Soil carbon balance in intensively managed, humid grasslands

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Synopsis

A carbon budget was calculated for humid grassland at the experimental test site Siggen/Neuweiher. Budget parameters were monitored on two slurry amended and two unamended plots. Both treatments have been in progress since 1987.

The budget calculated resulted in annual soil carbon accumulation rates of zero to five percent of the combined carbon stock in roots and humus. These values have to be considered as exaggerated. Uncertainties connected with the input of **root detritus** into the soil and the magnitude of **root respiration** were the main reasons for this.

The carbon budget presented serves (a) as indicator on the magnitude and annual variability of fluxes, aides (b) to determine the relative importance of system components, helps (c) to assess the influence of management and fertilizer treatments and finally (d) points out areas that should receive much more attention in future attempts to calculate carbon budgets (like root turnover).

Grasslands, carbon budget, root respiration, soil respiration

Grünland, Kohlenstoffbilanz, Wurzelatmung, Bodenatmung

1 Introduction

There have been several attempts to determine carbon budgets of grassland ecosystems: (a) carbon was labelled (WAREMBOURG & PAUL 1977) and tracked continuously on its way through the system; (b) the system was encapsulated and total flux measurements (OECHEL & al. 1992) were made or (c) net carbon exchange measured by means of eddy correlation sensors (KIM & al. 1992). All of these procedures require a substantial effort in terms of technology and equipment, while (a) is merely a laboratory procedure, with the use of radioactive carbon in the field presenting acceptance problems; (b) is restricted to systems with low growing vegetation like the arctic tundra and (c) is so costly, that it yielded only 40 days of measurement within two years (KIM & al. 1992).

With the exception of procedure (a), the system is treated by the above methods like a black box, with a possible change in soil carbon content receiving no attention. Therefore, a change in soil carbon content can not be detected with approaches of this nature.

The alternative to this, the direct measurement and monitoring of carbon pools (COLEMAN 1973, SCHLESINGER 1977, TESAROVA 1993) within the ecosystem relies on destructive sampling techniques, i. e. measurements of soil carbon content, primary production, litterfall, fertilizer input, decomposition, root growth etc. To further complicate the matter, accepted and standardized procedures to estimate important fluxes like the input of organic matter to the soil through living roots (sloughed root cells, root hairs, mucilage and root exudates) are not available. So there are severe shortcomings to this way of estimating soil carbon changes as well.

The reason for attempting a carbon balance in spite of the limitations mentioned above was the availabilty of most of the budget parameters (Root production was the major balance component that could not be measured as extensive as necessary (= from the beginning) since the relatively small plots would otherwise have been destroyed) as byproducts of a carbon exchange study (KLEBER *1996*) executed as part of the Sonderforschungsbereich 183 at the University of Hohenheim.

2 Materials and Methods

2.1 Site

All measurements were made at the experimental test site »Siggen-Neuweiher«, located in south-east Baden-Württemberg, 8 km north-east of Wangen (for detailed description of site properties see KLEBER & STAHR 1995). The research site Siggen was set up on the northwestern slope of a terminal moraine of the Würm-glaciation. The site was converted from arable land to grassland in 1964 (SCHUR 1989). In 1987 the test site was incorporated into the activities of the Collaborative Research Center 183 »Sustainable development of agricultural areas« at the Universität Hohenheim. For this reason, a 2.5 hectare portion was divided into three parts. The eastern subdivision was treated with liquid manure applications according to local practice. The intermediate, reduced input treatment, received about 60% of the above amount of fertilizer and the western portion was left without fertilizer at all. All three subdivisions were cut the usual 4 to 5 times a year. No mineral fertilizers were employed since 1987. Cutting and occasional grazing was always done simultaneously on all three divisions of the test site.

Plots of 20 m x 20 m extension were arranged in a catena extending down the slope of the terminal moraine. Four plots were arranged as paired plots at mid- and footslope positions, with one being fertilized (HMV, HFV) and the other situated in the part of the test site, that had not received fertilization (HMN, HFN) since 1987 and continued not to receive fertilizer throughout this study.

Data regarding management treatments were obtained from and are used with permission of the 'Institut für Pflanzenbau und Grünland (340)' at the University of Hohenheim.

2.2 Minor input/output parameters

The fluxes listed below were considered not to contribute substantially to the carbon budget (KLEBER 1997) and therefore omitted from budget calculations.

- Organic and inorganic Carbon input with rain water
- Chemical reaction of CO_2 in the soil
- Heterotrophic and autotrophic CO_2 fixation
- Carbon loss as dissolved organic carbon
- Carbon loss as dissolved inorganic carbon

At Siggen, minor inputs may accumulate to around 10–30 g C m^{-2} a^{-1}, while the loss of dissolved carbon is considered to reach about half that value.

2.3 Essential input/output parameters

Determination of carbon output was based on the general equation suggested by SZANSER (1991), who defined

$$R = R_{root} + R_{mic}$$

where R = total soil respiration, R_{root} = respiration of living roots and R_{mic} = heterotrophic respiration.

Following established practice (TESAROVA 1993) surface litter and root production were considered as input. Heterotrophic respiration, as the difference between total soil respiration and root respiration, was the central output parameter.

Harvest residues and slurry dry matter were considered as equivalent to surface litter input. In order to arrive at reasonable estimates for root production and rhizodeposition, the following steps were taken:

1. Root dry matter increase (RDM) between July and October 1995 was calculated (36 replicate measurements per plot and sampling event, KLEBER 1997)
2. Aboveground dry matter production for the same period was determined
3. Root growth was assumed to be proportional to aboveground dry matter production, the respective ratio was determined for the period July – October 1995.
4. Annual root dry matter production was calculated from annual aboveground production for the years 1993 – 1995, using the above ratio.
5. Finally, rhizodeposition was added, using 20% of annual root production (COLEMAN 1973) as an estimate.

Soil respiration rates can be used to calculate carbon budgets or turnover times of the soil carbon pool, provided an assumption is made regarding the contribution that live root respiration makes to total soil respiration. The remaining respiration is derived from the decomposition of soil organic matter, representing the true turnover of this pool (RAICH & SCHLESINGER 1992). Procedures to determine root respiration in the field were not available, so an indirect approach to estimate root respiration was proposed (KLEBER & al. 1995) and tested. This approach relies on the following assumptions:

- Microbial respiration is associated with nitrogen turnover in the soil, root respiration is not
- Net N-mineralization, then, is a function of microbial respiration (= mineralization of soil organic matter)
- With net N-mineralization known, microbial respiration can be calculated, taking into account the C/N ratio of the respective soil (for any Nitrogen mineralized, the multiple number of C as determined by the C/N ratio has to be mineralized)

Since root respiration was to be determined by subtracting microbial respiration from total soil respiration, it was important to employ a procedure that captures quantitatively all CO_2 that evolves from the soil.

The soda-lime technique for capturing CO_2 released from the soil surface has become popular in recent years, with most researchers following the recommendations of EDWARDS (1982). Details to the procedure as employed at Siggen are given by KLEBER & al. (1994).

3 Results

3.1 Carbon input with fertilizer (liquid manure) applications

Samples of the slurry were analyzed for carbon and nitrogen content in dry matter in 1994. Carbon content was found to be about 43 to 45% of slurry dry matter, and this value consequently used, to calculate Carbon inputs from slurry dry matter (Table 3). C/N ratio was constant at about 19, indicating the slurry dry matter to be slightly higher in nitrogen than ordinary plant litter (WHITEHEAD 1995; cut grass-clover mixture: C/N = 22 – 24).

In 1993, the responsibility for the farm management changed from father to son, resulting in a quite irregular pattern of management operations (Table 1):

3.2 Carbon input through harvest residues

Sampling for dry matter yield was done by cutting ten swards of about 1 m^2 per treatment (Univ. Hohenheim, grassland unit, Department 340; JACOB 1995), thereby determining total aboveground dry matter production per fertilizer treatment. Harvest residues were calculated according to ZIMMER (1987), who found that on average 4% of the dry matter yield are left behind, when grass is harvested for silage. Table 2 indicates total aboveground dry matter production (total), the fraction of dry matter taken away (output) and the fraction left behind as harvest residues (residues). Conversion from dry matter to carbon yield was made by applying the proportion given by RAVEN & al. (1981), who assume the C concentration in healthy plants to be = 44% of dry plant weight.

Table 1
C-input with slurry applications on intensive (= eastern) part of test site (kg ha^-1^).

Tab. 1
Kohlenstoffzufuhr mit der Gülle auf dem betriebsüblich bewirtschafteten, östlichen Teil der Versuchsfläche (kg ha^-1^).

	1993	1994	1995
Mar		1119	
Apr	1428		400
May		780	1143
Jun	383	790	
Jul			246
Aug	158	804	936
Sep		631	
Oct			452
Dec		646	
Σ	**1969**	**4569**	**3197**

3.3 Carbon input through root production

Table 3 gives the total standing crop of belowground organs and their development between July and October 1995. In July, total root dry matter is uniform on all plots. In October, the two upslope plots, HMV and HMN exhibit disproportionate high root dry matter values. The root dry matter increase (RDM) is strikingly similar for the plots on the same slope position, and is therefore obviously not affected by fertilizer treatment. Root dry matter increase (RDM) and, consequently, root/shoot ratios (R/S) as well are higher upslope than at the footslope plots. These findings are consistent with the paradigm of WHITEHEAD (1995, pp. 91), who states that fertilizer N has little effect on the production of grass roots. The different root growth pattern on the different slope positions is to be seen as occasioned by site specific properties (soil type, groundwater level, microclimate) associated with the slope position of the experimental plots.

It is acknowledged, that root/shoot ratio changes through the different stages of plant growth and development, but R/S being a function of site properties, and these being rather stable in contrast to management treatments, it seems justifiable to derive a mean or average R/S for the duration of the complete vegetation period by comparison of total aboveground with total belowground production. Consequently, here the assumption is made, that the amount of root dry matter produced throughout the vegetation period is proportional to the aboveground dry matter production on the respective site. Belowground dry matter production may than be calculated by multiplying aboveground dry matter production with the R/S determined for each individual plot (Table 4).

The results presented in Table 4 have to be considered as very rough estimates. They indicate carbon input through root turnover and rhizodeposition to be higher at the midslope positions by factor 1,5. Annual root turnover (Root dry matter input as fraction of peak root mass, calculated for 1995 and considering October to be the season with the highest root mass; KLAPP 1971) is 51 (HMV) and 49% (HMN) of root dry matter at the midslope plots, while the footslope plots are at 39 (HFV) and 38 (HFN)%. These values are in the range of the ratios given by COLEMAN (1973) for successional grassland (54%) and DAHLMAN & KUCERA (1965) for native prairie (25%). In Siggen, root turnover seems not to be influ-

Table 2

Dry matter (expressed as kg C ha^{-1}) yield at subsequent cuts for intensive and zero fertilizer treatment. Total aboveground dry matter production (total, calculated), the fraction of dry matter taken away (output, measured) and the fraction left behind as harvest residues (residues, calculated).

Tab. 2

Trockenmasseerträge (in kg C ha^{-1}) der jeweiligen Schnitte für betriebsüblich und nullgedüngte Parzelle. Gesamter oberirdische Trockenmasseertrag (total), Anteil des als Silage entnommenen Erntegutes (output) und zurückgelassene Bröckelverluste (residues).

	intensive (kg ha^{-1}) HMV + HFV			zero fertilizer (kg ha^{-1}) HMN + HFN		
Date	total	output	residues	total	output	residues
13.5.93	2210	2120	89	1230	1180	49
30.6.93	1220	1170	49	850	820	34
11.8.93	1010	970	40	880	850	35
14.9.93	730	700	29	510	490	20
∑ 93	**5170**	**4960**	**207**	**3470**	**3340**	**139**
12.5.94	1690	1620	67	1120	1080	45
24.6.94	1640	1570	66	1140	1100	46
04.8.94	1000	960	40	710	680	28
22.9.94	950	910	38	550	520	22
25.10.94	380	360	15	190	180	7
∑ 94	**5660**	**5420**	**226**	**3710**	**3560**	**148**
23.5.95	1780	1710	71	1180	1130	47
08.7.95	1520	1460	61	960	920	38
17.8.95	890	860	36	900	860	36
05.10.95	790	760	31	460	440	18
∑ 95	**4980**	**4790**	**203**	**3500**	**3350**	**140**

Table 3

Total standing crop of belowground organs (kg ha^{-1}) for July and October 1995, root dry matter increase (Δ RDM; kg ha^{-1}), C content (ΔC_{below}; kg ha^{-1}) of newly grown roots, C in aboveground plant material (ΔC_{above}; kg ha^{-1}) produced within same period and root/shoot ratio (R/S) in terms of C.

Tab. 3

Gesamtmenge der unterirdischen Pflanzenteile (kg ha^{-1}) in Juli und Oktober 1995, Zunahme der Wurzelmasse (ΔRDM; kg ha^{-1}), Kohlenstoffgehalt (ΔC_{below}; kg ha^{-1}) der aufgewachsenen Wurzelmasse, Kohlenstoff in der während des gleichen Zeitintervalles aufgewachsenen oberirdischen Phytomasse (ΔC_{above}; kg ha^{-1}) und Wurzel/Sproßverhältnis zwischen diesen (R/S).

	Jul	Oct	Δ RDM	ΔC_{below}*	ΔC_{above}**	R/S
HMV	4170	6110	1960	940	3200	0.294
HMN	4280	6370	2090	1000	2320	0.431
HFV	4050	5350	1300	620	3200	0.194
HFN	3830	5110	1280	610	2320	0.263

* C-content of root dry matter estimated at 48% according to Whitehead (*1995*)

** Values constitute sum of harvest operations 08.07.95; 18.08.95 and 05.10.95 for fertilized and unfertilized treatment, respectively

Table 4

Calculation of carbon input through root production. Carbon in aboveground biomass dry matter is multiplied with the root/shoot ratio to estimate annual turnover (root t/o) of roots. Carbon input through rhizodeposition assumed to be constant at 20% of annual root t/o. All data given in kg C ha^{-1} a^{-1}.

Tab. 4

Berechnung der Kohlenstoffzufuhr durch die Produktion von Wurzeln. Kohlenstoff in der oberirdischen Trockenmasse multipliziert mit dem Wurzel/Sproßverhältnisse, um den jährlichen Wurzelumsatz (root t/o) abzuschätzen. Kohlenstoffzufuhr über Rhizodeposition zu 20% des jährlichen Wurzelumsatzes eingeschätzt. Alle Werte in kg C ha^{-1} a^{-1}.

		above-ground C	Root – Shoot ratio	annual root t/o	Rhizo-deposition	∑ roots + rhizodep.
	HMV	5170	0,294	1520	300	1820
	HMN	3470	0,431	1500	300	1800
93						
	HFV	5170	0,194	1000	200	1200
	HFN	3470	0,263	910	180	1090
	HMV	5660	0,294	1660	330	1990
	HMN	3710	0,431	1600	320	1920
94						
	HFV	5660	0,194	1100	220	1320
	HFN	3710	0,263	970	190	1160
	HMV	4980	0,294	1490	300	1790
	HMN	3500	0,431	1510	300	1810
95						
	HFV	4980	0,194	980	200	1180
	HFN	3500	0,263	920	180	1100

enced by fertilizer practice, as was observed by TESAROVA (1993), who found 47% of dead roots in fertilized treatments and 33% in unfertilized plots.

Several conclusions may be drawn from the findings presented above: To determine root dry matter for budget calculations, it is not satisfactory to just once measure root dry matter, as was done by TESAROVA (1993). Annual root turnover can only be estimated with the required reliability, if the development and growth of the root system is monitored for the seasonal growth as well as decay period. As climate parameters influence not only aboveground but also belowground plant growth, C input through root systems has to be measured parallel to output measurements. The significance of the values presented in Table 7 is severely restricted through the following uncertainties:

1. The root/shoot ratio varies throughout the year. The variability is unknown.

2. No differentiated aboveground yield data were available at Siggen, since harvesting was done uniformly for the contrasting fertilizer treatments and no differences in grass yield with respect to the slope positions of plots were expected at the beginning of the investigation.

3. Rhizodeposition was not measured. The 20% (COLEMAN 1973) estimate is rather arbitrary. No practical field method to determine rhizodeposition is available.

3.4 Carbon output through total soil respiration

The C-flux in soil respiration defines the rate of C-cycling through soils, thereby constraining estimates of above- and belowground detritus production and root respiration rates and enabling the estimation of soil-C turnover rates (RAICH & SCHLESINGER 1992). Mean rates of soil respiration at the test site Siggen are presented in Table 5.

The annual values of total soil respiration are high compared to literature data. RAICH & SCHLESINGER (1992) give a mean rate of soil respiration of 4420 ± 780 kg C ha^{-1} a^{-1} for temperate grassland as a biome, but their data were mainly derived from locations with a continental climate. Other authors found

Table 5
Annual total CO_2-efflux (expressed as kg C ha^{-1} a^{-1}) on separate plots.

Tab. 5
Jährlicher CO_2-efflux von der Bodenoberfläche. (kg C ha^{-1} a^{-1})

	kg C ha^{-1} a^{-1}			
Period	HMV	HMN	HFV	HFN
Jul 93 – Jun 94	11170	11270	11720	11010
Jul 94 – Jun 95	10350	11340	11820	11190
1993	10770	11010	11770	10690
1994	11890	12210	12380	11920
1995	9480	10250	11170	10330

values of 6900 (DÖRR & MÜNNICH 1987); 10400 (KOWALENKO et al. 1978) and 14100 kg C ha^{-1} a^{-1} (YONEDA & OKATA 1987). TESAROVA & GLOSER (1976) observed 6000 and 8300 kg C ha^{-1} a^{-1} in two Czechoslovakian meadows receiving about half the precipitation than the Siggen test site.

3.5 Calculation of carbon budget

In theory it should be possible to balance the level of soil CO_2 release in steady state plant-soil systems with carbon input by litter and the CO_2 produced by root respiration. In practice, it is often difficult to show good correlations between productivity and soil respiration (SCHLESINGER 1977). Table 6 illustrates, that this also applies to the situation at Siggen.

The budget indicates carbon to accumulate at rates between 0 and 5% of the combined stock of roots and humus (Table 7), with the fertilized plots showing rather exaggerated accumulation rates and the unfertilized plots indicating either very low accumulation (HFN) or steady state (HMN). At the fertilized plots, this would mean a doubling of the C-Stock in the soil within 15 to 25 years, which can be ruled out as a serious possibility.

4 Discussion

The shortcomings of the »poor man's approach to a carbon budget« may be characterized as follows: generally, too many budget items are not directly measured. Harvested dry matter and fertilizer input were measured, but only related to the respective treatment, and not on a per plot basis. Calculation of fertilizer input was done by analyzing one slurry sample for its nutrient and dry matter content and multiplying this information with the volume and number of slurry barrels that were put out to the field. Dry matter yield was determined per treatment, and not per plot. While this may be judged as a problem of experimental design, the harvesting of root dry matter on a 20 m x 20 m plot with a frequency of 4 times a year (as seems to be the minimum to get an idea about root dynamics) and 36 replicates does not leave much space of such a plot suitable for respiration measurements. In the study presented here, roots were sampled at the end of the field term, believing the root dry matter to be a rather stable compartment. Unfortunately, it proved to be a very dynamic compartment. The procedure to estimate root respiration (KLEBER & al. 1995) was adversely affected by the excessive length of the incubation periods and to few replicates (n = 4). SPRINGOB & MOHNKE (1995) found 10 replicates necessary to estimate net nitrogen mineralization for a 100 square meter plot.

The main reason for the failure of the budgeting attempt however was the static view of the system, as adopted from several authors (COLEMAN 1973; SCHLESINGER 1977; TESAROVA 1988). Had there been enough awareness for the intensity of carbon turnover on short time scales, the twofold sampling of root dry matter at the end of the field term would not have been considered satisfactory.

5 Summary and Conclusion

Measurements of budget parameters are confounded by numerous difficulties of method. The parameters necessary to calculate the budget undergo large changes in magnitude throughout the year. There has to be long-term monitoring of the site of interest with parameter determinations being done in short time steps to characterize changes, which is complicated further by the fact, that sampling for roots and field incubations are methods destructive in nature and disturb the investigated plot. Finally, it is almost im-

Table 6

Soil carbon balance (kg C ha^{-1} a^{-1}) at Siggen/Neuweiher. F = C-input with fertilization, HR = harvest residues; RT = root detritus and rhizodeposition; tSR = total C-efflux from soil surface; RR = fraction of root respiration; HM = C-output through humus mineralisation (tSR – RR = HM). Balance = F + RT + HR – HM; auxiliary data in italics.

Tab. 6

Kohlenstoffbilanz (kg C ha^{-1} a^{-1}) in Siggen/Neuweiher. F = Kohlenstoffzufuhr durch Düngung, HR = Bröckelverluste; RT = Zufuhr durch tote Wurzeln und Rhizodeposition; tSR = Kohlenstoffefflux von der Bodenoberfläche; RR = Anteil der Wurzelatmung; HM = Kohlenstoffverlust durch Mineralisation von organischer Substanz (tSR – RR = HM). Bilanz somit = F + RT + HR – HM; Hilfsgrößen kursiv.

	Input (kg C ha^{-1} a^{-1})			Output (kg C ha^{-1} a^{-1})				∑
	F	HR	RT	*tSR*	*RR*		HM	kg C
93					*% tSR*	*kg C*		
HMV	1970	210	1820	*10770*	*90,4*	*9730*	1040	+2960
HMN	nil	140	1800	*11010*	*82,2*	*9050*	1960	-20
HFV	1970	210	1200	*11770*	*87,5*	*10340*	1430	+1950
HFN	nil	140	1100	*10690*	*90,4*	*9670*	1020	+220
94								
HMV	4570	230	1990	*11890*	*90,4*	*10740*	1150	+5640
HMN	nil	150	1920	*12210*	*82,2*	*10040*	2170	-100
HFV	4570	230	1320	*12380*	*87,5*	*10830*	1550	+4570
HFN	nil	150	1170	*11920*	*90,4*	*10780*	1140	+180
95								
HMV	3200	200	1790	*9480*	*90,4*	*8560*	920	+4270
HMN	nil	140	1810	*10250*	*82,2*	*8430*	1820	+130
HFV	3200	200	1180	*11170*	*87,5*	*9770*	1400	+3180
HFN	nil	140	1100	*10330*	*90,4*	*9330*	1000	+240

Table 7

Rates of carbon accumulation (kg C ha^{-1}) for calculated budget; root C = October values from Table 5.

Tab. 7

Kohlenstoffakkumulationsraten (kg C ha^{-1}) berechnet anhand der aufgestellten Kohlenstoffbilanz, root C = Oktoberwerte aus Tabelle 5.

	Carbon budget (kg C ha^{-1})		C-stock in roots and soil (kg C ha^{-1})			annual rate
	∑ 93–95	annual rate	Soil C 0–30	Root C 0–30	total 0–30	in % of total
HMV	12870	4290	79500	2930	82430	+5,2
HMN	10	0	116400	3060	119460	±0,0
HFV	9650	3220	97150	2570	99720	+3,2
HFN	640	210	67100	2450	69550	+0,3

possible to avoid the use of parameter estimates (see previous chapter) with uncertain precision.

The solution to this seemed to be some kind of »poor man's approach« to balance carbon fluxes at Siggen/Neuweiher: It was thought that the most important item (soil respiration) of the budget should be measured as accurately as possible, and most of the other parameters could be adopted from routine measurements concerning plant growth, which were conducted by a partner institute (Institut für Pflanzenbau und Grünland 340) sharing the test site. The relative importance of these »byproducts« was not judged properly at that time. Mainly the importance of the underground plant organs as a carbon source for the soil (rhizodeposition and root detritus) was overlooked.

Root production and carbon input as slurry dry matter were identified as major input parameters, while soil respiration was considered to constitute the dominant output pathway. Unfortunately, the respiration of living roots makes it difficult to use measurements of soil-CO_2 flux in budget calculations. The determination and subtraction of root respiration from soil-CO_2 efflux is a prerequisite to the calculation of a soil carbon balance.

The contribution of root respiration to total soil respiration as estimated by this procedure was in the range of 80 – 90% of total soil respiration, which is consistent with some recent findings (SWINNEN 1994). For several reasons, however, root respiration was overestimated by this procedure:

1. the soil C/N ratios of between 9 and 12 used to calculate root respiration do not reflect the C/N ratio of the actually decomposed material. As incubation experiments revealed, about 90 % of the stabilized soil organic matter do not take part in decomposition processes. For this reason, the C/N ratio of the actually decomposed material (mainly dead roots with a C/N between 23 and 42) needs to be determined (by means of an incubation experiment with simultaneous determination of carbon and nitrogen mineralization) and employed in calculations of root respiration
2. only rooting depth (30 cm) was considered. This seems to be justifiable in grassland, but neglects profile compartments of unknown importance
3. incubation periods were rather long, Nitrogen may have gone through several turnover processes during that time, yielding CO_2 on every one of these occasions
4. number of replicates (n = 4) in determinations of net Nitrogen mineralization was insufficient due to high variability
5. since only rough annual estimates of denitrification were available, these data were not incorporated in calculations.

What benefit might then be drawn from budgets, that do not balance? WOODMANSEE & al. (1981) found an answer to that:

»Given the uncertainty of various measurements and temporal variability, of what value is a budget, especially since we know that budgets rarely balance? The answer is that developing a budget is a necessary and sometimes even an interesting method of organizing information about a given site: First, we must state and examine critical assumptions. Then, we can evaluate the relative importance of processes and guardedly estimate the magnitude of transfers, an essential first step in understanding ecosystems. Finally, knowing the probable level of additions and losses and something of their variability and knowing something of how system processes operate, we can make judgments about how such systems function.«

6 References

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