10-2011

Soil Organic Carbon Maintenance Requirements and Mineralizatyion Rate Constants: Site Specific Calculations

David Clay
South Dakota State University, david.clay@sdstate.edu

Gregg Carlson
South Dakota State University, Gregg.Carlson@sdstate.edu

Sharon Clay
South Dakota State University, sharon.clay@sdstate.edu

Recommended Citation

Clay, David; Carlson, Gregg; and Clay, Sharon, "Soil Organic Carbon Maintenance Requirements and Mineralizatyion Rate Constants: Site Specific Calculations" (2011). *Agronomy, Horticulture and Plant Science Faculty Publications*. 39.
https://openprairie.sdstate.edu/plant_faculty_pubs/39

SOIL ORGANIC CARBON MAINTENANCE REQUIREMNETS AND MINERALIZATYION RATE CONSTANTS: SITE SPECIFIC CALCUATIONS

David Clay, Gregg Carlson, and Sharon Clay

Plant Science Department
South Dakota State University
Brookings, SD 57007

ABSTRACT

Over the past 100 years numerous studies have been conducted with the goal of quantifying the impact of management on carbon turnover. It is difficult to conduct a mechanistic evaluation of these studies because each study was conducted under unique soil, climatic, and management conditions. Techniques for directly comparing data from unique studies are needed. This paper: 1) demonstrates an approach for calculating SOC maintenance requirements and mineralization rate constants at different landscape positions; and 2) discusses techniques for conducting site-specific experiments and determining site-specific C sequestration potentials.

INTRODUCTION

The carbon cycle is driven by photosynthesis that produces organic biomass that is respired by microorganisms. Only a portion of the non-harvested carbon (NHC) that is returned to soil ends up in soil organic carbon and only a portion of the SOC end up as CO_2 (Fig. 1). The rates that non-harvested biomass is converted from fresh biomass to SOC and SOC is converted to CO_2 are functions of many factors including, management, climate, and biomass composition. The first order rate mineralization constants for nonharvested carbon (k_{NHC}) and SOC (k_{SOC}) can be used calculate mineralization rates (Clay et al., 2006). An approach for calculating the mineralization rates in historic studies is presented below.

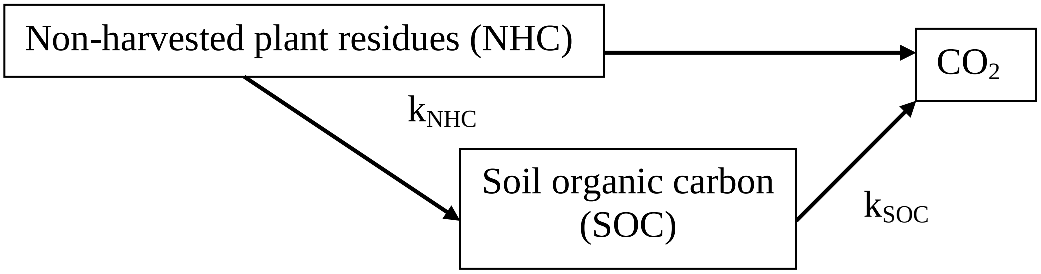

Figure 1. A relational diagram showing the relationship between three carbon pools and the associated rate constants.

Based on the carbon flow diagram shown in Figure 1, two equations can be defined. The first equation is,

$$\frac{dSOC}{dt} = k_{NHC}\left[NHC_a - NHC_m\right]$$

This equation states that the temporal change in SOC ($dSOC/dt$) is equal to the non-harvested carbon mineralization rate constant (k_{NHC}) times the difference between the amounts of carbon added to the soil (NHC_a) and the maintenance requirement (NHC_m). The second equation is,

$$k_{SOC} \bullet SOC_e = k_{NHC} \bullet NHC_m$$

This equation states that at the SOC equilibrium point (SOC_e), the rate that non-harvested C (NHC) is converted into SOC ($k_{NHC} \bullet NHC_m$) is equal to the rate that SOC is mineralized into CO_2 ($k_{SOC} \bullet SOC_e$). These two equations were combined to produce the equation,

$$\frac{NHC_a}{SOC_e} = \frac{k_{SOC}}{k_{NHC}} + \frac{dSOC}{dt}\left[\frac{1}{k_{NHC} \bullet SOC_e}\right]$$

This equation was solved by defining either SOC_i (initial SOC) or SOC_{final} as SOC_e, NHC_a/SOC_e as y, and $dSOC/dt$ as x. After these substitutions, the equation

$$\frac{NHC_a}{SOC_{time0}} = \frac{k_{SOC}}{k_{NHC}} + \left[\frac{dSOC}{dt} \bullet \frac{1}{k_{NHC} \bullet SOC_e}\right]$$

was derived. When fit to a zero order equation, the y-intercept and slopes are $\frac{k_{SOC}}{k_{NHC}}$ and $\frac{1}{k_{NHC} \bullet SOC_e}$, respectively (Fig. 2). After determining the slope (m) and y-intercept (b) the SOC maintenance (NHC_m) and rate constants can be calculated with the equations,

$$NHC_m = b \bullet SOC_e$$
$$k_{NHC} = 1/(m \bullet SOC_e)$$
$$k_{SOC} = b/(m \bullet SOC_e)$$

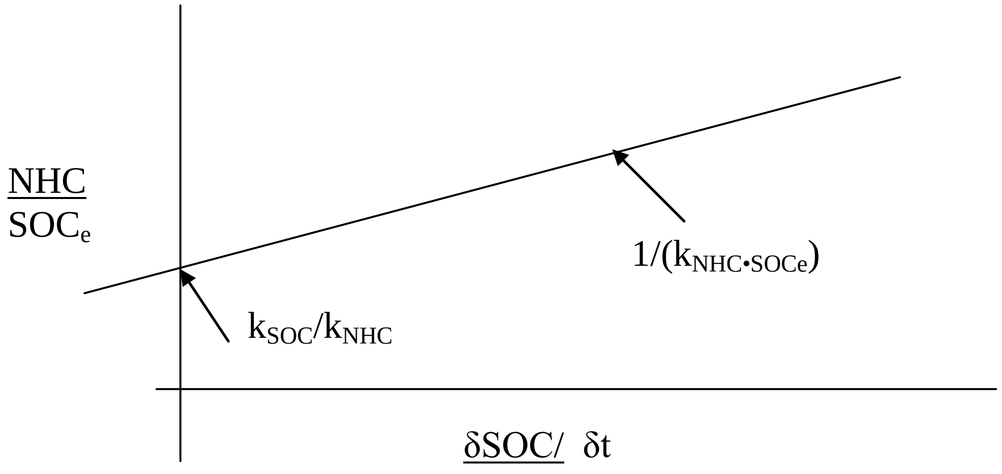

Figure 2. A graphical representation of the maintenance calculations.(Clay et al.,2006).

This approach assumed that above and below ground biomass make equal contributions to SOC; that the amount of below ground biomass is known; and NHC is known and that initial (SOC_e) and final (SOC_{final}) SOC values are near the equilibrium point. Advantages with this approach are that k_{SOC} and k_{NHC} are calculated directly from the data and the assumptions needed for these calculations can be tested. A disadvantage with this solution is that surface and subsurface NHC are combined, and therefore $k_{NHC\ Below}$ and $k_{NHC\ Surface}$ can not be calculated directly. Combining, $k_{NHC\ Below}$ and $k_{NHC\ Surface}$ into a single rate constant (k_{NHC}) may contain errors (Barber and Martin, 1976; Gale and Cambardella, 2000), resulting from surface and below ground biomass having different mineralization rate constants. If an experiment contains a no-plant control area it may be possible to separate these value (Barber, 1979).

The Clay et al. (2006) approach requires an accurate measure of above and below ground C inputs (Ortega et al., 2002; Prakash et al., 2002). Obtaining dependable values for above ground biomass is relatively easy and typically accomplished by weighing above ground biomass or estimating the value using the harvest index. However, obtaining accurate measurements of below ground biomass is very difficult (Kuzyakoz and Domanski, 2000; Kuzyakov, 2001; Amos and Walters, 2006). In the past, nearly all attempts have underestimated this value. For mass balance purposes, below ground values should include all plant parts not included in above ground measurements. Root-to-shoot ratios and/or simulation models are the most common approaches for estimating below ground biomass (Kuzyakov and Domanski, 2000; Johnson et al., 2006; Bolinder et al., 2007). The approach for calculating rate constants and turnover kinetics is demonstrated below using a historical data set (Larson et al., 1972).

MATERIALS AND METHODS

Creating data bases

The data set used in these calculations was obtained from Larson et al. (1972). This study was conducted in Clarinda Iowa. Soil at the site was a fine, silty, mixed, mesic, Typic Hapludoll. The soil was plowed, disked, and cultivated several times. Yield data for this experiment are available in Morachan et al. (1972). Below ground biomass was estimated using root-to-shoot values. For these calculations above ground biomass must be added (grain, cob, and stover). For this calculation, grain weights must be converted to dry weight. Data shown in Table 1 can be used to convert yield data from one moisture percentage to another. For these calculations dry weight values should be used. The process for developing the data base is discussed below.

	Grain Moisture (%)					
Commodity	20%	18%	15.50%	13%	10%	0%
	----------Weight (lbs/Bu.)----------					
Corn	59.15	57.71	56	54.39	52.58	47.32
Soybeans	65.25	63.65	61.78	60	58.0	52.2
Wheat	64.88	63.29	61.42	60	57.67	51.9

Table 1. Corn, soybean, and wheat weights are various moisture contents. Corn is typically reported at 15.5 % moisture, while soybean and wheat are reported at 13% moisture.

Step 1. Calculate the average grain dry yields from 1953 to 1964. This can be done in Microsoft excel by using =average(C4:M4). In this example, the average yields from 1955 to 1964 range from 5385 to 5517 kg grain/ha. Dry grain weights can be converted to bu/acre by converting to lbs/ac and then dividing by 47.32 (Column O, Table 2).

a. Grain yields are often reported on a wet-weight basis. The equation for percent moisture is, 100*(wet grain – dry grain)/(wet grain). Weights for grains at different moisture percentages are shown in Table 1. The amount of dry grain contained in a bushel of corn at 15.5% moisture is determined by substituting 0.155 for moisture percentage and 56 pounds for wet grain weight and then solving for dry grain. The resulting equation is, dry grain = 0.855*56 lbs/bu.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	Residue	NHC						Year						Ave.	Dry	Est.
2	Type	Added	54	55	56	57	58	59	60	61	62	63	64	Grain (15.5%	Grain (0%)	Stover
3		Mg/ha						Mg/ha								
4	CK	none	0	5.09	5.09	5.09	5.09	5.09	5.09	6.60	6.82	7.52	6.35	5.26	4.44	4.44
5	Alfalfa	2	0	5.28	5.28	5.28	5.28	5.28	5.28	7.06	7.52	7.89	6.31	5.50	4.67	4.67
6	Alfalfa	4	0	5.22	5.22	5.22	5.22	5.22	5.22	7.56	7.49	7.52	6.78	5.52	4.66	4.66
7	Alfalfa	8	0	5.36	5.32	5.32	5.32	5.32	5.32	7.03	7.53	7.60	6.25	5.48	4.63	4.63
8	Alfalfa	16	0	5.22	5.22	5.22	5.22	5.22	5.22	7.55	7.19	7.51	6.03	5.41	4.58	4.58
9	Corn	2	0	5.37	5.37	5.37	5.37	5.37	5.37	6.92	7.00	7.62	6.22	5.45	4.61	4.61
10	Corn	4	0	5.28	5.28	5.28	5.28	5.28	5.28	6.97	7.09	7.48	5.79	5.36	4.53	4.53
11	Corn	8	0	5.32	5.32	5.32	5.32	5.32	5.32	7.05	7.38	7.40	5.71	5.41	4.57	4.57
12	Corn	16	0	5.42	5.42	5.42	5.42	5.42	5.42	7.45	6.71	7.12	5.44	5.38	4.55	4.55

	A	B	C	D	E	F	G	H
1	Residue	Amount residue	Total root +	Total	50% roots	Biomass	Biomass	Total
2	type	Mg/a	Ex biomass	Root + ex-C	0-15 cm	total	carbon	NHC
3					kg root-C/ha	kg BS/ha	kg BS-C/ha	kg C/ha
4	CK	none	4886	2101	1050	0	0	1050
5	Alfalfa	2	5110	2197	1098	2000	860	1958
6	Alfalfa	4	5128	2205	1103	4000	1720	2823
7	Alfalfa	8	5096	2191	1096	8000	3440	4536
8	Alfalfa	16	5033	2164	1082	16000	6880	7962
9	Corn	2	5070	2180	1090	2000	860	1950
10	Corn	4	4988	2145	1073	4000	1720	2793
11	Corn	8	5024	2160	1080	8000	3440	4520
12	Corn	16	5006	2153	1077	16000	6880	7957
	Equations incolumns			=C*0.43	=D/2		=F*0.43	=G+E
				Assumes 43% carbon in the samples	Assumes roots are 50% of above ground biomass	Treatments added to the soils	Assumes 43% carbon in the samples	Total C = roots + treatment

Table 2. Yield data associated with the Larson et al.(1972) and Morachan et al (1972) experiment.

Table 3. Amounts of calculated root and residue carbon added to each plot in Larson et al. (1972). In these calculations the root+exudate/shoot ratio was 0.55 and carbon content was 43%.

Step 2. Estimate above ground non-harvested carbon, this can be estimated by assuming there is a 50% harvest index (grain/grain + stover).

Step 3. Calculate below ground biomass (roots + exudates) (Column C, Table 3). In this example, it was estimated that the root + exudates-to-shoot ratio [k_{rec} = (roots+exudates)/(grain + stover)] was 0.55 (Johnson et al., 2006). In this calculation, roots consist of all above and below ground plant parts that are not included in the measured above ground portions. This may include the small amount of stalk above the soil surface. Johnson et al. (2006) used k_{rec} values of 0.82, 0.55, and 0.62 for wheat, corn, and soybean, respectively. Total root biomass (Column C, Table 3) was converted to root-C (Column D, Table 3) by assuming that roots contained 43% carbon.

Step 4. Calculate *d*SOC/*d*t (surface 15 cm) and NHC/SOC and organize into a data base (Table 4). For these calculations, subtract SOC final from SOC initial and divide the difference by 11 years. NHC/SOC is determined by dividing the NHC values (Column D, Table 4) by SOC (Column B, Table 4). Note, SOC and NHC must have identical units.

Table 12.4. The NHC and NHC/SOC values in Larson et al. (1972).

	A	B	C	D	E
1	SOC final	kgC/ha(i)	*d*SOC/*d*t	NHC	NHC/SOC
2	kg/ha		Kg/(ha·year)	Kg/ha	
3	23,700	26,750	-277.4	1050	0.0392
4	24,820	26,750	-175.4	1958	0.0732
5	25,580	26,750	-106.6	2823	0.1055
6	28,080	26,750	112.6	4536	0.1696
7	33,350	26,750	599.5	7962	0.2976
8	24,080	26,750	-242.5	1950	0.0729
9	26,020	26,750	-66.5	2793	0.1032
10	27,340	26,750	53.7	4520	0.1690
11	33,400	26,750	598.9	7957	0.2975
Equation in columns			= (col A - col B)/11		= col D/ col B

Calculating mineralization rate constants

Once the data sets are organized, it can be used to calculate the rate constants. These steps are stated in steps 5 and 6 below.

Step 5. Determine the regression equation between NHC/SOC (y) and *d*SOC/*d*t (Table 5).

a. In Microsoft Excel, select tool, data analysis, and regression; Insert the cell ranges for X (*d*soc/*d*t) and Y(NHC/SOC) and select OK. The results of this analysis are shown in Table 5. The resulting equation is NHC/SOC = 0.131 + 0.000284 (*d*SOC/*d*t). The values for this equation are in B17 and B18. The adjusted r^2 for this equation is 0.984 (cell B6).

Table 12.5. Regression analysis of NHC/SOC (y) and *d*soc/*d*t (x).

	A	B	C	D	E	F	G	H	I
1	Summary								
2									
3	*Regression Statistics*								
4	Multiple R	0.993007							
5	R Square	0.986064							
6	Adjusted R Square	0.984073							
7	Standard Error	0.012016							
8	Observations	9							
9									
10	ANOVA								
11		*df*	*SS*	*MS*	*F*	*Significance F*			
12	Regression	1	0.071511	0.071511	495.2906	9.35E-08			
13	Residual	7	0.001011	0.000144					
14	Total	8	0.072522						
15									
16		*Coefficients*	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
17	Intercept	0.131635	0.004068	32.35534	6.97E-09	0.122015	0.141255	0.122015	0.141255
18	X Variable 1	0.000284	1.27E-05	22.25513	9.35E-08	0.000253	0.000314	0.000253	0.000314

Step 6. Calculate SOC maintenance requirement and the mineralization rate constants.

a. The maintenance requirement is the y-intercept times SOC,
   $\text{SOC}_{\text{main}} = 0.131 \cdot 26{,}750 = 3{,}504$ kg C (ha year)$^{-1}$.
b. In this analysis, approximately 1,000 kg ha-C ha^{-1} are provided by the roots, resulting in an above ground requirement of 2,500 kg surface residue carbon/year. This carbon can be provided by returning crop residues or applying manure.
c. Calculate K_{soc} and K_{NHC} values

$$k_{\text{NHC}} = \frac{1}{\text{slope}\times \text{SOC}_e} = \frac{1}{0.000284\times 26750} = 0.132 \text{ g NHC } (\text{g}\times\text{NHC}\times\text{year})^{-1}$$

$$k_{\text{SOC}} = \frac{\text{intercept}}{\text{slope}\times \text{SOC}_e} \frac{0.131}{= 0.000284\times 26750} = 0.0173 \text{ g SOC } (\text{g}\times\text{SOC}\times\text{year})^{-1}$$

RESULTS AND DISCUSSION

Using the rate constants: site specific turnover

The calculation approach described above relies on two types of measurements, temporal changes in soil organic carbon and the amount of NHC returned to soil. In whole field experiments, this information can be obtained from strip experiments containing two treatments, crop residue removed and crop residue returned. In these experiments, the amount of crop residues returned (NHC) can be measured or estimated from the yield monitor data (using a harvest index and residue removal rate). By combining temporal changes in soil organic carbon with annual NHC additions the rate constants can be calculated using the approaches described above. These calculations assume that the current SOC level is near the equilibrium value (SOC_e). Once the rate constants are calculated, the impact of different residue management approaches on SOC levels can be determined. If the rate constants are known they can be used for a variety of purposes. For example, if the rate constants and NHC are known, then the resulting SOC value resulting from these values can be calculated. These calculations use the equation, $k_{SOC} \bullet SOC_e = k_{NHC} \bullet NHC_m$, which is rearranged to $SOC_e = k_{NHC} \bullet NHC_m / k_{SOC}$. changes in SOC based on NHC values can be estimated. In an example, based on NHC, k_{SOC}, and k_{NHC} values of 4,000 kg C/ha and is 0.0173 g-C (g-C • year)$^{-1}$ and 0.132 g-C (g-C• year)$^{-1}$, respectively SOC at equilibrium should be 30,520 kg C/ha [(0.132 • 4,000)/0.0173=30,520 kg C/ha].

If the rate constants are not known, then they must be measured or estimated using several approaches. The first approach described above requires at least two treatments where different amounts of NHC are returned to the soil. In whole field experiments, three NHC rates can be implemented (residue removed, residue returned, and residue returned plus residue from the harvested site) by removing the non-harvested C from one strip and adding this carbon to a second strip. Two rates can be implemented by removing the carbon from one strip. At differentially corrected global positioning system (DGPS) identified sampling points, NHC, soil organic carbon and bulk density must be measured at adjacent points in the different treatments. For NHC it must be measured or estimated from the annual yield monitor data, while for SOC it must be measured at the beginning and end of the experiment. Soil depths often measured are the 0-15 and 0-30 cm soil zones. Protocols for collecting soil samples are to composite at least 10 individual cores from each depth interval. The same relative amount of soil must be sampled at each date. Large changes in bulk density can confound calculations.

Care must be used when collecting and processing these samples. Removal of biomass or roots from the sample can bias results. In our laboratory, samples are ground and sieved. The portion of the sample that does not pass the sieve is ground with a mortar and pestle. Soil samples should be analyzed for organic carbon using the appropriate technology. Wet oxidation or combustion in an oven may not provide accurate values. At many sites, 4 to 5 years may be required to produce measureable changes in soil carbon. NHC can either be estimated from the yield monitor data or measured. Once the $d\mathrm{SOC}/dt$ and NHC values are known, the rate constants can be calculated (see above).

In the second approach, several assumptions are made. First, SOC is near the equilibrium level. Second, NHC can be estimated from measured yield values. Third, k_{NHC} and k_{SOC} are identical at the sampling points. In this calculation, NHC and SOC are measured at two locations. These values are then substituted into the equation, $k_{SOC} \bullet SOC_e = k_{NHC} \bullet NHC_m$, resulting in two equations,

$k_{SOC} \bullet SOC_{e,1} = k_{NHC} \bullet NHC_{m,1}$
$k_{SOC} \bullet SOC_{e,2} = k_{NHC} \bullet NHC_{m,2}$

which can be combined to produce the equation, $k_{SOC} \times SOC_{e,1} = \left[\frac{(k_{nhc} \times NHC_{m,2})}{SOC_{e,2}}\right] \times NHC_{m,1}$. In this equation, all the values except k_{soc} are measured or estimated. Once k_{SOC} is calculated, it can be substituted back into the equation to calculate k_{NHC}.

In summary this paper demonstrates an approach that can be used to calculate mineralization rate constants for SOC at different landscape positions. The approach is only as accurate as the information used to derive the models. For accurate SOC turnover prediction, accurate measures of SOC and NHC are required. Once the rate constants are known, they can be used within a GIS program to calculate the impact of different management scenarios (within a tillage system).

When evaluating carbon turnover data it is important to consider that the findings are only as good as the data. Good soil sampling procedures must be followed. In carbon experiments, accurate information from the beginning and end of the experiment are needed. Details about the efficiency of carbon analysis approach are required. Wet oxidation procedures are often not 100% effective. Sieving, grinding, and the removal of plant parts from the ground soil samples may bias results.

ACKOWLEDGMENT

Support for this chapter was provided by NC SARE, USDA-CSREES, USDA-NRCS, SD Corn Utilization Council, SD Wheat Commission, and SD Soybean Research and Promotion Council.

REFERENCES

Amos, B., and D.T. Walters, 2006 Maize root biomass and net rhizodeposited carbon: An analysis of the literature. Soil Sci. Soc. Am. J. 70:1489

Barber, S.A. 1979. Corn residue management and soil organic matter. Agron. J. 71:625.

Barber, S.A., and J.K. Martin, 1976 The release of organic substance by cereal roots in the soil. New Phytol. 76:69.

Bolinder, M.A., H.H. Janzen, E.G. Gregorich, D.A.,Angers, and A.J. Vanden Bygaart.2007 An approach for estimating net primary productivity and annual carbon inputs to soil for common agricultural crops in Canada. Agri. Ecosystem. 118:29.

Clay, D.E., C.G. Carlson, S.A. Clay, C. Reese, Z. Liu, and M.M Ellsbury. 2006. Theoretical Derivation of New Stable and Non-isotopic Approaches for Assessing Soil Organic C Turnover. Agron. J. 102:443.

Gale, W.J. and C.A. Cambardella. 2000. Carbon dynamics of surface residue- and root-derived organic matter under simulated no-till. Soil Sci. Soc. Am. J. 64, 190-195.

Johnson, J.M.F., R.R. Allmaras, and D.C. Reicosky, 2006. Estimating source carbon from crop residues, roots, and rhizodeposits using the national grain-yield data-base. Agron. J. 98: 622.

Kuzyakov, Y. and G. Domanski, 2000 Carbon inputs by plants into the soil. Review. *J.* Plant Nutr. Soil Sci. 163:421.

Kuzyakov, Y.V.2001. Tracer studies of carbon translocation by plants from the atmosphere into the soil. Eurasian Soil Sci. 34:28.

Larson, W.E., C.E. Clapp, W.H. Pierre, and Y.B. Morachan, Y.B. 1972. Effect of increasing amounts of organic residues on continuous corn: Organic carbon, nitrogen, phosphorous, and sulfur. Agron. J. 64:204.

Morachan, Y.B.,W.C. Moldenhauer, and W.E. Larson. 1972. Effects of increasing amount of organic residues on continuous corn: 1. Yields and soil physical properties. Agron. J. 64:199

Ortega, R., G.A. Peterson, and D.J. Westfall. 2002. Residue accumulation and changes in soil organic matter as affected by cropping intensity in no-till dryland agroecosystems. Agron. J. 94:944.

Prakash, V., S. Kundu, B.N. Ghosh, R.D. Singh, and H.S. Gupta. 2002. Annual carbon input to soil through rainfed soybean (*Glycine max*) – wheat (T*riticum aestivum*). Indian J. Agric. Sci. 72:14..