eco} and NEE fluxes (GPP was not measured directly but derived by empirical modelling, hence no test was performed) for each year to Tab. 1. The results show significant differences between CO_2 fluxes (R_{eco} and NEE) measured during the same time by the four chambers during most years and indicate the presence of significant differences between the four chambers and thus spatial differences within a transect length of <30 m regarding obtained gaseous CO2 exchange.

7. It’s not clear your hypothesis about the potential difference between the four topographic steps. Could you add some information about that, and confirm it in the discussion?

We added a schematic representation of the topographic gradient to Fig. 2. Along the topographic gradient we hypothesized an increase in wetness downslope due to a groundwater level closer to the surface as well as a related trend of decreasing redox potentials. However, as these gradients are strongly related to the annual weather conditions, esp. rainfall dynamics, we avoid an a-priori hypothesis on their (net) effects to carbon balance or NEE.

8. Estimation about the ecosystem compartment effect? For Reco, which part of soil and aboveground compartment?

We do not fully understand this comment. R_{eco} refers to the (total) ecosystem respiration as the sum of autotrophic and heterotrophic respiration. Thus it includes root, shoot and soil respiration.

Top better state this, we added a short description of R_{eco} to the MS.

“The atmospheric sign convention was used for the components of gaseous C exchange (ecosystem respiration (R_{eco}; sum of autotrophic and heterotrophic respiration), gross primary production (GPP) and NEE), whereas positive values for ΔSOC indicate a gain and negative values a loss in SOC.”

Specific comments:

9. Maybe the abstract need to more concise.

   We agree and shortened (~ 9%) and specified the Abstract to make it more concise (please see answer to comment 1).

10. P 4, L 67, what kind of land-use?

    We stated in L 67 of the MS, that “Erosion and land use change” (such as ploughing of grassland or peatland drainage for agricultural purposes) are reinforcing “natural spatial and temporal variability”. Hence, we are actually referring to the change in land use itself, irrespective of certain kinds of land use. However, some kinds of land use such as agriculture are known to reinforce erosion and thus also reinforce small scale spatial heterogeneity through tillage and bare soil periods.

11. P4 L 71: I am not sure to understand the third point. For me it is also time dependent.

    We totally agree that the magnitude of ΔSOC compared to total SOC stocks is dependent on the respective time horizons of the observations. However, the *“rather small magnitude of ΔSOC compared to total SOC stocks”* complicate the detection of ΔSOC in a short or medium term time horizon, which is usually a requirement during scientific studies, which aim to compare e.g. fertilization treatments or different crop rotations and their impact on ΔSOC. We therefore state, that a method is advantageous, when it is able to detect ΔSOC in a short- to medium term (3-5 years).

12. P6, L 110: with the same land use?

No, Leifeld et al. (2011) showed temporal dynamics of a degraded intensively and extensively used grassland on drained peat. We accordingly specified the sentence to better express this.

"Even though temporal dynamics in ΔSOC were shown e.g. for grazed pastures and intensively used grasslands (Skinner and Dell 2015; Leifeld et al., 2011), no attempt was made to additionally detect small-scale differences in ΔSOC."

13. P6, L 110, could you add also the study of Skinner & Dell 2015.

We already referred to Skinner and Dell 2015 in L 93. In addition we now added Skinner & Dell 2015 to L 110 of the MS.

14. P6, L 127: soil or air temperature?

We specified and clarified this sentence by adding *"air"*.

15. P8, L 157: So 5 different crops during your study?

Yes, as stated in the MS a crop rotation of maize – winter fodder rye – sorghum sudan grass hybrid – winter triticale – alfalfa was measured, resulting in a total of 5 different crops. To make this more clear, we changed the sentence.

"The measurement site was cultivated with five different crops during the study period, following a practice-orientated and erosion-expedited farming procedure. The crop rotation was silage maize (Zea mays) - winter fodder rye (Secale cereale) - sorghum-

Sudan grass hybrid (Sorghum bicolor x sudanese) - winter triticale (Triticosecale) - alfalfa (Medicago sativa).”

16. P8, L 174: it’s a closed system?

We agree that this sentence might be misleading. This sentence refers to the “closed chamber measurement system” as described in detail by e.g. Livingston and Hutchinson (1995) but not the measured ecosystem. As mentioned by Livingston and Hutchinson (1995) *“The terms “dynamic” or “open” are sometimes used synonymously to describe steady-state systems and “static” or “closed” are often applied to non-steady-state systems”*. Since we define the measurements as flow-through non-steady-state measurements right before, we understand the confusion resulting from the use of “closed” in this sentence. We therefore deleted the word “closed”.

17. P9, L 189: could you use the same unit for volume liter or m3

Yes, we changed the unit of the flow rate of the pump (1 l min^{-1}) into 0.001 m^{-3} min^{-1} accordingly.

18. P10, L206: I surprised because the C sink is a negative value and a C source a positive value, basically.

We corrected signs given in Tab. 1 and Fig. 5. As stated in the MS, the atmospheric sign convention was used for the components of gaseous C exchange (ecosystem respiration (R_{eco}), gross primary production (GPP) and NEE), whereas the soil perspective was used for ΔSOC, thus indicating a gain with positive values and a loss in SOC with negative values (as used in soil sciences).

19. P10, L 212: Could you add the equation of your fluxes? and more information about your choice: time length for the measurements, number of measurement by day

We agree and added the Eq. 1 to the MS as suggested. Length of measurements and number of measurements per chamber per day are addressed in section 2.2.1 of the MS:

“The chambers closed in parallel at an hourly frequency, providing one flux measurement per chamber and hour. The measurement duration was 5-20 minutes, depending on season and time of day. Nighttime measurements usually lasted 10 min during the growing season and 20 min during the non-growing season (due to lower concentration increments). The length of the daytime measurements was up to 10 min, depending on low PAR fluctuations (< 20 %).”

Nighttime and non-growing season measurements were in general longer, due to a lower concentration change (more details are given in Hoffmann et al. 2015).

20. P11, L 241: unit: µmol-1 m-2 s-1 => µmol CO2 m-2 s-1, right?

We agree and changed the unit accordingly.

“R_{eco} *is the measured ecosystem respiration rate [µmol C* m^{-2} s^{-1}*]* “

21. L 243 : temperature of “air” ?

Not exactly, according to Hoffmann et al. 2015, Arrhenius-type temperature-dependency models are derived by using different temperature sets measured during flux measurements. Similar to Hoffmann et al. (2015), we used soil temperatures in 2 cm, 5 cm and 10 cm soil depth as well as the air temperature. Thus T_{ref} can be referring to soil or air temperature, depending on the chosen best fit temperature dependency model. To better address this important issue, we rewrote this paragraph adding more detailed information.

"To account for measurement gaps and to obtain cumulative NEE values, empirical models were derived based on nighttime R_{eco} and daytime NEE measurements following Hoffmann et al. (2015). For R_{eco}, temperature-dependent Arrhenius-type models were used and fitted for recorded air as well as soil temperatures in different depths (Lloyd and Taylor 1994; Eq. 2).

$$R_{eco} = R_{ref} * e^{E_0\left(\frac{1}{T_{ref}-T_0}-\frac{1}{T-T_0}\right)}$$

[Eq. 2]

where R_{eco} is the measured ecosystem respiration rate [µmol m^{-2} s^{-1}], R_{ref} is the respiration rate at the reference temperature (283.15 K; T_{ref}); E_0 is an activation energy like parameter; T_0 is the starting temperature constant (227.13 K) and T is the mean air or soil temperature during the flux measurement. Out of the four R_{eco} models (one model for air temperature, soil temperature in 2 cm, 5 cm and 10 cm depth) obtained for nighttime R_{eco} measurements of a certain period, the model with the lowest Akaike Information Criterion (AIC) was used."

22. P12, L 263: could you explain the range 2-21 consecutive days?

As mentioned in the MS *“Due to plant growth and season, parameters of derived R_{eco} and GPP models may vary with time.”*, wherefore model parameters obtained based on a seasonal data set are not necessarily suitable (smoothed model) to gap-fill measured CO_2 dynamics. However, the actual length of a period, showing similar temperature and PAR dependencies and thus model parameter sets might vary with time as well (depending on dominant weather conditions, crop growth and phenology). During the non-growing season longer periods may not show a change, whereas during the short period of crop growth and senescence a change in temperature or PAR dependency of the flux components may occur within a couple of days. We therefore decided to use a variable moving window (2-21 days; user defined), which searches for the appropriate length of a data set taken into account to obtain parameters for R_{eco} and GPP used for subsequent gap-filling. The minimum length of the variable moving window was set to two, since short term measurement gaps as well as short nights during summer might reduce the used data set to <5 measurements (e.g. due to a 5 hours night from 22 o´clock to 4 o´clock). The maximum length of 21 days was primarily set to avoid extensive calculation time. In reality, most data subsets used for parametrization were longer than 2 days but shorter than 21 days, and in principle longer during the non-growing season and shorter during the growing season.

23. P14, L 298: Could you give us a mean of your CH4 measurements? and what about the N2O ? If you want to discuss about the C budget, you need to add information about the two others greenhouse gases.

We added the average annual CH_4-emission (-0.01 g m^{-2} y^{-1}; small uptake during drier years and small CH_4 release during the rather wet summer 2011) to the MS. We disagree on the statement that N_2O measurements (0.34 g m^{-2} y^{-1}) are needed for estimates of the C budget. Since we do not discuss the GHG budgets, we decided to not include N_2O emission measurements within the MS.

24. P15, L 324: only topsoil? what about the subsoil ? We know that the subsoil have a high contribution to the soil C stock.

Indeed, subsoils at depositional sites are important segments for total SOC stocks, e.g., down to 1m depth. The colluvial subsoils at the CarboZALF-D study site store 60% of total SOC stock whereas the plough layer (Ap) contains 40%. This is mainly due to the larger thickness of the colluvial horizons. However, as the manipulation affected only the plough layer, we expected/assumed detectable and significant SOC changes during our 4 years of observation only for the plough layer. Here, strong transient states were induced by the manipulation, because the soil material from eroded upslope soils is under saturated in respect to its C-sequestration potential. Furthermore topsoils, like plough layers, represent the soil compartment of highest SOC turnover (C-input; O_2 supply). Of course, we will include subsoils (down to 1.5 m) in a resampling campaign 10 years after manipulation (2020). This is the expected time scale on which we might detect (probably small) SOC changes in subsoils by using the soil resampling approach. In addition, the good fit of changes in SOC between the two methodological approaches support this assumption, since it shows that changes in subsoil SOC are minor (hardly detectable) during the four years of our study.

25. P15, L 335: unit: I think that it will be better: gC m-2 y-1 , right ?

We agree and changed the Latin abbreviation for year (“a” for “annus”) by using “y” throughout the entire MS.

26. P19, L 431: add reference about the gap filling? your own method or adapted to already published methodology ?

Yes, this refers to an algorithm presented in Agricultural and Forest Meteorology. We added Hoffmann et al. (2015) as reference to this sentence. The method used for gap filling, is also explained within the method section of the MS (please see 2.2.2).

27. P21, L 465: what about the daily pattern of NEE, R_{eco} and GPP, and so soil C storage?

We added a short description of monitored daily patterns to section 3.1.1. C storage (ΔSOC), was only calculated on a daily frequency (due to daily frequency for NPP_{shoot} estimates). Hence no daily patterns for ΔSOC can be given using the presented AC-based approach.

“NEE and its components R_{eco} and GPP were characterized by a clear seasonality and diurnal patterns. Seasonality followed plant growth and management events (e.g., harvest; Fig. 3), Highest CO_2 uptake was thus observed during the growing season, whereas NEE fluxes during the non-growing season were significantly lower. Diurnal patterns were more pronounced during the growing season and less obvious during the non-growing season. In general R_{eco} fluxes were higher during daytime, whereas GPP and NEE, in case of present cover crops, were lower or even negative, representing a C uptake during daytime by the plant-soil system.”

28. P21, L 477: Could you add more references? they are lots of studies on the soil C sequestration in pastures in different biomes, inverse to crop land.

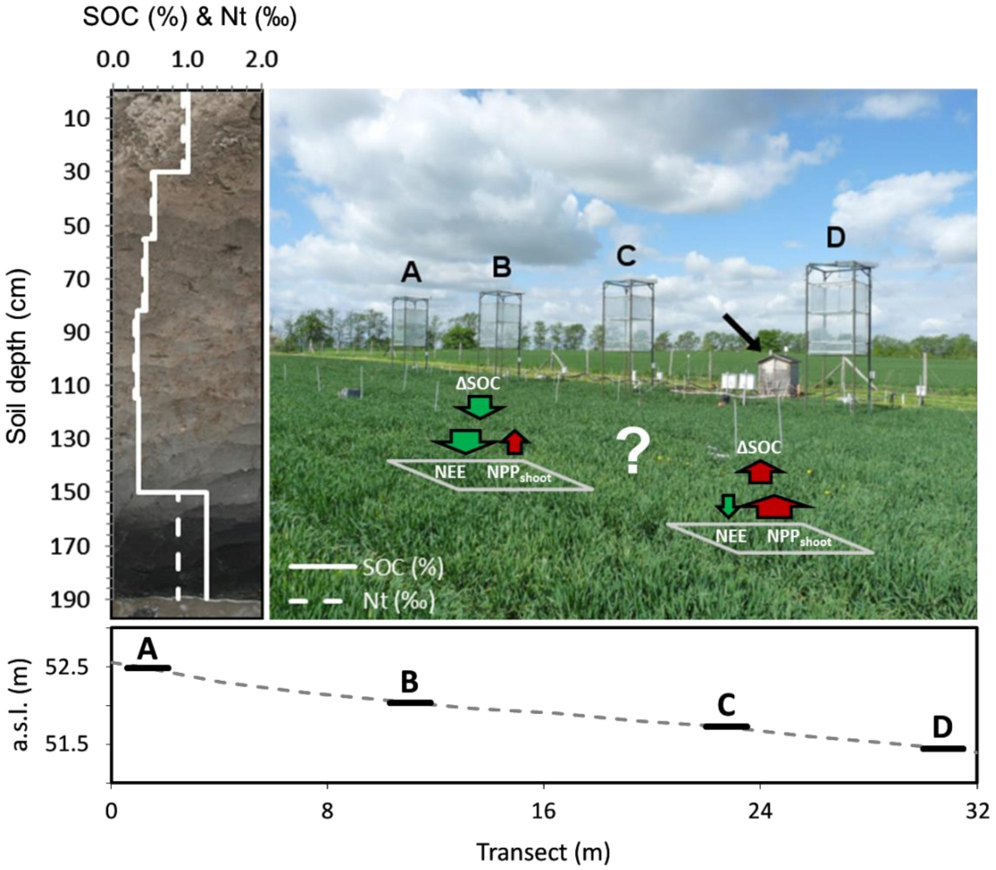
    Since this sentence compares obtained results for alfalfa on an agricultural used landscape with balances given in literature we rather want to refer to references for perennial crops/grasses instead of permanent grassland like pastures, which are most-likely not comparable to cropping systems due to different C dynamics.

29. Figures 1: The temporal measurement was nicely represented. But, did you add a schematic representation of the spatial aspect?

    The spatial aspect (that different Pedon's might show a different development in ΔSOC) is referred to in Fig. 2. We decided to not add it to Fig. 1 (in terms of multiple lines with a different development), in order to keep the concept of temporal changes in SOC easily understandable for the reader.

30. Figures 2: I prefer to see SOC in stock (g C m-2) rather than %. Could you add a scale in your picture? and also a cross-section of your site in order to see the different altitude and distance among chamber.

We added the scale (length of transect) and cross section of our site to Fig 2. We decided to give SOC in “%” rather than “g C m^{-2}”, because we wanted to give N_t in the same figure (“‰”). If needed we will change “%” to “g C m-2” for SOC. However, in this case we will have to delete N_t.



31. Figure 5: Could you add in the caption the signification of the 4 symbols, and add in the graph a dotted horizontal line for zero.

We added the significance of (spatial) differences between the chamber positions during different years of the study period (Reco, NEE, NPP) to Tab. 1. Zero is marked by a solid horizontal gray line within the figure. We changed the Figure regarding mentioned confusion with positive/negative values representing gains/losses, following reviewer comments. Used symbols are explained by the figure legend.

32. Figures 6: problem with unit: gC m-2 y-1 , right ?

We agree and changed the Latin abbreviation for year ("a" for "annus") for "y" throughout the entire MS. In addition, accidentally mixed up error bars were corrected.

Could you add a test (a t-test ?) in order to know if they are difference between the two estimations of C budget in each chamber?

We added the results of the test between the results obtained by the two methods for the entire period used to detect ΔSOC (2011-2014) to the figure caption. Since the *t* test requires normal distribution, we used the Wilcoxon rank-sum test instead.

Currently, we need more information about the added value of your C budget.

We are not sure whether this refers to the initial manipulation in 2010 or not. If it refers to the added C due to soil manipulation it does not matter for this figure, since this figure only refer to the period after manipulation (as shown in Fig. 5 and mentioned in section 3.3). Since this seems to be misleading, we added the period taken into account to the figure caption. Moreover, we now mention it more precisely in section 2.1.

"The change in SOC for each chamber was monitored by three topsoil inventories, carried out (I) prior to soil manipulation during April 2009, (II) after soil manipulation during April 2011, and (III) during December 2014. ΔSOC derived through soil

resampling and AC-based C budgets, was compared for the period between April 2011 and December 2014 (Fig. 1).”

Same as for figure 3, 4, 5. It will be nice to know if the chambers are significantly different.

We agree and added results of Wilcoxon rank sum tests (regarding spatial (chamber-related) differences between measured R_{eco} and NEE fluxes (GPP was not measured directly but derived by empirical modelling, hence no test was performed) and estimates of NPP_{shoot} (based on LAI or biomass sampling campaigns)) for each year to Tab. 1. The results show significant differences between CO_2 fluxes (R_{eco} and NEE) measured during the same time by the four chambers during most years but only minor differences regarding NPP_{shoot} (due to rather low sample size for NPP_{shoot} as well as spatially biased samples (biomass samples (except for final harvests) were collected around but not in each chamber)).

We decided to not present a test for the entire study period, using annual values. The reason therefore is that we would only expect similar differences in annual CO_2 exchange, NPP_{shoot} and ΔSOC, and thus significant differences between the chamber positions, in case of comparable weather conditions and same cover crops during all year of the study. This however was not the case. Hence multiple variables, such as GWL, cover crop and position (soil) might influence CO_2 exchange, NPPshoot and ΔSOC, resulting in higher as well as lower values for one chamber position during different years of the study period. This high variation per chamber, is leading to non-significant differences between the chamber positions during the study period, when using annual values, but does not necessarily mean that they are equal or comparable.

Anonymous Referee #2

The manuscript "Detecting small-scale spatial heterogeneity and temporal dynamics of soil organic carbon (SOC) stocks: a comparison between automatic chamber-derived C budgets and repeated soil inventories" analyses 4 yrs of soil organic C changes by uses of flux chamber technique and repeated soil inventory measurements over a crop field. Data set confirms that AC-based C budgets are suitable to reveal small-scale spatial and short- term temporal dynamics of ΔSOC. The paper is well written and interesting and definitely worth to be published in order to i) show a method comparison and ii) provide evidence on the accuracy of flux vs soil inventory measurement to determine SOC changes over time. I had a number of small remarks I thus recommend (minor) revisions.

General comments:

1. I think authors should not mix terms up being established by the scientific community. Accordingly I recommend to use ΔSOC for the repeated soil sampling and NBP (net biome productivity) NCS (Net C storage) for annual C budgets of chambers (for references see Schulze et al 2007 and Soussana et al 2007, 2010).

   A number of different terms have been used by the scientific community to refer to changes in the soil organic carbon stock (ΔSOC). Smith et al. 2010 used the term NECB (net ecosystem carbon budget), which equals NBP (Net biome productivity) when integrated over time. Leifeld et al. 2011 used the term ΔSOC, whereas NCS is e.g. used by Soussana et al. 2010. All of these refer more or less to the same target value (changes in soil organic carbon stock), but vary regarding the way of how to achieve this value (e.g. direct vs. indirect). To reduce confusion within the MS which compares changes in soil organic carbon stocks, we decided to use ΔSOC for both methods (soil resampling as well as chambers), instead of referring to two different terms for the same target value. To better address this, we included the following sentence within the Introduction.

"By contrast, the net ecosystem carbon budget (NECB; Smith et al. 2010) and thereon based temporal dynamics of ΔSOC can be easily derived through the eddy covariance (EC) technique as a common approach to obtain gaseous C exchange (Alberti et al., 2010; Leifeld et al., 2011; Skinner and Dell, 2015)."

However, if required we will change ΔSOC derived by the C-budget method into NECB.

2. Before experiment field site received soil, this increased SOC stock and %soilC. To my opinion authors cannot start ΔSOC estimations from that date on as this has nothing to do with the accumulation of C by the ecosystem functioning. I recommend to skip this section in MM and results and estimate ΔSOC as the difference between 2011 and 2014. M&M section.

We regret the misunderstanding and agree that estimating ΔSOC should not start prior to the soil manipulation experiment. As shown in Fig. 1, 3 and 5, estimation of ΔSOC only refers to the period after soil manipulation (2011-2014) for both, chamber derived C budgets and soil resampling based ΔSOC estimates. We decided to keep the year 2010 inside the data set in order to show the important information about the soil manipulation event. However, to better address this really important issue and to avoid misunderstandings, we added the following to paragraph 2.1 of the MS.

"ΔSOC derived through soil resampling and AC-based C budgets, was compared for the period between April 2011 and December 2014 (Fig. 1)."

3. Beside I got it wrong (L137ff), I found it a bit scary that chambers had no replicate measurements and that authors privileged the topographic gradient. I think this is the most critical point of the study. Accordingly I was wondering how mean ±SE was estimated for the AC measurements?

We agree that when aiming to detect small-scale spatial heterogeneity, spatial replication is a prerequisite. However, the focus of our study rather was to show, that AC measurements are able to achieve the same resolution in detecting spatial differences as the soil resampling method whilst also handing us information about the critical temporal dynamics that lead to spatial differentiation.

The measurement errors of the AC measurements do not include spatial uncertainty but are rather a result of given measurement precisions of flux measurements and performed gap filling. Moreover, soil properties, plant growth and microbial activity might change within a meter, which is exactly the spatial scale we wanted to address. To better express this we changed parts of the introduction, referring to the small-scale spatial heterogeneity and the advantages of the presented chamber based approach (please see answer to comment 1). Moreover, *"small-scale spatial variation"* is now referred to as *"small-scale spatial differences"* throughout the entire MS.

4. I was wondering why authors estimated NPPshoot per day and not by uses of degree day which would have been more adapted to physiological biomass evolution and easier to compare between years . This is misleading and has nothing to do with the experiment except some CO2 exchange from soil which is difficult separate from CO2 flux.

We estimated NPP_{shoot} per day based on a growth function, which usually predict crop growth as a function of crop age (Zeide 1993). Daily NPP_{shoot} is an essential part of Eq. 4 and needed to derive ΔSOC for AC-measurements. Daily NPP_{shoo} was used to calculate daily ΔSOC values ($NEE+NPP_{shoot}=\Delta SOC$), which were day wise summed and used in Fig. 5 to display the ΔSOC dynamics throughout the study period. Thus, we estimated NPP_{shoot} per day to keep the relation with measured NEE per day. In addition to that, (growing) degree days (GDD) as a measure of cooling or heating are a one-dimensional/mono-causal variable used to predict plant development rates. This is neglecting differences in soil moisture or the influence of heat stress and PAR on plant/biomass development. The one-dimensionality as well as different baseline temperatures for different crops (e.g. 10°C for maize and 5.5°C for wheat) might also hamper a clear comparison between different years.

5. I suggest to set soil inventory ΔSOC as the difference between April 2011 and 2014.

We agree. However, soil inventory ΔSOC actually already refers to the difference between 2011 and 2014 within the MS (please see Fig. 1, 3 and 5). To better address this important issue and to avoid misunderstandings, we added the following sentence to the MS.

"ΔSOC derived through soil resampling and AC-based C budgets, was compared for the period between April 2011 and December 2014 (Fig. 1)."

6. The soil sampling part is a bit unclear, -as the depth of horizons are not clear and do vary with ecosytstems – recommend to use cm depths -the mixed soil? here I suggest to skip the 2010 sampling. - missing information on the estimation of soil C stocks. Eg did bulk density vary with depth, location?. Was bulk density normalized (for layers, year) before estimation?

We rewrote and specified the soil sampling paragraph (for more details, please see answers to specific comments 17, 18 and 19). We decided to keep the year 2010 inside the data set and MS in order to show the important information about soil manipulation. However, if required, we will remove it.

7. Discussion, I awaited more discussion on the effect of ecosystem on NCS. So to say the crop rotation and why is doing better than the other. Having some data analyses on the effects climate, crop species and duration of bare soil. Soil N content was mention in results but not in discussion.

We agree that the accuracy and precision of presented AC-derived ΔSOC values in general allow for comparisons between different crop rotations, soil types, fertilization treatments and weather conditions. However, since the exemplary field study in our MS (presented to show the accuracy and precision of AC-derived ΔSOC compared to soil resampling based ΔSOC) contains only one crop rotation with different crops during different years, analyses regarding the impact of weather conditions and crop species are difficult. We neither have measurements of the same crop species during different years, nor different crop rotations measured during the same years, since this aspect was not within the scope of our study. However, showing the accuracy and precision of our approach to detect ΔSOC, studies focusing on this could be done in future.

Specific comments

8. L138.... were set up at the depression (Sommer et al., 2016) (see 2.2.1).

We agree and added "(see 2.2.1)" to the sentence.

"During June 2010, four automatic chambers and a WXT520 climate station (Vaisala, Vantaa, Finland) were set up at the depression (Sommer et al. 2016) (see 2.2.1)."

9. L141-143 this is misleading I suggest to remove this section from M&M and results...the soil inventory ΔSOC is thus april 2011 to 2014!!

We agree. This is misleading indeed. Actually we already only compared the period April 2011 to December 2014 (as shown in Fig. 1, 3 and 5). To better address this important issue, we added the period also to the figure caption of Fig. 6. Moreover the following sentence was added to 2.1:

"ΔSOC derived through soil resampling and AC-based C budgets, was compared for the period between April 2011 and December 2014 (Fig. 1)."

10. L185- 187 "An For easy...site" remove this phrases

We agree and removed the sentence from the MS.

11. L191 what about chamber heating?

As stated within section 2.2.2 *“the following exclusion criteria: (i) range of within-chamber air temperature not larger than ± 1.5 K (R_{eco} and NEE fluxes) and a PAR deviation (NEE fluxes only) not larger than ± 20 % of the average”* were used *“to ensure stable environmental conditions within the chamber throughout the measurement;”*. Despite this precaution to extract an almost undisturbed measurement, the big chamber volume (several cubic meters (see 2.2.1)) and the relatively short measurement time during daytime/summer period (5-10 minutes) mostly prevented a heating up of the chamber headspace.

12. L 206 replace ΔSOC AC by NCS

Please see answer to comment 1.

13. L231 “...of CO2 concentration data as suggested by....”end of the sentence is missing

We removed the fragment “as suggested by” from the sentence, as it was accidentally left from a previous wording.

14. L281 I am not sure that the LAI_C content relation is useful and is of any help in the present manuscript

As explained in the MS, the LAI to C-content relationship is needed to calculate daily changes in C-content of the aboveground biomass (NPPshoot). No biomass samples were taken between two alfalfa cuts. Instead LAI was measured biweekly and correlated with the C-content in harvested biomass at each cut. These relationships were used to model the C-content development of alfalfa between two cuts.

“For alfalfa in 2013 and 2014, NPP$_{shoot}$ was modeled based on biweekly measurements of LAI because no additional biomass sampling was performed between the multiple cuts per year. To calculate the C content corresponding to the measured LAI, the relationship between LAI prior to the chamber harvest and the C content measured in the chamber harvest of all six alfalfa cuts was used.”

15. L288 Calculation of Net Carbon Storage (NCS)

Please see answer to comment 1.

16. L293ff suggest mention the whole equation as used in literature for NCS (NBP), describing which components were ignored and not.

We agree and are now presenting the entire equation used to calculate NECB and thus ΔSOC. Since DOC and DIC are affecting ΔSOC as balances between lateral input and output, both are given as delta within the equation. NEE and CH4 are added due to the use of the atmospheric sign convention (negative values indicate a C gain for the soil-plant system, positive once a loss).

17. L311 Horizons Ap is difficult to understand and varies between sites and ecosystems, I suggest to use the depth (eg 0-15cm) instead

We agree and rewrote and specified the sentence including made suggestion.

“After soil manipulation, a 5-m raster sampling of topsoils (Ap horizons) was performed during April 2011. Each Ap horizon was separated into an upper (0-15 cm) and lower

segment (15-25 cm), which were analyzed separately for bulk density, SOC, Nt and coarse fraction (< 2 mm) (data not shown). From these data, SOC and Nt mass densities were calculated separately for each segment and finally summed up for the entire Ap-horizon (0-25 cm). The mean SOC and Nt content for the Ap horizon of each raster point was calculated by dividing SOC or Nt mass densities (0-25 cm) through the fine-earth mass (0-25 cm). In December 2014, composite soil samples of the Ap horizon were collected. Composite samples consist of samples from four sampling points in a close proximity around each chamber."

18. L313 soil cores need more details on diameter, depth...

    We agree and specified/changed "cores" into "samples" and added details about how these samples were taken (pleases see answer to comment above).

19. L313....In December 2014, mixed soil samples were collected from the Ap horizon next to each chamber...What are mixed soil samples?

    Mixed soil samples refer to a composite sample, which consist of several samples taken in close proximity to a chamber. These samples were mixed prior to analysis. To better address this, we rewrote the sentence.

    "In December 2014, composite soil samples of the Ap horizon were collected. Composite samples consist of samples from four sampling points in a close proximity around each chamber. "

20. L348 "NPP shoot between chamber positions and...." - not clear what means positions

Chamber position simply refers to the different chambers and their position within the landscape (along a small-scale gradient/transect). To better address this, we deleted the word "positions" from the sentence.

"Again, lower differences in annual NPP$_{shoot}$ between the chambers and no spatial trends were found for alfalfa in 2013 and 2014."

21. L368" As a result of soil translocation in 2010, initially m...." delete

Please see answer to comment 9.

22. L379 ""Average annual ΔSOC values for the soil resampling and C budget method are shown in Fig. 6." Difficult to see from Fig 6 suggest to add the numbers in table 1 .

We agree and added the average annual ΔSOC values to Tab.1 as suggested.

23. L391 soils (Conant et al., 2010; Xiong et al., 2016). Delete citation as not its place here

We agree and deleted the reference from the sentence as suggested.

24. L488 "We confirmed that AC-based C budgets are able to reveal small-scale spatial and short-term" not sure this is true with 4 chambers only

We agree and added results of Wilcoxon rank sum tests (regarding spatial (chamber-related) differences between measured R$_{eco}$ and NEE fluxes (GPP was not measured directly but derived by empirical modelling, hence no test was performed) and estimates of NPP$_{shoot}$ (based on LAI or biomass sampling campaigns)) for each year to Tab. 1. The results show significant differences between CO_2 fluxes (R_{eco} and NEE) measured during the same time by the four chambers during most years but only minor differences regarding NPP_{shoot} (due to rather low sample size for NPP_{shoot} as well as spatially biased samples (biomass samples (except for final harvests) were collected around but not in each chamber)).

We decided to not present a test for the entire study period, using annual values. The reason therefore is that we would only expect similar differences in annual CO_2 exchange, NPP_{shoot} and ΔSOC, and thus significant differences between the chamber positions, in case of comparable weather conditions and same cover crops during all year of the study. This however was not the case. Hence multiple variables, such as GWL, cover crop and position (soil) might influence CO_2 exchange, NPP_{shoot} and ΔSOC, resulting in higher as well as lower values for one chamber position during different years of the study period. This high variation per chamber, is leading to non-significant differences between the chamber positions during the study period, when using annual values, but does not necessarily mean that they are equal or comparable.

In addition we rewrote and specified the sentence:

"We confirmed that AC-based C budgets are in principle able to detect small-scale spatial differences and might be thus used to detect spatial heterogeneity of ΔSOC similar to the soil resampling method. However, compared to soil resampling AC-based C budgets also reveal short-term temporal dynamics"

25. Table 1 : Suggest to add a column ΔSOC values (2011-2014) for soil resampling and cumulated C budget (2011-2014). Would be nice to have the crop rotation in the 1st column. What about standard deviation for soil sampling?

We agree and added ΔSOC values for soil resampling (difference between 2011 and 2014) as well as average annual ΔSOC values for both methods to Tab. 1. Crop rotation was implemented in Tab. 1 as suggested. No SD can be given for composite samples. Instead a CV (<10%) of laboratory analyses repetitions is given.

List of relevant changes in the MS:

- Abstract:
  - Shortened (9%) and specified
- Introduction:
  - Description of benefits of the AC-based approach
  - Conant et al. reference corrected
  - Scale of mall-scale spatial differences specified/Transect length given
- Material and Methods:
  - Specified study design and period used for method comparison (April 2011 to December 2014)
  - Specification and extension of method section regarding flux calculation (equation 1) and empirical modelling to gap-fill CO_2 exchange measurements.
  - Full equation 5 is given
  - Added details to section 2.3. (Soil resampling method)
- Results:
  - Added description of obtained diurnal variability in measured CO2 exchange

- Conclusion:
    - Specified conclusion about confirmed small-scale spatial differences and temporal dynamics of ΔSOC
- Changes in Figures and Tables:
    - Tab.1:
        - Mean annual values added to Tab.1
        - Crop rotation added to Tab.1
        - ΔSOC obtained by soil resampling added to Tab.1
        - Wilcoxon rank sum tests results (differences between chamber positions) added to Tab.1and caption
    - Fig.2:
        - A.s.l. of chamber positions of the established transect added to Fig.2
        - Figure caption specified
    - Fig.5:
        - Signs changed to represent soil science sign convention instead of before used atmospheric sign convention for ΔSOC
        - Added zero line
        - Specified figure caption
    - Fig.6:
        - Unit corrected
        - Error bars corrected
        - Added results of Wilcoxon rank sum test (differences between used methods to determine ΔSOC)

Detecting small-scale spatial heterogeneity and temporal dynamics of soil organic carbon (SOC) stocks: a comparison between automatic chamber-derived C budgets and repeated soil inventories

Mathias Hoffmann[a,*], Nicole Jurisch[b], Juana Garcia Alba[a], Elisa Albiac Borraz[a], Marten Schmidt[b], Vytas Huth[b], Holger Rogasik[a], Helene Rieckh[a], Gernot Verch[c], Michael Sommer[a, d], Jürgen Augustin[b]

[a]Institute of Soil Landscape Research, Leibniz Centre for Agricultural Landscape Research (ZALF), Eberswalder Str. 84, 15374 Müncheberg, Germany

[b]Institute of Landscape Biogeochemistry, Leibniz Centre for Agricultural Landscape Research (ZALF), Eberswalder Str. 84, 15374 Müncheberg, Germany

[c]Research Station Dedelow, Leibniz Centre for Agricultural Landscape Research (ZALF), Eberswalder Str. 84, 15374 Müncheberg, Germany

[d]Institute of Earth and Environmental Sciences, University Potsdam, Karl-Liebknecht-Str.24-25, 14476 Potsdam, Germany

*Corresponding author:
Mathias Hoffmann
Eberswalder Str. 84, 15374 Müncheberg, Germany
E-mail: Mathias.Hoffmann@zalf.de
Tel.: +49(0)33432 82 327
Fax: +49(0)33432 82 280

Abstract

Carbon (C) sequestration in soils plays a key role in the global C cycle. It is therefore crucial to adequately monitor dynamics in soil organic carbon (ΔSOC) stocks when aiming to reveal underlying processes and potential drivers. However, small-scale spatial (10-30 m) and temporal changes in SOC stocks, particularly pronounced on arable lands, are hard to assess. The main reasons for this are limitations of the well-established methods. On the one hand, repeated soil inventories, often used in long-term field trials, reveal spatial patterns and trends in ΔSOC but require a longer observation period and a sufficient number of repetitions. On the other hand, eddy covariance measurements of C fluxes towards a complete C budget of the soil-plant-atmosphere system may help to obtain temporal ΔSOC patterns but lack small-scale spatial resolution.

To overcome these limitations, this study presents a reliable method to detect both short-term temporal dynamics as well as small-scale spatial differences of ΔSOC. Therefore, a combination of automatic chamber (AC) measurements of CO_2 exchange and empirically modeled aboveground biomass development (NPP_{shoot}) was used. To verify our method, results were compared with ΔSOC observed by soil resampling.

Soil resampling and AC measurements were performed from 2010 to 2014 at a colluvial depression located in the hummocky ground moraine landscape of NE Germany. The measurement site is characterized by a variable groundwater level (GWL) and pronounced small-scale spatial heterogeneity regarding SOC and nitrogen (Nt) stocks. . Tendencies and magnitude of ΔSOC values derived by AC-measurements and repeated soil inventories corresponded well. The period of maximum plant growth was identified as being most important for the development of spatial differences in annual ΔSOC. Hence, we were able to confirm that AC-based C budgets are able to reveal small-scale spatial differences and short-term temporal dynamics of ΔSOC.

Keywords

Net ecosystem exchange (NEE), net primary productivity (NPP), biomass modeling, soil resampling

1. Introduction

Soils are the largest terrestrial reservoirs of organic carbon (SOC), storing two to three times as much C as the atmosphere and biosphere (Chen et al., 2015; Lal et al., 2004). In the context of climate change mitigation as well as soil fertility and food security, there has been considerable interest in the development of SOC, especially in erosion-affected agricultural landscapes (Berhe and Kleber, 2013; Conant et al., 2011; Doetterl et al., 2016; Stockmann et al., 2015; Van Oost et al., 2007; Xiong et al., 2016). Detecting the development of soil organic carbon stocks (ΔSOC) in agricultural landscapes needs to consider three major challenges: First, the high small-scale spatial heterogeneity of SOC (e.g., Conant et al., 2011; Xiong et al., 2016). Erosion and land use change reinforce natural spatial and temporal variability, especially in hilly landscapes such as hummocky ground moraines where correlation lengths in soil parameters of 10-30 m are very common. Second, pronounced short-term temporal dynamics, caused by, e.g., type of cover crop, frequent crop rotation and soil cultivation practices. Third, the rather small magnitude of ΔSOC compared to total SOC stocks (e.g., Conant et al., 2011; Poeplau et al., 2016).

However, information on the development of SOC is an essential precondition to improve the predictive ability of terrestrial C models (Luo et al., 2014). As a result, sensitive measurement techniques are required to precisely assess short-term temporal and small-scale (10-30 m) spatial dynamics in ΔSOC (Batjes and van Wesemael, 2015). To date, the assessment of ΔSOC is typically based on two methods, namely (i) destructive, repeated soil inventories through soil resampling and (ii) non-destructive determination of ecosystem C budgets by measurements of gaseous C exchange, C import and C export (Leifeld et al., 2011).

The first method is usually used during long-term field trials (Batjes and van Wesemael, 2015; Chen et al., 2015; Schrumpf et al., 2011). Given a sufficient time horizon of 5 to 10 years, the soil resampling method is generally able to reveal spatial patterns and trends within ΔSOC

(Batjes and van Wesemael, 2015; Schrumpf et al., 2011). Most repeated soil inventories are designed to study treatment differences in the long-term. As a result, short-term temporal dynamics in C exchange remain concealed (Poeplau et al., 2016; Schrumpf et al., 2011). A number of studies tried to overcome this methodical limitation by increasing (e.g., monthly) the soil sampling frequency (Culman et al., 2013; Wuest, 2014). This allows for the detection of seasonal patterns of ΔSOC but still mixes temporal and spatial variability of SOC because every new soil sample represents not only a repetition in time but also in space. Temporal differences observed through repeated soil sampling are therefore always spatially biased.

By contrast, the net ecosystem carbon budget (NECB; Smith et al. 2010) and thereon based temporal dynamics of ΔSOC can be easily derived through the eddy covariance (EC) technique as a common approach to obtain gaseous C exchange (Alberti et al., 2010; Leifeld et al., 2011; Skinner and Dell, 2015). However, C fluxes based on EC measurements are integrated over a larger, altering footprint area (several hectares). As a result, small-scale (< 20 m) spatial differences in ΔSOC are not detected.

Accounting for the above-mentioned methodical limitations, a number of studies investigated spatial patterns in gaseous C exchange by using manual chamber measurement systems (Eickenscheidt et al., 2014; Pohl et al., 2015). Compared to EC measurements, these systems are characterized by a low temporal resolution, where the calculated net ecosystem CO_2 exchange (NEE) is commonly based on extensive gap filling (Gomez-Casanovas et al., 2013; Savage and Davidson, 2003) conducted, e.g., using empirical modeling (Hoffmann et al., 2015). Therefore, management practices and different stages in plant development that are needed to precisely detect NEE often remain unconsidered (Hoffmann et al., 2015).

Compared to mentioned approaches for detecting ΔSOC by either repeated soil sampling or observations of the gaseous C exchange, automatic chamber (AC) systems combine several advantages. On the one hand flux measurements of the same spatial entity avoid the mixing of spatial and temporal variability, as done in case of point measurements by repeated soil inventories. On the other hand, AC measurements combine advantages of EC and manual chamber systems because they not only increase the temporal resolution compared to manual chambers but also allow for the detection of small-scale spatial differences and treatment comparisons regarding the gaseous C exchange (Koskinen et al., 2014).

To date hardly any direct comparisons between AC-derived C budgets and soil resampling-based ΔSOC values have been reported in the literature. Leifeld et al. (2011) and Verma et al. (2005) compared the results of repeated soil inventories with EC-based C budgets over 5- and 3-year study periods, respectively. Even though temporal dynamics in ΔSOC were shown e.g. for grazed pastures and intensively used grasslands (Skinner and Dell 2015; Leifeld et al., 2011), no attempt was made to additionally detect small-scale differences in ΔSOC. In our study, we introduce the combination of AC measurements and empirically modeled aboveground biomass production (NPP_{shoot}) as a precise method to detect small-scale spatial differences and short-term temporal dynamics of ΔSOC. Measurements were performed from 2010 to 2014 under a *silage maize/winter fodder rye/sorghum-Sudan grass hybrid/alfalfa* crop rotation at an experimental plot located in the hummocky ground moraine landscape of NE Germany.

We hypothesize that the AC-based C budget method is able to detect small-scale spatial and short-term temporal dynamics of ΔSOC in an accurate and precise manner. Therefore, we compare ΔSOC values measured by soil resampling with ΔSOC values derived through AC-based C budgets (Fig. 1).

2. Materials and methods

2.1 Study site and experimental setup

Measurements were performed at the 6-ha experimental field “CarboZALF-D”. The site is located in a hummocky arable soil landscape within the Uckermark region (NE-Germany; 53°23`N, 13°47`E, ~50-60 m a.s.l.). The temperate climate is characterized by a mean annual air temperature of 8.6°C and annual precipitation of 485 mm (1992–2012, ZALF research station, Dedelow). Typical landscape elements vary from flat summit and depression locations with a gradient of approximately 2 %, across longer slopes with a medium gradient of approx. 6 %, to short and rather steep slopes with a gradient of up to 13 %. The study site shows complex soil patterns mainly influenced by erosion, relief and parent material, e.g., sandy to marly glacial and glaciofluvial deposits. The soil type inventory of the experimental site consists of non-eroded Albic Luvisols (Cutanic) at the flat summits, strongly eroded Calcic Luvisols (Cutanic) on the moderate slopes, extremely eroded Calcaric Regosols on the steep slopes, and a colluvial soil, i.e., Endogleyic Colluvic Regosols (Eutric), over peat in the depression (IUSS Working Group WRB, 2015).

During June 2010, four automatic chambers and a WXT520 climate station (Vaisala, Vantaa, Finland) were set up at the depression (Sommer et al., 2016) (see 2.2.1). The chambers were arranged along a topographic gradient (upper (A), upper middle (B), lower middle (C), and lower (D) chamber position; length ~30 m; difference in altitude ~1 m) within in a distance of approx. 5 m of each other (Fig. 2). As part of the CarboZALF project, a manipulation experiment was carried out at the end of October 2010, i.e., after the vegetation period. Topsoil material from a neighboring hillslope was incorporated into the upper soil layer of the depression (Ap horizon). The amount of translocated soil was equivalent to tillage erosion of a decennial time horizon (Sommer et al., 2016). The change in SOC for each chamber was monitored by three topsoil inventories, carried out (I) prior to soil manipulation during April 2009, (II) after soil manipulation during April 2011, and (III) during December 2014. ΔSOC derived through soil resampling and AC-based C budgets, was compared for the period between April 2011 and December 2014 (Fig. 1).

Records of meteorological conditions (1 min frequency) include measurements of air temperature at 20 cm and 200 cm height, PAR (inside and outside the chamber), air humidity, precipitation, air pressure, wind speed and direction. Soil temperatures at depths of 2 cm, 5 cm, 10 cm and 50 cm were recorded using thermocouples, installed next to the climate station (107, Campbell Scientific, UT, USA).

The groundwater level (GWL) was measured using tensiometers assuming hydrostatic equilibrium. The tensiometers were installed at a soil depth of 160 cm, at soil profile locations in the upper and lower end of the transect. The average GWL of both profiles was used for further data analysis. Data gaps < 2 days were filled using simple linear interpolation. Larger gaps in GWL did not occur. The measurement site was cultivated with five different crops during the study period, following a practice-orientated and erosion-expedited farming procedure. The crop rotation was silage maize (*Zea mays*) - winter fodder rye (*Secale cereale*) - sorghum-Sudan grass hybrid (*Sorghum bicolor* x *sudanese*) - winter triticale (*Triticosecale*) - alfalfa (*Medicago sativa*). Cultivation and fertilization details are presented in Tab. A.1. Aboveground biomass ($\text{NPP}_{\text{shoot}}$) development was monitored using up to four biomass sampling campaigns during the growing season, covering the main growth stages. Additional measurements of leaf area index (LAI) started in 2013. Collected biomass samples were chopped and dried to a constant weight (48 h at 105°C). The C, N, K and P contents were determined using elementary analysis (C, N: TruSpec CNS analyzer, LECO Ltd., Mönchengladbach, Germany) and Kjehldahl digestion (P, K; AT200, BeckmanCoulter (Olympus), Krefeld, Germany and AAS-iCE3300, ThermoFisher-SCIENTIFIC GmbH, Darmstadt, Germany). To assess the potential impact of chamber placement on plant growth, chemical analyses were carried out for the final harvests of each chamber and compared to biomass samples collected next to each chamber.

2.2 C budget method

2.2.1 Automatic chamber system

Automatic flow-through non-steady-state (FT-NSS) chamber measurements (Livingston and Hutchinson, 1995) of CO_2 exchange were conducted from January 2010 until December 2014. The AC system consists of 4 identical, rectangular, transparent polycarbonate chambers (thickness of 2 mm; light transmission ~70 %). Each chamber has a height of 2.5 m and covers a surface area of 2.25 m^2 (volume: 5.625 m^3). To adapt for plant height (alfalfa), the chamber volume was reduced to 3.375 m^3 in autumn 2013. Airtight closure during measurements was ensured by a rubber belt that sealed at the bottom of each chamber. A 30-cm open-ended tube on the slightly concave top of the chambers guided rain water into the chamber and additionally assured pressure equalization. Two small axial fans (5.61 m^3 min^{-1}) were used for mixing the chamber headspace. The chambers were mounted onto steel frames with a height of 6 m and lifted between measurements using electrical winches at the top. For controlling the AC system and data collection, a CR1000 data logger was used (Campbell Scientific, UT, USA). The CO_2 concentration changes over time were measured within each chamber using a carbon dioxide probe (GMP343, Vaisala, Vantaa, Finland) connected to a vacuum pump (0.001 m^3 min^{-1}; DC12/16FK, Fürgut, Tannheim, Germany). All CO_2 probes were calibrated prior to installation using ± 0.5 % accurate gases containing 0 ppm, 200 ppm 370 ppm, 600 ppm, 1000, ppm and 4000 ppm CO_2. The operation schedule of the AC system, decisively influenced by agricultural treatments, is presented in A.2. The chambers closed in parallel at an hourly frequency, providing one flux measurement per chamber and hour. The measurement duration was 5-20 minutes, depending on season and time of day. Nighttime measurements usually lasted 10 min during the growing season and 20 min during the non-growing season (due to lower concentration increments). The length of the daytime measurements was up to 10 min, depending on low PAR fluctuations (< 20 %). CO_2 concentrations (inside the chamber) and general environmental conditions, such as PAR (SKP215, Skye, Llandridad Wells, UK) and air temperatures (107, Campbell Scientific, UT, USA), were recorded inside and outside the chambers at a 1 min frequency from 2010 to 2012 and a 15 sec frequency from October 2012.

2.2.2 CO_2 flux calculation and gap filling

An adaptation of the modular R program script, described in detail by Hoffmann et al. (2015), was used for stepwise data processing. The atmospheric sign convention was used for the components of gaseous C exchange (ecosystem respiration (R_{eco}; sum of autotrophic and heterotrophic respiration), gross primary production (GPP) and NEE), whereas positive values for ΔSOC indicate a gain and negative values a loss in SOC. Based on records of environmental variables and CO_2 concentration change within the chamber headspace, CO_2 fluxes were calculated and parameterized for R_{eco} and GPP within an integrative step. Subsequently, R_{eco}, GPP, and NEE were modeled for the entire measurement period using climate station data. Statistical analyses, model calibration and comprehensive error prediction were provided for all steps of the modeling process.

CO_2 fluxes (F, µmol C m^{-2} s^{-1}) were calculated according to the ideal gas law (Eq. 1).

$$F = \frac{pV}{RTA} * \frac{\Delta c}{\Delta t} \qquad \text{[Eq. 1]}$$

where $\Delta c/\Delta t$ is the concentration change over measurement time, A and V denote the basal area and chamber volume, respectively, and T and p represent the air temperature inside the chamber (K) and air pressure. Because plants below the chambers accounted for < 0.2 % of the total chamber volume, a static chamber volume was assumed. R is a constant (8.3143 m^3 Pa K^{-1} mol^{-1}). To calculate $\Delta c/\Delta t$, data subsets based on a variable moving window with a minimum length of 4 minutes were used (Hoffmann et al., 2015). $\Delta c/\Delta t$ was computed by applying a linear regression to each data subset, relating changes in chamber headspace CO_2 concentration to measurement time (Leiber-Sauheitl et al., 2013; Leifeld et al., 2014; Pohl et al., 2015). In the case of the 15-sec measurement frequency, a death-band of 5 % was applied prior to the moving window algorithm. Thus, data noise that originated from either turbulence or pressure fluctuation caused by chamber deployment or from increasing saturation and canopy microclimate effects was excluded (Davidson et al., 2002; Kutzbach et al., 2007; Langensiepen et al., 2012). Due to the low measurement frequency, no data points were discarded for records with 1-min measurement frequency (2010-2012). The resulting CO_2 fluxes per measurement (based on the moving window data subsets) were further evaluated according to the following exclusion criteria: (i) range of within-chamber air temperature not larger than ± 1.5 K (R_{eco} and NEE fluxes) and a PAR deviation (NEE fluxes only) not larger than ± 20 % of the average to ensure stable environmental conditions within the chamber throughout the measurement; (ii) significant regression slope ($p \leq 0.1$, *t*-test); and (iii) non-significant tests ($p > 0.1$) for normality (Lillifor´s adaption of the Kolmogorov-Smirnov test), homoscedasticity (Breusch-Pagan test) and linearity of CO_2 concentration data. Calculated CO_2 fluxes that did not meet all exclusion criteria were discarded. In cases where more than one flux per measurement met all exclusion criteria, the CO_2 flux with the steepest slope was chosen.

To account for measurement gaps and to obtain cumulative NEE values, empirical models were derived based on nighttime R_{eco} and daytime NEE measurements following Hoffmann et al. (2015). For R_{eco}, temperature-dependent Arrhenius-type models were used and fitted for recorded air as well as soil temperatures in different depths (Lloyd and Taylor 1994; Eq. 2).

$$R_{eco} = R_{ref} * e^{E_0\left(\frac{1}{T_{ref}-T_0}-\frac{1}{T-T_0}\right)} \qquad \text{[Eq. 2]}$$

where R_{eco} is the measured ecosystem respiration rate [μmol^{-1} C m^{-2} s^{-1}], R_{ref} is the respiration rate at the reference temperature (283.15 K; T_{ref}); E_0 is an activation energy like parameter; T_0 is the starting temperature constant (227.13 K) and T is the mean air or soil temperature during the flux measurement. Out of the four R_{eco} models (one model for air temperature, soil temperature in 2 cm, 5 cm and 10 cm depth) obtained for nighttime R_{eco} measurements of a certain period, the model with the lowest Akaike Information Criterion (AIC) was used.

GPP fluxes were derived using a PAR-dependent, rectangular hyperbolic light response function based on the Michaelis-Menten kinetic (Elsgaard et al., 2012; Hoffmann et al., 2015; Wang et al., 2013; Eq. 3). Because GPP was not measured directly, GPP fluxes were calculated as the difference between measured NEE and modeled R_{eco} fluxes.

$$GPP = \frac{GP_{max} * \alpha * PAR}{\alpha * PAR + GP_{max}} \qquad \text{[Eq. 3]}$$

where GPP is the calculated gross primary productivity [μmol^{-1} CO_2 m^{-2} s^{-1}]; GP_{max} is the maximum rate of C fixation at infinite PAR [μmol CO_2 m^{-2} s^{-1}]; α is the light use efficiency [mol CO_2 mol^{-1} photons] and PAR is the photon flux density (inside the chamber) of the photosynthetically active radiation [μmol^{-1} photons m^{-2} s^{-1}]. In cases where the rectangular hyperbolic light response function did not result in significant parameter estimates, a non-rectangular hyperbolic light-response function was used (Gilmanov et al. 2007, 2013; Eq. 4).

$$GPP = \alpha * \mathrm{PAR} + \mathrm{GP}_{\max} - \sqrt{(\alpha * \mathrm{PAR} + \mathrm{GP}_{\max})^2 - 4 * \alpha * \mathrm{PAR} * \mathrm{GP}_{\max} * \theta} \quad \text{[Eq. 4]}$$

where θ is the convexity coefficient of the light-response equation (dimensionless).

Due to plant growth and season, parameters of derived R_{eco} and GPP models may vary with time. To account for this, a moving window parameterization was performed, by applying fluxes of a variable time window (2-21 consecutive measurement days) to Eq.2-4. Temporally overlapping R_{eco} and GPP model sets were evaluated and discarded in case of positive (GPP), negative (R_{eco}) or insignificant parameter estimates. Finally, the model set with the lowest AIC (R_{eco}) was used. If no fit or a non-significant fit was achieved, averaged flux rates were applied for R_{eco} and GPP. The length of the averaging period was thereby selected by choosing the variable moving window with the lowest standard deviation (SD) of measured fluxes. This procedure was repeated until the whole study period was parameterized.

Based on continuously monitored temperature and PAR (outside the chamber), R_{eco}, GPP and NEE were modeled in half-hour steps for the entire study period. Because GPP was parameterized based on PAR records inside but modeled with PAR records outside the chamber, no PAR correction in terms of reduced light transmission was needed. Uncertainty of annual CO_2 exchange was quantified using a comprehensive error prediction algorithm described in detail by Hoffmann et al. (2015).

2.2.3 Modeling aboveground biomass dynamics

Aboveground biomass development (NPP_{shoot}) was predicted using a logistic empirical model (Yin et al., 2003; Zeide, 1993). From 2010 to 2012, modeled NPP_{shoot} was based on the relationship between sampling date and the C content of harvested dry biomass measured during sampling campaigns (three to four times per year following plant development). For alfalfa in 2013 and 2014, NPP_{shoot} was modeled based on biweekly measurements of LAI because no additional biomass sampling was performed between the multiple cuts per year. To calculate the C content corresponding to the measured LAI, the relationship between LAI prior to the chamber harvest and the C content measured in the chamber harvest of all six alfalfa cuts was used. Daily values of C stored within NPP_{shoot} were calculated using derived logistic functions.

2.2.4 Calculation of ΔSOC

Annual ΔSOC for each chamber was determined as the sum of annual NEE and NPP_{shoot}, representing C removal due to the chamber harvest (Eq. 4; Leifeld et al., 2014). Temporal dynamics in ΔSOC were calculated as the sum of daily NEE and NPP_{shoot}.

$$\Delta SOC_n = \sum_{i=1}^{n}[NEE_i + CH_4 + (NPP_{shoot\,i} - C_{import}) + \Delta DOC_i + \Delta DIC_i] \qquad \text{[Eq. 5]}$$

Several minor components of Eq. 5 were not considered (see also Hernandez-Ramirez et al., 2011). First, C import (C_{import}) due to seeding and fertilization, which was close to zero because the measurement site was fertilized by a surface application of mineral fertilizer throughout the entire study period. Second, methane (CH_4-C) emissions, which were measured manually at the same experimental field but did not exceed a relevant order of magnitude (-0.01 g C m^{-2} y^{-1}) and were therefore not included in the ΔSOC calculation. Third, lateral C fluxes, originating from dissolved organic (DOC) and inorganic carbon (DIC) as well as particulate soil organic carbon

(SOC_p). In addition to the rather small magnitude of the subsurface lateral C fluxes in soil solution (Rieckh et al., 2012), it was assumed that their C input equaled C output at the plot scale. Lateral SOC_p transport along the hillslope was excluded by grassland stripes established between experimental plots in 2010 (Fig. 1 in Sommer et al., 2016).

2.3 Soil resampling method

To obtain ΔSOC using the soil resampling method, soil samples were collected three times during the study period. Initial SOC along the topographic gradient was monitored prior to soil manipulation during April 2009 at two soil pits, which were sampled by pedogenetic horizons. After soil manipulation, a 5-m raster sampling of topsoils (Ap horizons) was performed during April 2011. Each Ap horizon was separated into an upper (0-15 cm) and lower segment (15-25 cm), which were analyzed separately for bulk density, SOC, Nt and coarse fraction (< 2 mm) (data not shown). From these data, SOC and Nt mass densities were calculated separately for each segment and finally summed up for the entire Ap-horizon (0-25 cm). The mean SOC and Nt content for the Ap horizon of each raster point was calculated by dividing SOC or Nt mass densities (0-25 cm) through the fine-earth mass (0-25 cm). In December 2014, composite soil samples of the Ap horizon were collected. The composite samples consist of samples from four sampling points in a close proximity around each chamber. Prior to laboratory analysis coarse organic material was discarded from collected soil samples (Schlichting et al. 1995). Thermogravimetric desiccation at 105°C was performed in the laboratory for all samples to determine bulk densities (Mg m^{-3}). Bulk soil samples were air dried, gently crushed and sieved (2 mm) to obtain the fine fraction (particle size < 2 mm). The total carbon and total nitrogen contents were determined by elementary analysis (TruSpec CNS analyzer, LECO Ltd., Mönchengladbach, Germany) as carbon dioxide via infrared detection after dry combustion at

1250°C (DIN ISO10694, 1996), in duplicate. As the soil horizons did not contain carbonates, total carbon was equal to SOC.

2.4 Uncertainty prediction and statistical analysis

Uncertainty prediction for ΔSOC derived by the C budget method was performed according to Hoffmann et al. (2015), following the law of error propagation. To test for differences in topsoil SOC (SOC_{Ap}) and total nitrogen (Nt) stocks between soil resampling performed after soil manipulation in 2010 and 2014, a paired *t*-test was applied. Computation of uncertainty prediction and calculation of statistical analyses were performed using R 3.2.2.

3. Results

3.1 C budget method

3.1.1 NEE and NPP_{shoot} dynamics

NEE and its components R_{eco} and GPP were characterized by a clear seasonality and diurnal patterns. Seasonality followed plant growth and management events (e.g., harvest; Fig. 3), Highest CO_2 uptake was thus observed during the growing season, whereas NEE fluxes during the non-growing season were significantly lower. Diurnal patterns were more pronounced during the growing season and less obvious during the non-growing season. In general R_{eco} fluxes were higher during daytime, whereas GPP and NEE, in case of present cover crops, were lower or even negative, representing a C uptake during daytime by the plant-soil system. Annual NEE was crop dependent, ranging from -1600 g C m^{-2} y^{-1} to -288 g C m^{-2} y^{-1}. Highest annual uptakes were observed for maize and sorghum during 2011 and 2012, whereas alfalfa cultivation showed lower annual NEE (Tab. 1). From 2010 to 2012, annual NEE followed the topographic gradient, with higher NEE in the direction of the depression and lower NEE away from the depression. These small-scale spatial differences in gaseous C exchange changed with alfalfa cultivation. As a result, only minor differences between the chamber positions were observed, showing no clear trend or tendency (Tab. 1).

C in living biomass (due to biomass sampling campaigns and LAI measurements) and C removals due to harvest were in general well reflected by modeled NPP_{shoot} (Fig. 4). Annual C removal due to harvest was clearly crop dependent, with highest NPP_{shoot} for maize and sorghum ranging from 420 g C m^{-2} to 1238 g C m^{-2}, and lower values in the case of winter fodder rye and alfalfa. Similar to NEE from 2010 to 2012, annual sums of NPP_{shoot} followed the topographic gradient, with lower values close to the depression (Tab. 1). Again, lower differences in annual NPP_{shoot} between the chambers and no spatial trends were found for alfalfa in 2013 and 2014.

3.1.2 ΔSOC dynamics

Temporal and spatial dynamics of continously cumulated daily ΔSOC values during the four years after soil manipulation are shown in Fig. 5. Differences in ΔSOC were in general less pronounced during the non-growing season compared to the growing season. During the non-growing season, differences were mainly driven by differences in R_{eco} rather than GPP or NPP_{shoot}. This changed at the beginning of the growing season, when ΔSOC responded to changes in cumulative NEE and NPP_{shoot}. Hence, up to 79 % of the standard deviation of estimated annual ΔSOC developed during the period of maximum plant growth. Except for the lower middle chamber position, alfalfa seemed to counterbalance spatial differences in ΔSOC that developed during previous years (Fig. 5).

Annual ΔSOC values derived by the C budget method are presented in Tab. 1. Highest annual SOC gains were obtained in 2012 for winter fodder rye and sorghum-Sudan grass, reaching an average of 474 g C m^{-2} y^{-1}. In contrast, maize cultivation during 2011 was characterized by C losses between 59 g C m^{-2} y^{-1} and 169 g C m^{-2} y^{-1}. However, prior to soil manipulation, maize showed an average SOC gain of 102 g C m^{-2} y^{-1}.

3.2 Soil resampling method

As a result of soil translocation in 2010, initially measured SOC_{Ap} stocks increased by an average of 780 g C m^{-2}. However, due to the lower C content of the translocated topsoil material (0.76 %), the SOC_{Ap} content of the measurement site dropped by 10 - 14 % after soil manipulation (Tab. 1). Significant differences (paired *t*-test; $t = -2.48$, $p < 0.09$), which showed an increase in SOC_{Ap} of up to 11 %, were found between SOC_{Ap} stocks measured in 2010 and 2014. Three out of the four chamber positions showed a C gain during the 4 measurement years following soil manipulation. C gains were similar for the upper and lower chamber positions, but lower for the upper middle position. No change in SOC was obtained in the case of the lower middle (Fig. 5; Fig. 6) chamber position.

3.3 Method comparison

Average annual ΔSOC values for the soil resampling and C budget method are shown in Fig. 6. ΔSOC based on these methods showed a good overall agreement, with similar tendencies and magnitudes (Fig. 6). Irrespective of the applied method, significant differences were found between SOC stocks measured directly after soil manipulation in 2010 and SOC stocks measured in 2014. Following soil manipulation, both methods revealed similar tendencies in site and chamber-specific ΔSOC (Fig. 6). Both methods indicated a clear C gain for three out of the four chamber positions. C gains derived by the C budget method were similar for the upper, upper middle and lower chamber positions. By contrast, C gains derived by the soil resampling method were slightly but not significantly lower (paired *t*-test; $t = -1.23$, $p > 0.30$). This was most pronounced for the upper middle chamber position. No change in ΔSOC and only a minor gain in C was observed for the lower middle chamber position according to both methods. Differences between chamber positions indicate the presence of small-scale spatial ΔSOC dynamics typical of soils.

4. Discussion

4.1 Accuracy and precision of applied methods

Despite the similar magnitude and tendencies of the observed ΔSOC values, both methods were subject to numerous sources of uncertainty. These errors affect the accuracy and precision of observed ΔSOC values differently, which might help to explain differences between the soil resampling and the C budget method.

The soil resampling method is characterized by high measurement precision, which allows for the detection of relatively small changes in SOC. Related uncertainty in derived spatial and temporal ΔSOC dynamics is therefore mainly attributed to the measurement accuracy, affected by sampling strategy and design (Batjes and van Wesemael, 2015; De Gruijter et al., 2006). This includes (i) the spatial distribution of collected samples, (ii) the sampling frequency, (iii) the sampling depth and (iv) whether different components of soil organic matter (SOM) are excluded prior to analyses. The first aspect determines the capability to detect the inherent spatial differences in SOC stocks. This allows the conclusion that point measurements do not necessarily represent AC measurements, which integrate over the spatial variability within their basal area. The second aspect defines the temporal resolution, even though the soil resampling method is not able to perfectly separate spatial from temporal variability because repeated soil samples are biased by inherent spatial variability of the measurement site. The third aspect sets the vertical system boundary, which is often limited because only topsoil horizons are sampled within a number of soil monitoring networks (Van Wesemael et al., 2011) and repeated soil inventories (Leifeld et al., 2011). Similarly, the fourth aspect defines which components of SOM are specifically analyzed. Usually, coarse organic material is discarded prior to analysis (Schlichting et al., 1995) and therefore, total SOC is not assessed (e.g., roots, harvest residues, etc.).

In comparison, the C budget method considers any type of organic material present in soil by integrating over the total soil depth. As a result, both methods have a different validity range and area, which makes direct quantitative comparison more difficult. This may explain the higher uptake reported for three out of four chamber positions in the case of the C budget method.

In contrast to the soil resampling method, we postulate a higher accuracy and a lower precision in the case of the AC-based C budget method. The reasons for this include a number of potential errors affecting especially the measurement precision of the AC system, whereas over a constant area and maximum soil depth, integrated AC measurements increase measurement accuracy. First, it is currently not clear whether microclimatological and ecophysiological disturbances due to chamber deployment, such as the alteration of temperature, humidity, pressure, radiation, and gas concentration, may result in biased C flux rate estimates (Juszczak et al., 2013; Kutzbach et al., 2007; Lai et al., 2012; Langensiepen et al., 2012). Second, uncertainties related to performed flux separation and gap-filling procedures may influence the obtained annual gaseous C exchange (Gomez-Casanovas et al., 2013; Görres et al., 2014; Moffat et al., 2007; Reichstein et al., 2005). Although continuous operation of the AC system should allow for direct derivation of C budgets from measured CO_2 exchange and annual yields, in practice, data gaps always occur. To fill the measurement gaps, temperature- and PAR-dependent models are derived and used to calculate R_{eco} and GPP, respectively (Hoffmann et al. 2015). Due to the transparent chambers used, modeled R_{eco} is solely based on nighttime measurements. Hence, systematic differences between nighttime and daytime R_{eco} will yield an over- or underestimation of modeled R_{eco}. Because modeled R_{eco} is used to calculate GPP fluxes, GPP will be affected in a similar manner. However, the systematic over- or underestimation of fluxes in both directions may counterbalance the computed NEE, and estimated C budgets may be unaffected. Third, the development of NPP_{shoot} underneath the chamber might be influenced by the permanently installed AC system. Fourth, several minor components such as leaching losses of dissolved inorganic and organic carbon (DIC and DOC), C transport via runoff and atmospheric C deposition were not considered within the applied budgeting approach (see also 2.7).

Despite the uncertainties mentioned above, error estimates for annual NEE in this study are within the range of errors presented for annual NEE estimates derived from EC measurements (30 to 50 g C m^{-2} y^{-1}) (e.g., Baldocchi, 2003; Dobermann et al., 2006; Hollinger et al., 2005) and below the minimum detectable difference (MDD) reported for most repeated soil inventories (e.g., Batjes and Van Wesemael, 2015; Knebl et al., 2015; Necpálová et al., 2014; Saby et al., 2008; Schrumpf et al., 2011; VandenBygaart, 2006).

4.2 Plausibility of observed ∆SOC

Both the soil resampling and the C budget method showed C gains during the four years following soil manipulation. A number of authors calculated additional C sequestration due to soil erosion (Berhe et al., 2007; Dymond, 2010; VandenBygaart et al., 2015; Yoo et al., 2005), which was explained by the burial of replaced C at depositional sites and dynamic replacement at eroded sites (e.g., Doetterl et al., 2016). This is in accordance with erosion-induced C sequestration postulated by, e.g., Berhe and Kleber (2013) and Van Oost et al. (2007). In addition, observed C sequestration could also be a result of the manipulation-induced saturation deficit in SOC. By adding topsoil material from an eroded unsaturated hillslope soil, the capacity and efficiency to sequester C was theoretically increased (Stewart et al., 2007). Hence, additional

C was stored at the measurement site. This might be due to physicochemical processes, such as physical protection in macro- and micro aggregates (Six et al., 2002) or chemical stabilization by clay and iron minerals (Kleber et al., 2015).

Irrespective of the similar C gain observed by both methods, crop-dependent differences in ΔSOC were only revealed by the C budget method. The reason is the higher temporal resolution of AC-derived C budgets, displaying daily C losses and gains. Observed crop-dependent differences in ΔSOC are in accordance with, e.g., Kutsch et al. (2010), Jans et al. (2010), Hollinger et al. (2005) and Verma et al. (2005), who reported comparable EC-derived C balances for inter alia, maize, sorghum and alfalfa.

In 2012, substantial positive annual ΔSOC values were observed. Due to low precipitation during May and June, germination and plant growth of sorghum-Sudan grass was delayed (Fig. 4). As a result, the reproductive phenological stage was drastically shortened. This reduced C losses prior to harvest due to higher R_{eco}:GPP ratios (Wagle et al., 2015). In addition, the presence of cover crops during spring and autumn could have increased SOC, as reported by Lal et al. (2004), Ghimire et al. (2014) and Sainju et al. (2002). No additional C sequestration was observed for alfalfa in 2013 and 2014 or for the lower middle chamber position, which acted neither as a net C source nor sink (Tab. 1; Fig. 5). This opposes the assumption of increased C sequestration by perennial grasses (Paustian et al., 1997) or perennial crops (Zan et al., 2001). However, NEE estimates of alfalfa were within the range of -100 to -400 g C m^{-2}, which is typical for forage crops (*Lolium*, alfalfa, etc.) in different agro-ecosystems (Bolinder et al., 2012; Byrne et al., 2005; Gilmanov et al., 2013; Zan et al., 2001). In addition, Alberti et al. (2010) reported a soil C loss of > 170 g C m^{-2} after crop conversion from continuous maize to alfalfa, concluding that no effective C sequestration occurs in the short-term.

Regardless of the crop type, the AC-derived dynamic ΔSOC values showed that up to 79 % of the standard deviation of estimated annual ΔSOC occurred during the growing season and the main plant growth period from the beginning of July to the end of September.

5. Conclusions

We confirmed that AC-based C budgets are in principle able to detect small-scale spatial differences and might be thus used to detect spatial heterogeneity of ΔSOC similar to the soil resampling method. However, compared to soil resampling AC-based C budgets also reveal short-term temporal dynamics. AC-derived C budgets showed not only pedon-scale differences but also pronounced temporal dynamics in ΔSOC (Fig. 5). In addition, AC-based ΔSOC values corresponded well with the tendencies and magnitude of the results observed in the repeated soil inventory. The period of maximum plant growth was identified as being most important for the development of spatial differences in annual ΔSOC. For upscaling purposes of the presented results, further environmental drivers, processes and mechanisms determining C allocation in space and time within the plant-soil system need to be identified. This type of an approach will be pursued in future within the CarboZALF experimental setup (Sommer et al., 2016; Wehrhan et al., 2016). Moreover, the AC-based C budget method opens new prospects for clarifying unanswered questions, such as the influence of plant development or erosion on ΔSOC.

Acknowledgments

This work was supported by the Brandenburg Ministry of Infrastructure and Agriculture (MIL), who financed the land purchase, the Federal Agency for Renewable Resources (FNR), who co-financed the AC system, and the interdisciplinary research project CarboZALF. The authors want to express their special thanks to Mr. Peter Rakowski for excellent operational and technical maintenance during the study period as well as to the employees of the ZALF research station, Dedelow, for establishing and maintaining the CarboZALF-D field trial.

References

Alberti, G., Delle Vedove, G.D., Zuliani, M., Peressotti, A., Castaldi, S., Zerbi, G., 2010. Changes in CO_2 emissions after crop conversion from continuous maize to alfalfa. Agric. Ecosyst. Environ. 136, 139-147.

Baldocchi, D.D., 2003. Assessing the eddy covariance technique for evaluating carbon dioxide exchange rates of ecosystems: past, present and future. Glob. Change Biol. 9, 479-492.

Batjes, N.H., van Wesemael, B., 2015. Measuring and monitoring soil carbon, in: Banwart, S. A., Noellemeyer, E., Milne, E. (Eds.), Soil Carbon: Science, Management and Policy for Multiple Benefits. SCOPE Series 71. CABI, Wallingford, UK, pp. 188-201.

Berhe, A.A., Harte, J., Harden, J.W., Torn, M.S., 2007. The significance of the erosion-induced terrestrial carbon sink. BioScience 57, 337-346.

Berhe, A.A., Kleber, M., 2013. Erosion, deposition, and the persistence of soil organic matter: mechanistic consideration and problems with terminology. Earth Surf. Processes Landforms 38, 908-912.

Bolinder, M.A., Kätterer, T., Andrén, O., Parent, L.E., 2012. Estimating carbon inputs to soil in forage-based crop rotations and modeling the effects on soil carbon dynamics in a Swedish long-term field experiment. Can. J. Soil. Sci. 92, 821-833.

Byrne, K.A., Kiely, G., Leahy, P., 2005. CO_2 fluxes in adjacent new and permanent temperate grasslands. Agric. For. Meteorol. 135, 82–92.

Chen, L., Smith, P., Yang, Y., 2015. How has soil carbon stock changed over recent decades? Glob. Change Biol. 21, 3197-3199.

Conant, R.T., Ogle, S.M., Paul, E.A., Paustian, K., 2011. Measuring and monitoring soil organic carbon stocks in agricultural lands for climate mitigation. Front. Ecol. Environ. 9, 169-173.

Culman, S.W., Snapp, S.S., Green, J.M., Gentry, L.E., 2013. Short- and long-term labile soil carbon and nitrogen dynamics reflect management and predict corn agronomic performance. Agron. J. 105, 493-502.

Davidson, E. A., Savage, K., Verchot, L. V., Navarro, R., 2002. Minimizing artifacts and biases in chamber-based measurements of soil respiration. Agric. For. Meteorol. 113, 21-37.

De Gruijter, J.J., Brus, D.J., Bierkens, M.F.P., Knotters, M., 2006. Sampling for Natural Resource Monitoring. Springer Verlag, Berlin.

Dobermann, A.R., Walters, D.T., Baker, J.M., 2006. Comment on “Carbon budget of mature no-till ecosystem in north central region of the United States.” Agric. For. Meteorol. 136, 83-84.

Doetterl, S., Berhe, A.A., Nadeu, E., Wang, Z., Sommer, M., Fiener, P., 2016. Erosion, deposition and soil carbon: a review of process-level controls, experimental tools and models to address C cycling in dynamic landscapes. Earth Sci. Rev. 154, 102-122.

Dymond, J.R., 2010. Soil erosion in New Zealand is a net sink of CO_2. Earth Surf. Processes Landforms 35, 1763-1772. doi:10.1002/esp.2014.

Eickenscheidt, T., Freibauer, A., Heinichen, J., Augustin, J., Drösler, M., 2014. Short-term effects of biogas digestate and cattle slurry application on greenhouse gas emissions affected by N availability from grasslands on drained fen peatlands and associated organic soils. Biogeosciences 11, 6187-6207.

Elsgaard, L., Görres, C., Hoffmann, C.C., Blicher-Mathiesen, G., Schelde, K., Petersen, S.O., 2012. Net ecosystem exchange of CO_2 and carbon balance for eight temperate organic soils under agricultural management. Agric. Ecosyst. Environ. 162, 52-67.

Foken, T., 2008. Micrometeorology. Springer Verlag, Berlin.

Ghimire, R., Norton, J.B., Pendall, E., 2014. Alfalfa-grass biomass, soil organic carbon, and total nitrogen under different management approaches in an irrigated agroecosystem. Plant Soil 374, 173-184.

Gilmanov, T.G., Soussana, J.F., Aires, L., Allard, V., Ammann, C., Balzarolo, M., Barcza, Z., Bernhofer, C., Campbell, C.L., Cernusca, A., Cescatti, A., Clifton-Brown, J., Dirks, B.O.M., Dore, S., Eugster, W., Fuhrer, J., Gimeno, C., Gruenwald, T., Haszpra, L., Hensen, A., Ibrom, A., Jacobs, A.F.G., Jones, M.B., Lanigan, G., Laurila, T., Lohila, A., Manca, G., Marcolla, B., Nagy, Z., Pilegaard, K., Pinter, K., Pio, C., Raschi, A., Rogiers, N., Sanz, M.J., Stefani, P., Sutton, M., Tuba, Z., Valentini, R., Williams, M.L., Wohlfahrt, G., 2007. Partitioning European grassland net ecosystem CO_2 exchange into gross primary productivity and ecosystem respiration using light response function analysis. Agric. Ecosyst. Environ. 121, 93–120.

Gilmanov, T.G., Wylie, B.K., Tieszen, L.L., Meyers, T.P., Baron, V.S., Bernacchi, C.J., Billesbach, D.P., Burba, G.G., Fischer, M.L., Glenn, A.J., Hanan, N.P., Hatfield, J.L., Heuer, M.W., Hollinger, S.E., Howard, D.M., Matamala, R., Prueger, J.H., Tenuta, M., Young, D.G., 2013. CO_2 uptake and ecophysiological parameters of the grain crops of midcontinent North America: estimates from flux tower measurements. Agric. Ecosyst. Environ. 164, 162–175.

Gomez-Casanovas, N., Anderson-Teixeira, K., Zeri, M., Bernacchi, C.J., DeLucia, E.H., 2013. Gap filling strategies and error in estimating annual soil respiration. Glob. Change Biol. 19, 1941-1952.

Görres, C.-M., Kutzbach, L., Elsgaard, L., 2014. Comparative modeling of annual CO_2 flux of temperate peat soils under permanent grassland management. Agric. Ecosyst. Environ. 186, 64–76.

Hernandez-Ramirez, G., Hatfield, J.L., Parkin, T.B., Sauer, T.J., Prueger, J.H., 2011. Carbon dioxide fluxes in corn-soybean rotation in the midwestern U.S.: inter- and intra-annual variations, and biophysical controls. Agric. For. Meteorol. 151, 1831-1842.

Hoffmann, M., Jurisch, N., Borraz, E.A., Hagemann, U., Drösler, M., Sommer, M., Augustin, J., 2015. Automated modeling of ecosystem CO_2 fluxes based on periodic closed chamber measurements: a standardized conceptual and practical approach. Agric. For. Meteorol. 200, 30-45.

Hollinger, S.E., Bernacchi, C.J., Meyers, T.P., 2005. Carbon budget of mature no-till ecosystem in north central region of the United States. Agric. For. Meteorol. 130, 59-69.

IUSS Working Group WRB, 2015. World reference base for soil resources 2014. International soil classification system for naming soils and creating legends for soil maps. Update 2015. World Soil Resources Reports No. 106. FAO, Rome.

Jans, W.W.P., Jacobs, C.M.J., Kruijt, B., Elbers, J.A., Barendse, S., Moors, E.J., 2010. Carbon exchange of a maize (*Zea mays* L.) crop: influence of phenology. Agric. Ecosyst. Environ. 139, 316-324.

Juszczak, R., Humphreys, E., Acosta, M., Michalak-Galczewska, M., Kayzer, D., Olejnik, J., 2013. Ecosystem respiration in a heterogeneous temperate peatland and its sensitivity to peat temperature and water table depth. Plant Soil 366, 505-520.

Kleber, M., Eusterhues, K., Keiluweit, M., Mikutta, C., Mikutta, R., Nico, P. S., 2015. Chapter one – Mineral-Organic associations: Formation, Properties, and relevance in soil environments. Adv. Agro. 130, 1-140.

Knebl, L., Leithold, G., Brock, C., 2015. Improving minimum detectable differences in the assessment of soil organic matter change in short-term field experiments. J. Plant Nutr. Soil Sci. 178, 35-42.

Koskinen, M., Minkkinen, K., Ojanen, P., Kämäräinen, M., Laurila, T., Lohila, A., 2014. Measurements of CO_2 exchange with an automated chamber system throughout the year: challenges in measuring night-time respiration on porous peat soil. Biogeosciences 11, 347-363.

Kutsch, W.L., Aubinet, M., Buchmann, N., Smith, P., Osborne, B., Eugster, W., Wattenbach, M., Schrumpf, M., Schulze, E.D., Tomelleri, E., Ceschia, E., Bernhofer, C., Béziat, P., Carrara, A., Di Tommasi, P., Grünwald, T., Jones, M., Magliulo, V., Marloie, O., Moureaux, C., Olioso, A., Sanz, M.J., Saunders, M., Søgaard, H., Ziegler, W., 2010. The net biome production of full crop rotations in Europe. Agric. Ecosyst. Environ. 139, 336-345.

Kutzbach, L., Schneider, J., Sachs, T., Giebels, M., Nykänen, H., Shurpali, N.J., Martikainen, P.J., Alm, J., Wilmking, M., 2007. CO_2 flux determination by closed-chamber methods can be seriously biased by inappropriate application of linear regression. Biogeosciences 4, 1005-1025.

Lai, D.Y.F., Roulet, N.T., Humphreys, E.R., Moore, T.R., Dalva, M., 2012. The effect of atmospheric turbulence and chamber deployment period on autochamber CO_2 and CH_4 flux measurements in an ombrotrophic peatland. Biogeosciences 9, 3305-3322.

Lal, R., Griffin, M., Apt, J., Lave, L., Morgan, G., M., 2004. Managing Soil carbon. Science 304, 393.

Langensiepen, M., Kupisch, M., van Wijk, M.T., Ewert, F., 2012. Analyzing transient closed chamber effects on canopy gas exchange for flux calculation timing. Agric. For. Meteorol. 164, 61-70.

Leiber-Sauheitl, K., Fuß, R., Voigt, C., Freibauer, A., 2013. High greenhouse gas fluxes from grassland on histic gleysol along soil C and drainange grasslands. Biogeosci. Discuss. 10, 11283-11317.

Leifeld, J., Ammann, C., Neftel, A., Fuhrer, J., 2011. A comparison of repeated soil inventory and carbon flux budget to detect soil carbon stock changes after conversion from cropland to grasslands. Glob. Change Biol. 17, 3366-3375.

Leifeld, J., Bader, C., Borraz, E., Hoffmann, M., Giebels, M., Sommer, M., Augustin, J., 2014. Are C-loss rates from drained peatlands constant over time? The additive value of soil profile based and flux budget approach. Biogeosci. Discuss. 11, 12341-12373.

Livingston, G.P., Hutchinson, G.L., 1995. Enclosure-based measurement of trace gas exchange: applications and sources of error, in: Matson, P.A., Harris, R.C. (Eds.), Methods in Ecology. Biogenic Trace Gases: Measuring Emissions from Soil and Water. Blackwell Science, Oxford, UK, pp. 14–51.

Lloyd, J., Taylor, J.A., 1994. On the temperature dependence of soil respiration. Funct. Ecol. 8, 315-323.

Luo, Y., Ahlström, A., Allison, S.D., Batjes, N.H., Brovkin, V., Carvalhais, N., Chappell, A., Ciais, P., Davidson, E.A., Finzi, A., Georgiou, K., Guenet, B., Hararuk, O., Harden, J.W., He, Y., Hopkins, F., Jiang, L., Koven, C., Jackson, R.B., Jones, C.D., Lara, M.J., Liang, J., McGuire, A.D., Parton, W., Peng, C., Randerson, J.T., Salazar, A., Sierra, C.A., Smith, M.J., Tian, H., Todd-Brown, K.E.O., Torn, M., van Groenigen, k.J., Wang, Y.P., West, t.o., Wie, Y., Wieder, W.R., Xia, J., Xu, X., Xu, X., Zhou, T., 2016. Toward more realistic projections of soil carbon dynamics by Earth system models. Global Biogeochem. Cycles 30, 40-56.

Moffat, A.M., Papale D., Reichstein M., Hollinger, D.Y., Richardson, A.D., Barr, A.G., Beckstein, C., Braswell, B.H., Churkina, G., Desai, A.R., Falge, E., Gove, J.H., Heimann, M., Hui, D., Jarvis, A.J., Kattge, J., Noormets, A., Stauch, V.J., 2007. Comprehensive comparison of gap-filling techniques for eddy covariance net carbon fluxes. Agric. For. Meteorol. 147, 209–232.

Necpálová, M., Anex Jr., R.P., Kravchenko, A.N., Abendroth, L.J., Del Grosso, S.J., Dick, W.A., Helmers, M.J., Herzmann, D., Lauer, J.G., Nafziger, E.D., Sawyer, J.E., Scharf, P.C., Strock, J.S., Villamil, M.B., 2014. What does it take to detect a change in soil carbon stock? A regional comparison of minimum detectable difference and experiment duration in the north central United States. J. Soils Water Conserv. 69, 517-531.

Paustian, K., Collins, H.P., Paul, E.A., 1997. Management controls on soil carbon, in: Paul, E.A., Paustian, K., Elliott, E.T., Cole, C.V. (Eds.), Soil Organic Matter in Temperate Agroecosystems: Long-Term Experiments in North America. CRC Press, Boca Raton, FL, pp. 15-50.

Poeplau, C., Bolinder, M.A., Kätterer, T., 2016. Towards an unbiased method for quantifying treatment effects on soil carbon in long-term experiments considering initial within-field variation. Geoderma 267, 41-47.

Pohl, M., Hoffmann, M., Hagemann, U., Giebels, M., Albiac Borraz, E., Sommer, M., Augustin, J., 2014. Dynamic C and N stocks–key factors controlling the C gas exchange of maize in a heterogeneous peatland. Biogeosciences 11, 2737-2752.

Reichstein, M., Falge, E., Baldocchi, D., Papale, D., Aubinet, M., Berbiger, P., Bernhofer, C., Buchmann, N., Gilmanov, T., Granier, A., Grünwald, T., Havránková, K., Ilvesniemi, H., Janous, D., Knohl, A., Laurila, T., Lohila, A., Loustau, D., Metteucci, G., Meyers, T., Miglietta, F., Ourcival, J.-M., Pumpanen, J., Rambal, S., Rotenberg, E., Sanz, M., Tenhunen, J., Seufert, G., Vaccari, F., Vesala, T., Yakir, D., Valentini, R., 2005. On the separation of net ecosystem exchange into assimilation and ecosystem respiration: review and improved algorithm. Global Change Biol. 11, 1424–1439.

Rieckh, H., Gerke, H.H., Sommer, M., 2012. Hydraulic properties of characteristic horizons depending on relief position and structure in a hummocky glacial soil landscape. Soil Tillage Res. 125, 123-131.

Saby, N.P.A., Bellamy, P.H., Morvan, X., Arrouays, D., Jones, R.J.A., Verheijen, F.G.A., Kibblewhite, M.G., Verdoodt, A., Üveges, J.B., Freudenschuß, A., Simota, C., 2008. Will European soil-monitoring networks be able to detect changes in topsoil organic carbon content? Glob. Change Biol. 14, 2432-2442.

Sainju, U.M., Singh, B.P., Whitehead, W.F., 2002. Long-term effects of tillage, cover crops, and nitrogen fertilization on organic carbon and nitrogen concentrations in sandy loam soils in Georgia, USA. Soil Tillage Res. 63, 167-179.

Savage, K.E., Davidson, E.A., 2003. A comparison of manual and automated systems for soil CO_2 flux measurements: trade-offs between spatial and temporal resolution. J. Exp. Bot. 54, 891-899.

Schlichting, E., Blume, H.P., Stahr, K., Soils Practical (in German). Blackwell, Berlin, 1995.

Schrumpf, M., Schulze, E. D., Kaiser, K., Schumacher, J., 2011. How accurately can soil organic carbon stocks and stock changes be quantified by soil inventories? Biogeosciences 8, 1193-1212.

Six, J., Conant, R.T., Paul, E.A., Paustian, K., 2002. Stabilization mechanisms of soil organic matter: implications for C-saturation of soils. Plant Soil 241, 155-176.

Skinner, R.H., Dell, C.J., 2015. Comparing pasture C sequestration estimates from eddy covariance and soil cores. Agric. Ecosyst. Eviron. 199, 52-57.

Smith, P., Lanigan, G., Kutsch, W. L., Buchmann, N., Eugster, W., Aubinet, M., Ceschia, E., Béziat, P., Yeluripati, J. B., Osborne, B., Moors, E. J., Brut, A., Wattenbach, M., Saunders, M., Jones, M., 2010. Measurements necessary for assessing the net ecosystem carbon budget of croplands. Agric. Ecosyst. Eviron. 139, 302-315.

Sommer, M., Augustin, J., Kleber, M., 2016. Feedbacks of soil erosion on SOC patterns and carbon dynamics in agricultural landscapes – the CarboZALF experiment. Soil Tillage Res. 156, 182-184.

Stewart, C.E., Paustian, K., Conant, R.T., Plante, A.F., Six, J., 2007. Soil carbon saturation: concept, evidence and evaluation. Biogeochemistry 86, 19-31.

Stockmann, U., Padarian, J., McBratney, A., Minasny, B., de Brogniez, D., Montanarella, L., Hong, Y., S., Rawlins, B.G., Filed, D.J., 2015. Global soil organic carbon assessment. Glob. Food Secur. 6, 9-16.

Van Oost, K., Quine, T.A., Govers, G., De Gryze, S., Six, J., Harden, J.W., Ritchie, J.C., McCarty, G.W., Heckrath, G., Kosmas, C., Giraldez, J.V., da Silva, J.R., Merckx, R., 2007. The impact of agricultural soil erosion on the global carbon cycle. Science 318, 626-629.

Van Wesemael, B., Paustian, K., Andrén, O., Cerri, C.E.P., Dodd, M., Etchevers, J., Goidts, E., Grace, P., Kätterer, T., McConkey, B.G., Ogle, S., Pan, G., Siebner, C., 2011. How can soil monitoring networks be used to improve predictions of organic carbon pool dynamics and CO_2 fluxes in agricultural soils? Plant Soil 338, 247-259.

VandenBygaart, A.J., 2006. Monitoring soil organic carbon stock changes in agricultural landscapes: issues and a proposed approach. Can. J. Soil Sci. 86, 451-463.

VandenBygaart, A.J., Gregorich, E.G., Helgason, B.L., 2015. Cropland C erosion and burial: is buried soil organic matter biodegradable? Geoderma 239-240, 240-249.

Verma, S.B., Dobermann, A., Cassman, K.G., Walters, D.T., Knops, J.M., Arkebauer, T.J., Suyker, A.E., Burba, G.G., Amos, B., Yang, H., Ginting, D., Hubbard, K.G., Gitelson, A.A., Walter-Shea, E.A., 2005. Annual carbon dioxide exchange in irrigated and rainfed maize-based agroecosystems. Agric. For. Meteorol. 131, 77-96.

Wagle, P., Kakani, V.G., Huhnke, R.L., 2015. Net ecosystem carbon dioxide exchange of dedicated bioenergy feedstocks: switchgrass and high biomass sorghum. Agric. For. Meteorol. 207, 107-116.

Wang, K., Liu, C., Zheng, X., Pihlatie, M., Li, B., Haapanala, S., Vesala, T., Liu, H., Wang, Y., Liu, G., Hu, F., 2013. Comparison between eddy covariance and automatic chamber techniques for measuring net ecosystem exchange of carbon dioxide in cotton and wheat fields. Biogeosciences 10, 6865-6877.

Wehrhan, M., Rauneker, P., Sommer, M., 2016. UAV-based estimation of carbon exports from heterogeneous soil landscapes - a case study from the CarboZALF experimental area. Sensors (Basel) 16, 255.

Wuest, S., 2014. Seasonal variation in soil organic carbon. Soil Sci. Soc. Am. J. 78, 1442-1447.

Xiong, X., Grunwald, S., Corstanje, R., Yu, C., Bliznyuk, N., 2016. Scale-dependent variability of soil organic carbon coupled to land use and land cover. Soil Tillage Res. 160, 101-109.

Yin, X., Goudriaan, J., Lantinga, E.A., Vos, J., Spiertz, H.J., 2003. A flexible sigmoid function of determinate growth. Ann. Bot. 91, 361-371.

Yoo, K., Amundson, R., Heimsath, A.M., Dietrich, W.E., 2005. Erosion of upland hillslope soil organic carbon: coupling field measurements with a sediment transport model. Global Biogeochem. Cycles 19, 1-17.

Zan, C.S., Fyles, J.W., Girouard, P., Samson, R.A., 2001. Carbon sequestration in perennial bioenergy, annual corn and uncultivated systems in southern Quebec. Agric. Ecosyst. Environ. 86, 135-144.

Zeide, B., 1993. Analysis of growth equations. For. Sci. 39, 594-616.

List of tables:

Tab. 1.: Chamber-specific annual sums of CO_2 exchange (R_{eco}, GPP, NEE), NPP_{shoot} and ΔSOC (± uncertainty), as well as corresponding environmental variables measured during the study period from 2010 to 2014.

A.1.: Management information regarding the study period from 2010 to 2014. Gray shaded rows indicate coverage by chamber measurements.

List of figures:

Fig. 1.: Schematic representation of the study concept. Black stars represent SOC measured by the soil resampling method. Black circles represent annual SOC derived using the C budget method.

Fig. 2.: Transect of automatic chambers and chamber positions within the depression overlying the Endogleyic Colluvic Regosol (WRB 2015, left). The black arrow shows the position of the datalogger and controlling devices, which were placed within a wooden, weather-sheltered house.

The soil profile is shown on the right. Soil horizon-specific SOC (%) and Nt (%) contents are indicated by solid and dashed vertical white lines, respectively. Spatial differences in ΔSOC and the basic principle of the C budget method are shown as the scheme within the picture.

Fig. 3.: Time series of CO_2 exchange (A-D) for the four chambers of the AC system during the study period from 2010 to 2014. R_{eco} (black), GPP (light gray) and NEE (dark gray) are shown as daily sums (y-axis). NEE_{cum} is presented as a solid line, representing the sum of continuously accumulated daily NEE values (secondary y-axis). The presented values display cumulative NEE following soil manipulation to the end of 2014. Note the different scales of the y-axes. The grey shaded area represents the period prior to soil manipulation. The dashed vertical line indicates the soil manipulation. Dotted lines represent harvest events.

Fig. 4.: Time series of modeled aboveground biomass development (NPP_{shoot}) (A-D) for the four chambers of the AC system during the study period from 2010 to 2014. NPP_{shoot} is shown as cumulative values. The presented values display cumulative NPP_{shoot} following soil manipulation to the end of 2014. The biomass model is based on biomass sampling (2010-2012) and biweekly LAI measurements (2013-2014) during crop growth (grey dots). C removal due to chamber harvests is shown by black dots. The grey shaded area represents the period prior to soil manipulation. The dashed vertical line indicates the soil manipulation. Dotted lines represent harvest events.

Fig. 5.: Temporal and spatial dynamics in cumulative ΔSOC throughout the study period based on (A) the C budget method (measured/modeled; black lines) and (B) the soil resampling method (linear interpolation; gray lines). The grey shaded area represents the period prior to soil manipulation. The dashed vertical line indicates the soil manipulation. Dotted lines represent harvest events. Temporal dynamics revealed by the C budget method allow for the identification

of periods being most important for the development of ΔSOC. Major spatial deviation occurred during the maximum plant growth period (May to September). The proportion (%) of these periods with respect to the standard deviation of estimated annual ΔSOC accounted for up to 79 %.

Fig. 6.: Average annual ΔSOC observed after soil manipulation (April 2011 to December 2014) by soil resampling and the C budget method for (A) the entire measurement site and (B) single chamber positions within the measured transect. ΔSOC represents the change in carbon storage, with positive values indicating C sequestration and negative values indicating C losses. Error bars display estimated uncertainty for the C budget method and the analytical error of ± 5 % for the soil resampling method. A perfomed Wilcoxon rank-sum test showed no significant difference between ΔSOC values obtained by both methodological approaches for all four chambers (p-value=0.25).

A.3.: Time series of recorded environmental conditions throughout the study period from 2010 to 2014. Daily Precipitation and GWL are shown for the upper (solid line) and lower (dashed line) chamber position in the upper panel (A). The lower panel (B) shows the mean daily air temperature. The grey shaded area represents the period prior to soil manipulation. The dashed vertical line indicates the soil manipulation.

Tab.1

Year	Crop rotation	Position	R_{eco}	GPP	NEE	ΔSOC (C budget)	NPP_{shoot} harvested	NPP_{shoot} modeled	NPP_{shoot} N	NPP_{shoot} P	NPP_{shoot} K	SOC to 1 m depth	SOC in Ap horizon	ΔSOC (soil inventory)	Nt to 1 m depth	Nt in Ap horizon	Precip.	GWL
			(g C m^{-2})				(g C m^{-2})		(g m^{-2})			(Kg m^{-2} 1 m^{-1})	(Kg m^{-2} 0.3 m^{-1})	(g C m^{-2})	(Kg m^{-2} 1 m^{-1})	(Kg m^{-2} 0.3 m^{-1})	(mm)	(cm)
2010	**maize**	**A (upper)**	1014 ±9	-1845 ±8	-831^{a} ±12	86 ±66	744	745^{a}±65	28.1	5.0	25.6	11.6	5.1	-	1.3	0.6	516	135
		B (upper middle)	987 ±11	-1970^{a} ±8	-983 ±13	251 ±66	727	732^{a} ±64	24.7	4.1	18.0	9.1	4.2		0.9	0.4		103
		C (lower middle)	1064 ±38	-2000^{a} ±11	-935^{a} ±40	190 ±77	744	745^{a} ±65	25.5	4.2	16.9	9.1	4.2		0.9	0.4		95
		D (lower)	1110 ±21	-1737 ±10	-627^{a} ±23	-118 ±69	744	745^{a} ±65	25.0	4.2	18.2	12.8	5.0		1.3	0.5		69
2011	**maize**	**A (upper)**	891 ±13	-2022 ±18	-1131^{a} ±22	-149 ±103	1238	1280^{a} ±101	29.5	5.4	30.2	10.5	3.5	-	1.1	0.4	618	129
		B (upper middle)	855^{a} ±10	-1894 ±13	-1039^{a} ±16	-169 ±96	1167	1208^{a} ±95	36.4	5.9	32.7	8.7	3.4		0.9	0.4		97
		C (lower middle)	980 ±14	-2062 ±25	-1082 ±28	-79 ±95	1115	1161^{a} ±91	33.7	5.6	32.9	9.0	3.7		0.9	0.4		87
		D (lower)	843^{a} ±31	-1730 ±8	-888 ±32	-59 ±80	900	947^{a} ±73	35.0	5.7	31.8	12.2	4.0		1.3	0.4		61
2012	**winter wheat** **sorghum**	**A (upper)**	1058 ±86	-2659 ±12	-1600 ±87	648 ±104	297*/634	952^{a} ±56	36.3	6.3	42.6	-			-		585	139
		B (upper middle)	1075 ±8	-2591 ±11	-1516 ±13	472 ±65	310*/727	1044^{a} ±64	33.3	5.8	37.5							107
		C (lower middle)	1286 ±8	-2617 ±9	-1331 ±12	346 ±60	310*/665	985^{a} ±59	32.7	5.4	35.5							87
		D (lower)	1044 ±10	-2194 ±9	-1150 ±13	430 ±39	299*/420	720^{a} ±37	33.9	5.8	40.4							61
2013	**alfalfa**	**A (upper)**	1140 ±83	-1583 ±9	-443 ±83	43 ±91	290	$400^{a,b}$ ±37	14.0	1.7	11.6						499	154
		B (upper middle)	1283 ±80	-1819 ±8	-536 ±80	93 ±86	304	443^{b} ±32	14.7	1.8	12.1							122
		C (lower middle)	1438 ±20	-1726 ±7	-288 ±22	-107 ±36	324	395^{a} ±29	15.6	1.9	12.9							94
		D (lower)	1587 ±80	-2036 ±8	-448 ±80	6 ±87	329	442^{b} ±34	15.9	2.0	13.2							68
2014		**A (upper)**	1161 ±15	-1615 ±7	-455^{a} ±16	-126 ±26	605	581^{a} ±20	29.2	3.6	24.2	10.9	3.9	376	1.2	0.5	591	181
		B (upper middle)	1443 ±18	-2063 ±7	-619^{a} ±19	52 ±28	635	567^{a} ±20	30.7	3.8	25.4	8.9	3.5	156	0.9	0.4		149
		C (lower middle)	1683 ±18	-2111 ±6	-428 ±19	-36 ±26	632	535^{a} ±18	30.5	3.8	25.3	9.0	3.7	0	0.9	0.5		121
		D (lower)	1584 ±12	-2113 ±14	-528 ±19	-52 ±28	587	580^{a} ±21	28.3	3.5	23.5	12.5	4.2	276	1.3	0.4		95
annual average (2011-2014)		**A (upper)**	1063 ±49	-1970 ±12	-901 ±52	98 ±43	766	803 ±54	27.3	4.3	27.2	-		94 ±43	-		573	151
		B (upper middle)	1164 ±29	-2092 ±10	-919 ±32	104 ±37	786	815 ±53	28.8	4.3	26.9			39 ±43				119
		C (lower middle)	1347 ±15	-2129 ±12	-779 ±20	10 ±30	762	769 ±49	28.1	4.2	26.7			0 ±46				97
		D (lower)	1265 ±33	-2018 ±10	-739 ±38	67 ±32	634	672 ±41	28.3	4.3	27.2			69 ±47				71
		site	1209 ±32	-2052 ±11	-843 ±36	78 ±18	737	765 ±49	28.1	4.3	27.0			51 ±18				156

[*] NPP_{shoot} is based on biomass samples collected next to each chamber because no chamber harvest was performed for *winter fodder rye* in 2012; superscript letter indicate non-significant differences (Wilcoxon rank sum test; p-value > 0.05) between measured CO_2 fluxes and NPP_{shoot}.

Fig. 1

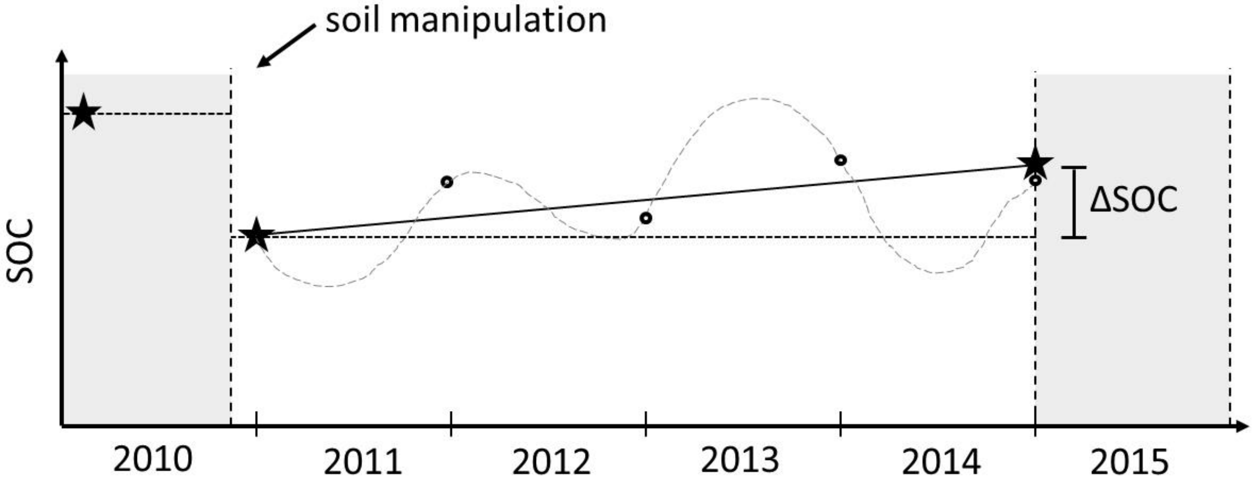
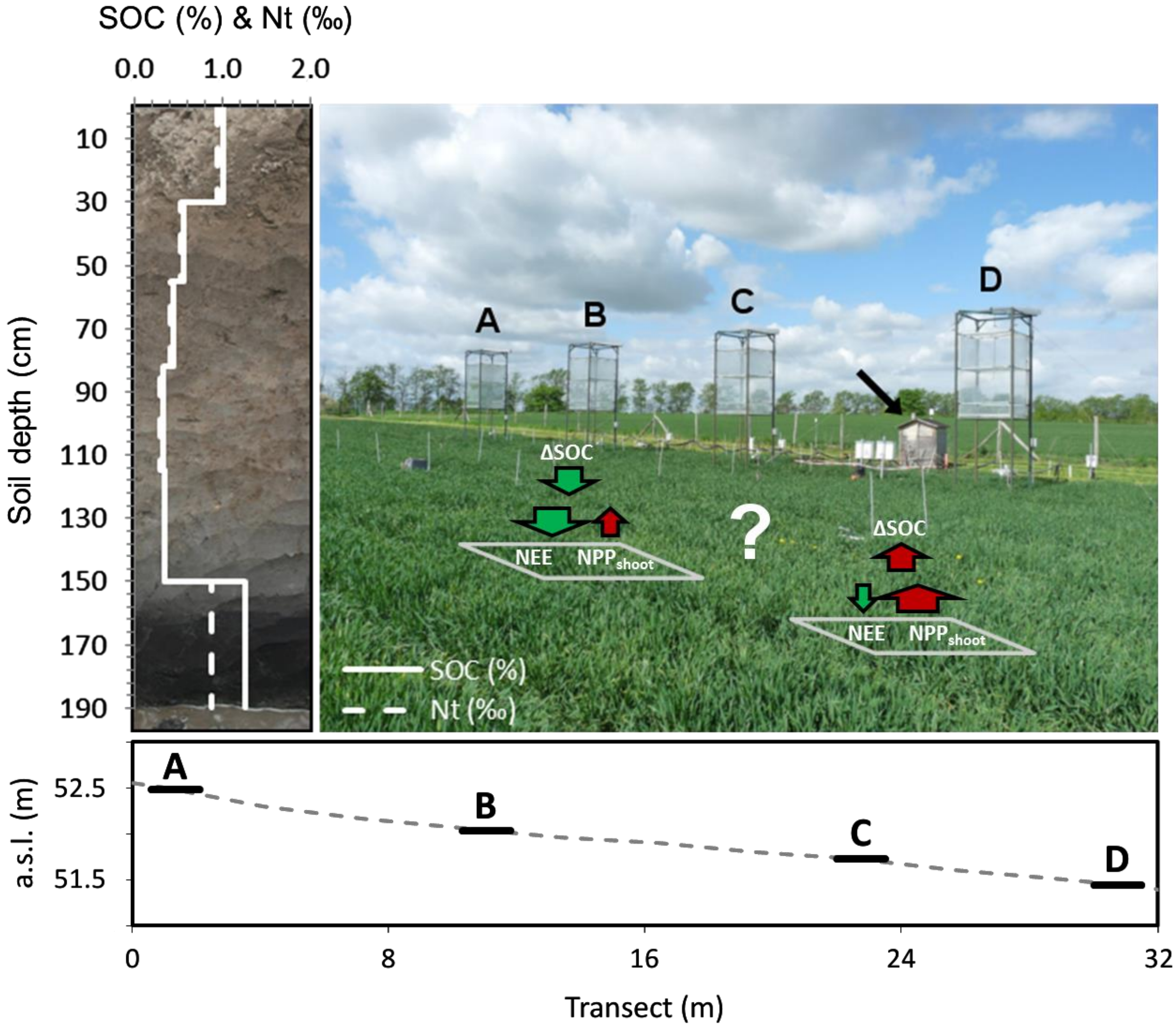


Fig. 2



SOC (%) & Nt (‰)
0.0
1.0
2.0
Soil depth (cm)
10
30
50
70
90
110
130
150
170
190
A
B
C
D
ΔSOC
NEE
NPP$_{shoot}$
?
ΔSOC
NEE
NPP$_{shoot}$
SOC (%)
Nt (‰)
a.s.l. (m)
52.5
51.5
A
B
C
D
0
8
16
24
32
Transect (m)

Fig. 3

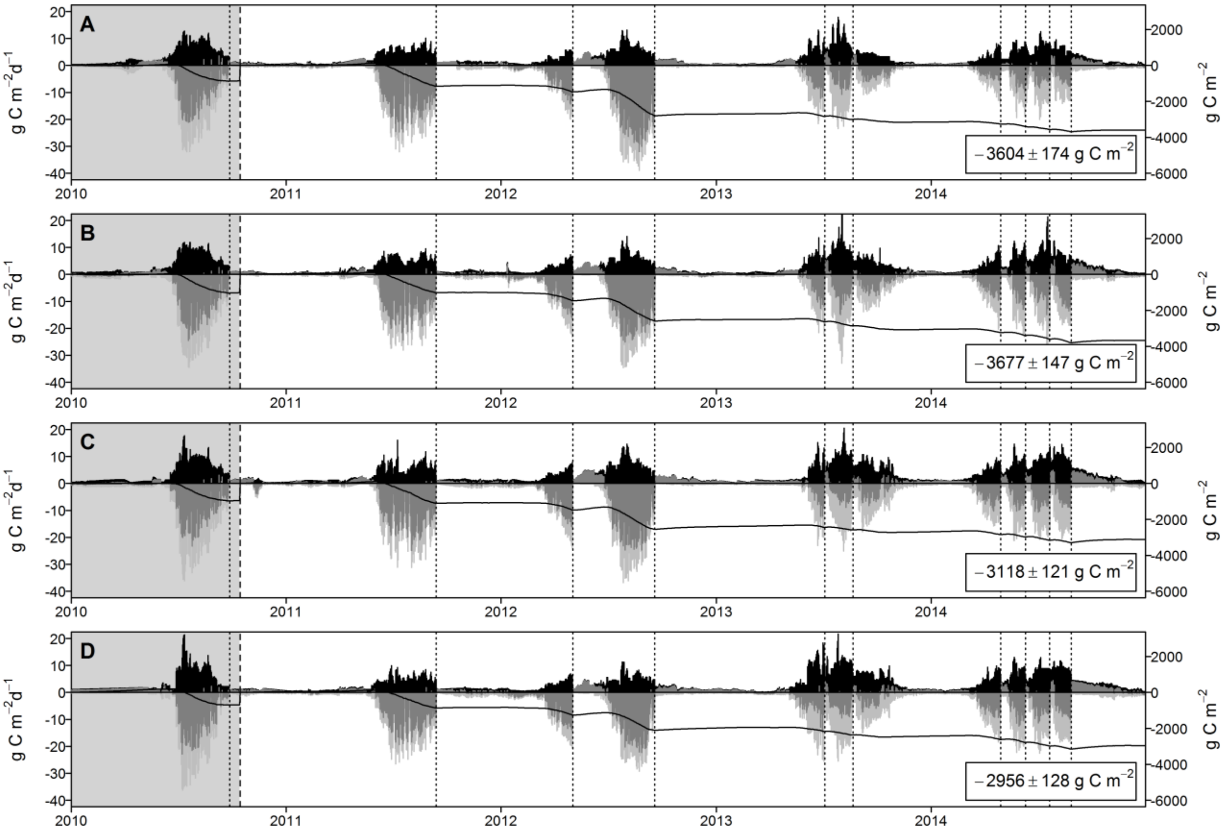

A
B
C
D
g C m^{-2}d^{-1}
g C m^{-2}
20
10
0
-10
-20
-30
-40
2000
0
-2000
-4000
-6000
2010
2011
2012
2013
2014
−3604 ± 174 g C m^{-2}
−3677 ± 147 g C m^{-2}
−3118 ± 121 g C m^{-2}
−2956 ± 128 g C m^{-2}

Fig. 4

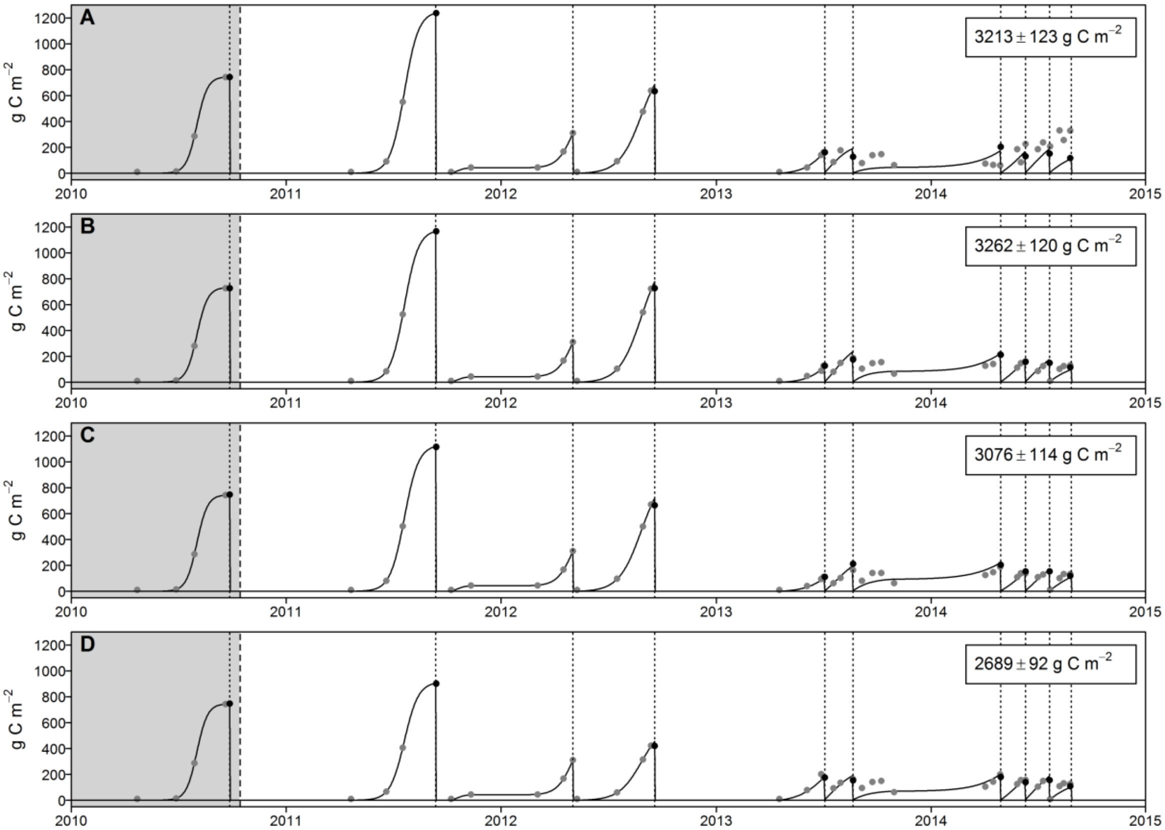

A
B
C
D
g C m^{-2}
0
200
400
600
800
1000
1200
2010
2011
2012
2013
2014
2015
3213 ± 123 g C m^{-2}
3262 ± 120 g C m^{-2}
3076 ± 114 g C m^{-2}
2689 ± 92 g C m^{-2}

Fig. 5

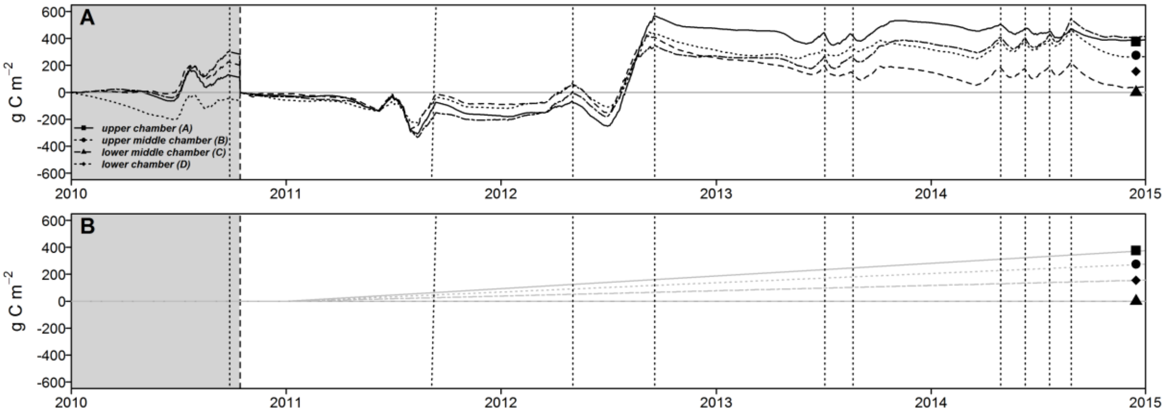
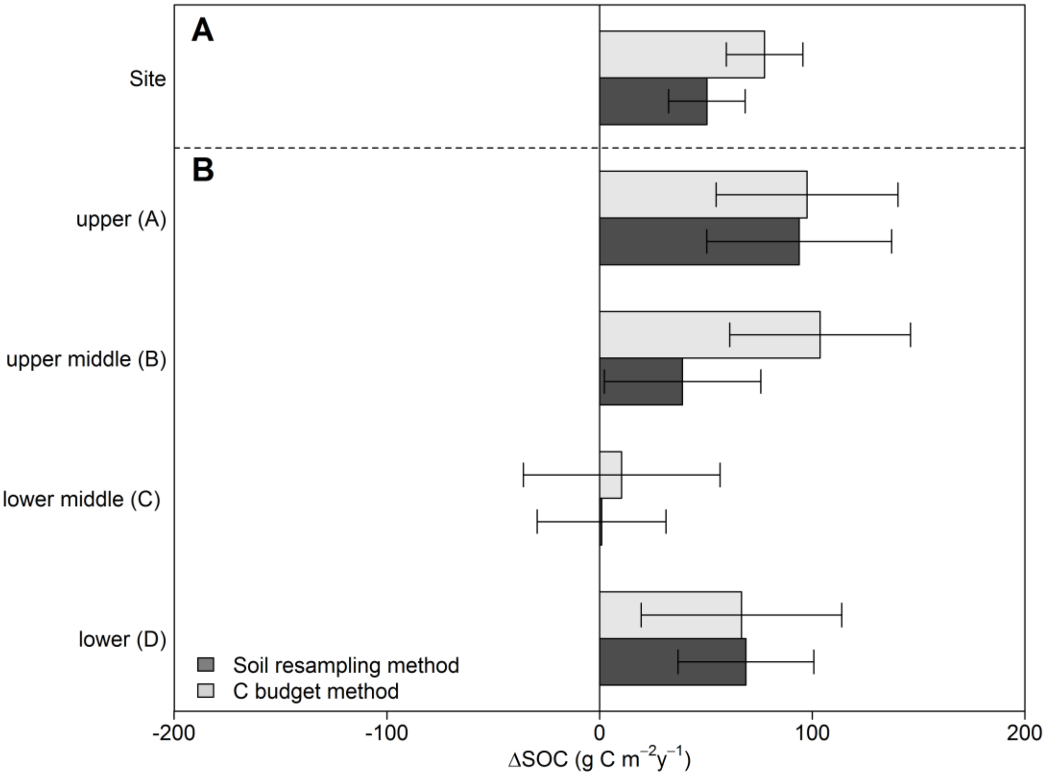

A
B
g C m^{-2}
600
400
200
0
-200
-400
-600
2010
2011
2012
2013
2014
2015
upper chamber (A)
upper middle chamber (B)
lower middle chamber (C)
lower chamber (D)

Fig. 6


A
B
Site
upper (A)
upper middle (B)
lower middle (C)
lower (D)
Soil resampling method
C budget method
-200
-100
0
100
200
ΔSOC (g C m⁻²y⁻¹)

Appendices

A.1

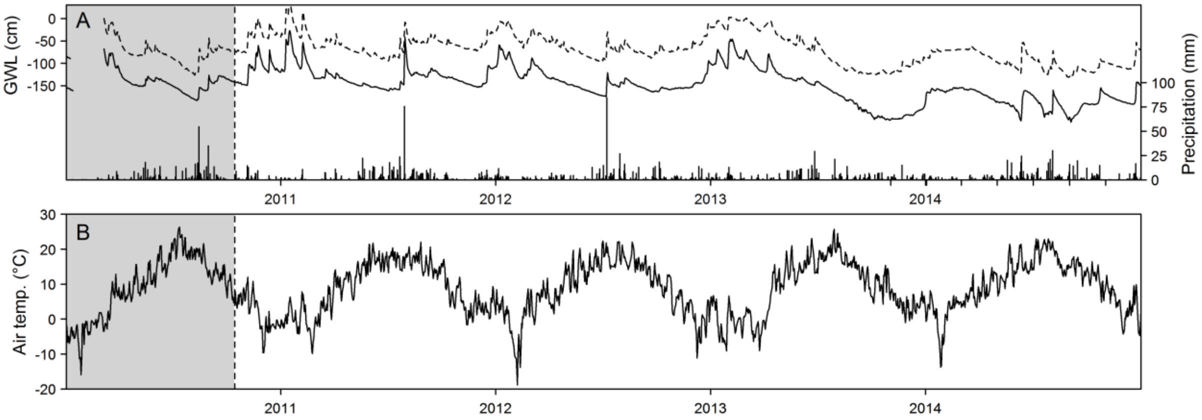
Crop	Treatment	Details	Date
Winter fodder rye (*Secale cereale***)**	Chamber dismounting		10/04/2010
	Herbicide application	Roundup (2 l/ha)	19/04/2010
	Fertilization	KAS (160 kg/ha N), 110 kg/ha P2O5, 190 kg/ha K2O, 22 kg/ha S and 27 kg/ha MgO	23/04/2010
	Ploughing	Chisel Plough	23/04/2010
Silage maize (*Zea mays***)**	Sowing	10 seeds/m^2	23/04/2010
	Chamber installation		04/05/2010
	Herbicide application	Zintan Platin Pack	26/05/2010
	Harvest		19/09/2010
Bare soil	Chamber dismounting		20/09/2010
	Chamber installation		27/10/2010
	Chamber dismounting		05/04/2011
	Fertilization	110 kg/ha P2O5, 190 kg/ha K2O, 22 kg/ha S and 27 kg/ha MgO	06/04/2011
	Ploughing	Chisel Plough	21/04/2011
Silage maize (*Zea mays***)**	Sowing	10 seeds/m^2	21/04/2011
	Herbicide application	Gardo Gold Pack, 3.5 l/ha	27/04/2011
	Fertilization	KAS (160 kg/ha N)	03/05/2011
	Chamber installation		04/05/2011
	Harvest		13/09/2011
Bare soil	Chamber dismounting		13/09/2011
	Ploughing	Chisel Plough	30/09/2011
Winter fodder rye (*Secale cereale***)**	Sowing	270 seeds/m^2	30/09/2011
	Chamber installation		05/10/2011
	Fertilization	KAS (80 kg/ha N)	06/03/2012
	Harvest		02/05/2012
Bare soil	Chamber dismounting		02/05/2012
	Ploughing		08/05/2012
Sorghum-Sudan grass (*Sorghum bicolor* **x** *sudanese***)**	Sowing	30 seeds/m^2	09/05/2012
	Fertilization	KAS (100 kg/ha N), Kieserite (100 kg/ha), 220 kg/ha P2O5, 190 kg/ha K2O	14/05/2012
	Chamber installation		22/05/2012
	Replanting		29/05/2012
	Herbicide application	Gardo Gold Pack (3 l/ha), Buctril (1.5 l/ha)	12/07/2012
	Harvest		18/09/2012
Bare soil	Chamber dismounting		19/09/2012
	Ploughing	Chisel Plough	09/10/2012
Winter triticale (*Triticosecale***)**	Sowing	400 seeds/m^2	09/10/2012
	Chamber installation		19/10/2012
	Chamber dismounting		20/09/2012
	Chamber installation		17/10/2012
Luzerne (*Medicago sativa***)**	Ploughing; fertilization	Chisel Plough; 44 kg/ha K2O, 48.4 kg/ha P40	15/04/2013
	Sowing	22 kg/ha	18/04/2013
	Harvest (first cut)		04/07/2013
	Fertilization	88 kg/ha K2O	10/07/2013
	Harvest (second cut)		21/08/2013
	Fertilization	200 kg/ha K2O, 110 kg/ha P2O5	27/02/2014

	Harvest (first cut)	29/04/2014
	Harvest (second cut)	10/06/2014
	Harvest (third cut)	21/07/2014
	Harvest (fourth cut)	27/08/2014
	Chamber dismounting	28/08/2014

A.2 Weather and soil conditions

A.3 shows the development of important environmental variables throughout the study period (January 2010 – December 2014). In general, weather condition were similarly warm (8.7°C) but also wetter (562 mm) compared to the long-term average (8.6°C; 485 mm). Temperature and precipitation were characterized by distinct inter- and intra-annual variability. The highest annual air temperature was measured in 2014 (9°C). The highest annual precipitation was recorded during 2011 (616 mm). Lower annual mean air temperature and comparatively drier weather conditions were recorded in 2010 (7.7°C; 515 mm) and 2013 (8.5°C; 499 mm). Clear seasonal patterns were observed for air temperature. The daily mean air temperature at a height of 200 cm varied between -18.8°C in February 2012 and 26.3°C in July 2010. Rainfall was highly variable and mainly occurred during the growing season (55 % to 93 %), with pronounced heavy rain events during summer periods, exceeding 50 mm d^{-1}. Despite a rather wet summer, only 67 mm was measured in March and April 2012, the driest spring period within the study, resulting in late germination and reduced plant growth. Annual GWL differed by up to 77 cm along the chamber transect and followed precipitation patterns. Seasonal dynamics were characterized by a lower GWL within the growing season (1.10 m) and enhanced GWL during the non-growing season (0.85 m). From a short-term perspective, GWL was closely related to single rainfall events. Hence, a GWL of 0.10 m was measured immediately after a heavy rainfall event in July 2011, whereas the lowest GWL occurred during the dry spring in 2010. From August 2013 to December 2014, the GWL was too low to apply the principal of hydrostatic equilibrium; therefore, the groundwater table depth (> 235 cm) had to be used as a proxy.

A.


A
GWL (cm)
0
-50
-100
-150
Precipitation (mm)
100
75
50
25
0
2011
2012
2013
2014
B
Air temp. (°C)
30
20
10
0
-10
-20
2011
2012
2013
2014