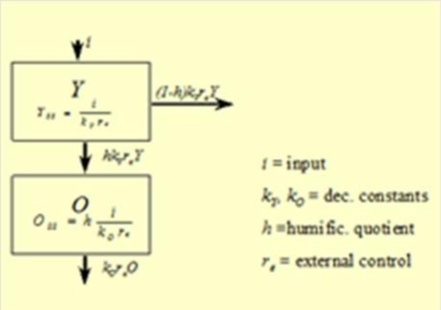
Calculating soil C balances in African long-term agricultural trials from limited data sets *(v.1.9 2012 08 29)*

Guidelines developed within the project: Long-term monitoring activities in sub-Saharan Africa for the development of guidelines of soil health management. Prof O. Andrén, (www.oandren.com)

A description of the steps necessary for calculating soil C balances in a 30-yr perspective.

Inputs	**Calculate**	**Worksheet**
Weather data Temperature Precipitation Evaporation *(daily)*	Climate drivers for Decomposition: $re_{\_clim}$ and r_e	*Afreclim_1*
Crop yield & manure Yield Manure Amendments *(annual/seasonal)*	Annual C inputs and quality: *i, h*	*Afallo_1*
Soil data Wilting point Field capacity (Or C content, texture) *(constant)*	Water storage capacity in mm	*Afreclim_1*
Parameters *i*, *h*, r_e, Y_0, O_0 *(initial Young and Old Soil C) fed to the ICBM model:*		*Af_ICBM_1.xlsx*

ICBM model



Summary

The figure above summarizes the contents of this paper, which is an extended manual describing how to use the Excel® worksheets available for download. This paper also gives a background to the equations and assumptions involved, shows examples on how to calculate C balances and points to relevant literature. Study the figure, download *Af_ICBM_1.xlsx* and test different parameter settings. But first, read through this short manual…

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Introduction

This report describes how to calculate soil carbon balances from climate data and cropping data, including residue and manure inputs to soil. It describes how to calculate rapidly from limited data and the shortcuts necessary when data are limited. Pointers to measurements that will increase the precision of the calculations are given, and a simple sensitivity analysis is performed.

The climate data set used here is from Embu, Kenya and is not in the public domain, and may only be used after permission (contact Advisor Alfred Micheni, alfredmicheni@yahoo.com). Crop yield and soil data are from the paper by Gentile et al. (2011), and from the databases within projects managed by Prof. Bernard Vanlauwe. A more detailed description of the methods and ideas behind can be found in Andrén et al. (2012) and in papers cited there. More information, programs etc. can be found at www.oandren.com/ICBM.

In short, the procedure for calculating soil C balances is as follows:

1. Adapt to local climate – adjust according to local weather station data and our procedures for calculating soil activity (r_{e_clim}) from these data. If possible, adapt to soil type and crop yield (for transpiration calculations) and calculate r_e. *Input data: Daily air temperature, rainfall and evaporation (Et0, can be calculated from pan evaporation or other meteorological variables). [If* r_e

is calculated, soil water holding capacity and wilting point or texture data. Sowing and harvest dates and crop yield.] Workbook: *Afreclim_1*

2. Calculate annual inputs of carbon, based on crop yields and added organic matter, noting that often there are two crops per year. Calculate the humification quotient, h, for the whole annual input, based on *tabulated values* ranging from about 0.1 to 0.5. If necessary, use weighted average of h. *Input data: Annual crop yield, residue return, organic amendments, if possible C concentration.* Workbook: *Afallo_1.*
3. Set the initial carbon mass in the topsoil from *measured values*, and divide this between initial Y (Y_0) and initial O (O_0) soil carbon, usually assuming steady-state balance. Set proportion of inert carbon from local data or default. Insert parameters and *measured soil carbon* into ICBM spreadsheet – one treatment per page and let the model calculate 30-yr dynamics and steady-state values. If necessary, use optimization routines for adjusting, e.g., h values to observed data. *Input data:* i, h, r_e/r_{e_clim}, *initial C mass in soil.* Workbook: *Af_ICBM_1.*

This manual covers all steps from input data to model outputs and the companion Excel® files are easy to use. What is not covered here is the localization of soil climate, i.e., from r_{e_clim} to r_e. This involves calculating soil water at wilting point and at saturation (easy) to adjust for local soil water storage capacity, and also to compensate for transpiration from different crops with different leaf areas (not so easy). However, using r_{e_clim} as a proxy for r_e is sufficient in most cases, and there are many other uncertainties in interpreting field trials that are more crucial, e.g.: How deep is the 'topsoil' concerning roots delivering C and cultivation depth? How deep do the roots have access to water, reducing the drying of topsoil? Do roots have a much higher humification factor than we have believed (Kätterer et al., 2011)?

Note that optimizations cannot fully be performed until measured soil carbon dynamics for an extended period of time is available. However, even without data, hypotheses can be tested and scenarios evaluated, e.g.: What will happen if I fertilize and increase yields by 75%?

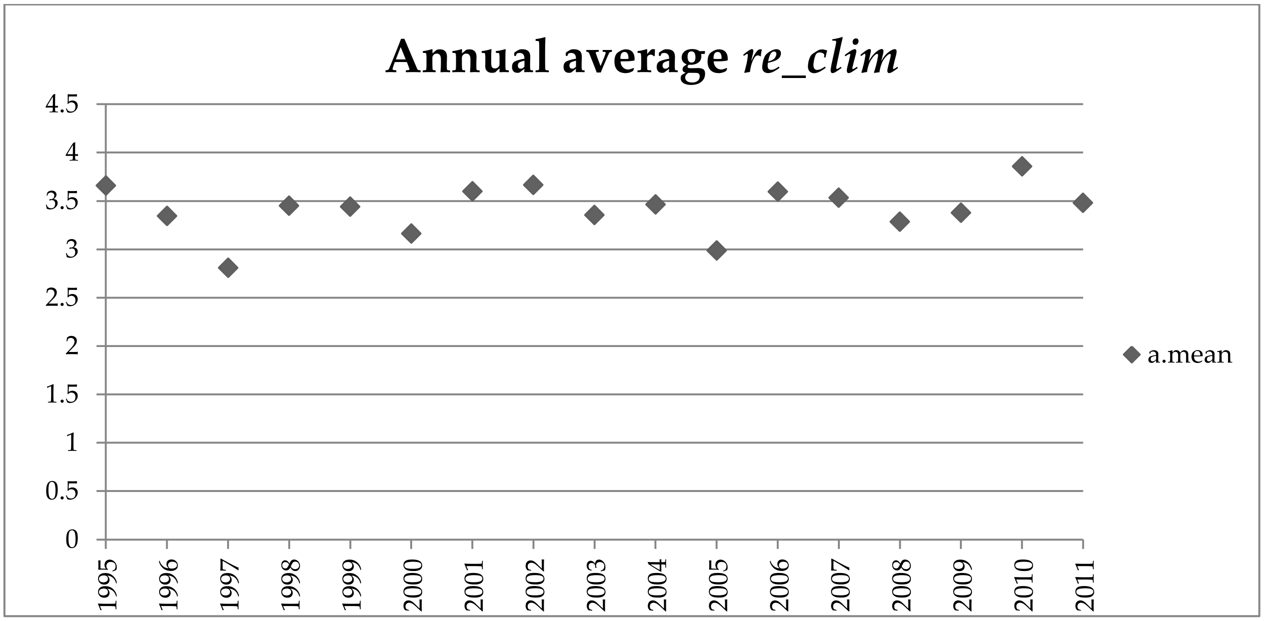
Download the Excel® programs and try!

Climate calculations

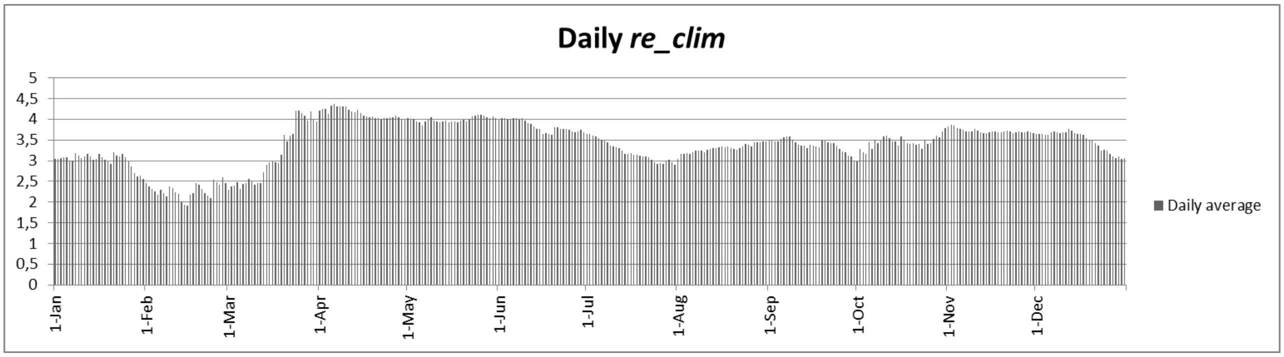
Parameter r_e summarizes the external influences on soil organic matter decomposition rates. This parameter is based on soil temperature and moisture, but it can also be modified according to different degree of cultivation or oxygen starvation due to water-logging. Soil temperature and moisture can be calculated from daily meteorological data paired with soil and crop properties, and the daily activity can be calculated using a factor $r_{e\_temperature} \times r_{e\_moisture}$. The daily calculations of activity can then be expressed as an annual mean, which in one value combines temperature and moisture conditions and their daily interaction. The degree of soil cultivation (or the difference between cereals and a grass ley) can then be applied as another multiplier, r_{e_cult}. We have normalized r_e to 1 for cereal cropping in central Sweden (Andrén et al. 2004), and for Sweden r_e ranges from about 1.3 in cereal cropping regions in Southern Sweden to about 0.7 in grass leys in Northern Sweden. The actual calculations of r_e that are used when climatic (daily temperature, rainfall and evapotranspiration), soil (wilting point, field capacity) and crop (green leaf area, degree of cultivation) data are available are made using a SAS program called *W2re* (Andrén et al. 2004) or within the spreadsheet *Afreclim_1.xlsx* . When the soil properties used for calculation of water storage parameters (water content at wilting point and field capacity) are unknown, these can be calculated from soil texture data (Kätterer et al. 2006).

There is also a simplified climate parameter, *re_clim*, which uses a standard soil (clay loam) and cropping system (black fallow) to give a pure climatic factor for comparisons. The value for *re_clim* is calculated from standard meteorological data only (daily temperature, rainfall and evapotranspiration), normalized to 1 for Central Swedish climate, and typical values have been calculated for sub-Saharan Africa (Andrén et al. 2007) as well as Canada (Bolinder et al. 2008). A *re_clim* value of 3 indicates that the decomposition rate of soil organic carbon is three times higher than in central Sweden just due to climatic differences, and that the same annual input as in Sweden would result in 1/3 of the soil C mass at steady state.

Here are the results from calculating *re_clim* from the 11-year climate data set from Embu, Kenya. The calculations are made with the Excel® workbook *Af_reclim_1.xlsx*. Average *re_clim* is 3.42, based on daily data. This indicates that decomposition here is more than three times faster than in central Sweden, and fits well with earlier data. The difference in *re_clim* between years in the Embu database 1995-2011 was small, ranging from about 2.8 to 3.9, indicating a fairly stable climate.



The average daily *re_clim* value for the 17-year dataset is shown here. Compared to other regions, the Embu site has weak seasonal dynamics, i.e., moderately severe dry seasons.



Modifying *re_clim* to the site-specific r_e includes soil properties, cultivation and crop green area development. However, this fine-tuning is not really necessary at this stage – so we can use *re_clim* as a proxy for r_e. See enclosed *Afreclim_1.xlsx.*

Crop and other organic inputs

This section owes a lot to Martin Bolinder, martin.bolinder@slu.se

The Excel worksheet (*Afallo_1.xlsx*) describes how to estimate annual crop residue carbon inputs for Maize, Soybeans, Sorghum and Groundnuts, including considerations if the maize or sorghum crops are grown as 'silage' (all above-ground parts removed from the field and only stubble and roots remaining). We use harvest index (HI) and root to shoot (R:S) ratios. These can be translated into C allometric coefficients (i.e., like in the Bolinder et al. (2007) paper).

There is an African paper by Bostick et al. (2007) which has been very useful in setting parameters, and some comments may be in order. They presented a model (Table 3 in that paper) where they estimate below-ground C inputs to soil using R:S ratios and a root distribution factor (RDF) for Groundnut, Sorghum, Cotton and Maize. They assumed that there was no significant organic C (OC) input from above-ground residue, and the main plant OC source was plant roots, so clearly all the above-ground biomass was removed in that experiment. They assumed all plant biomass contained 40% C, but based on other literature we use 45% here – if measured values are lacking. They do not make any assumptions about extra-root C (C delivered from roots during the growing season), but we include that, in spite of being very hard to estimate. We use an estimate of 65% root turnover from Bolinder et al. (2007), i.e., multiplying the estimated root biomass C by 0.65 and adding that as C input from root turnover.

Here we calculate the inputs from the long-term organic matter addition experiment in Embu, reported by Gentile et al. (2011) and papers cited therein. The calculations are made in the Excel® workbook *Afallo_1*, and from the yield data we calculate the annual inputs of carbon from crop to soil, considering that there are two harvests per year. The crop residues were exported, but we also include a treatment with annual additions of 1.2 t C ha^{-1} maize stover and one with *Tithonia sp.* bush added. Table below from *Afallo_1*.

Grain-maize general		Yield (grain)	Yield (grain)	Above-ground straw	Total above-ground biomass	Roots	Extra-root C	Total annual C input to soil		
HI	*0.50*	kg DM ha^{-1}	kg C m^{-2}	kg C m^{-2}	kg C m^{-2}	kg C m^{-2}	kg C m^{-2}	kg C m^{-2}		
R:S	*0.18*	1000	0.0450	0.0450	0.0900	0.0162	0.0105	0.0717		
Extra-root C	*0.65*				Yield values here from Gentile et al. (2011)					

Maize control, no N		Yield (grain)	Yield (grain)	Above-ground straw	Total above-ground biomass	Roots	Extra-root C	Total annual C input to soil	C input when stover exported, roots only	
HI	*0.50*	kg DM ha^{-1}	kg C m^{-2}	kg C m^{-2}	kg C m^{-2}	kg C m^{-2}	kg C m^{-2}	kg C m^{-2}	kg C m^{-2}	ton C/ha
R:S	*0.18*	**4100**	0.1845	0.1845	0.3690	0.0664	0.0432	0.2941	**0.110**	**1.096**
Extra-root C	*0.65*									
Maize + stover, no N		Yield (grain)	Yield (grain)	Above-ground straw	Total above-ground biomass	Roots	Extra-root C	Total annual C input to soil	C input when stover exported, roots only	
HI	*0.50*	kg DM ha^{-1}	kg C m^{-2}	kg C m^{-2}	kg C m^{-2}	kg C m^{-2}	kg C m^{-2}	kg C m^{-2}	kg C m^{-2}	ton C/ha
R:S	*0.18*	***5180***	0.2331	0.2331	0.4662	0.0839	0.0545	0.3716	0.138	1.385
Extra-root C	*0.65*									
Added C	**0.1200**								0.1200	1.200
TOTAL									**0.258**	**2.585**
Maize control, N		Yield (grain)	Yield (grain)	Above-ground straw	Total above-ground biomass	Roots	Extra-root C	Total annual C input to soil	C input when stover exported, roots only	
HI	*0.50*	kg DM ha^{-1}	kg C m^{-2}	kg C m^{-2}	kg C m^{-2}	kg C m^{-2}	kg C m^{-2}	kg C m^{-2}	kg C m^{-2}	ton C/ha
R:S	*0.18*	**6980**	0.3141	0.3141	0.6282	0.1131	0.0735	0.5007	**0.187**	**1.866**

Extra-root C	*0.65*										
Tithonia 1.2 t added, no N		Yield (grain)	Yield (grain)	Above-ground straw	Total above-ground biomass	Roots	Extra-root C	Total annual C input to soil	C input when stover exported, roots only	
HI	*0.50*	kg DM ha^{-1}	kg C m^{-2}	kg C m^{-2}	kg C m^{-2}	kg C m^{-2}	kg C m^{-2}	kg C m^{-2}	kg C m^{-2}	ton C/ha
R:S	*0.18*	**6680**	0.3006	0.3006	0.6012	0.1082	0.0703	0.4792	**0.179**	**1.786**
Extra-root C	*0.65*									
Added C	**0.1200**								0.1200	1.200
TOTAL									**0.299**	**2.986**

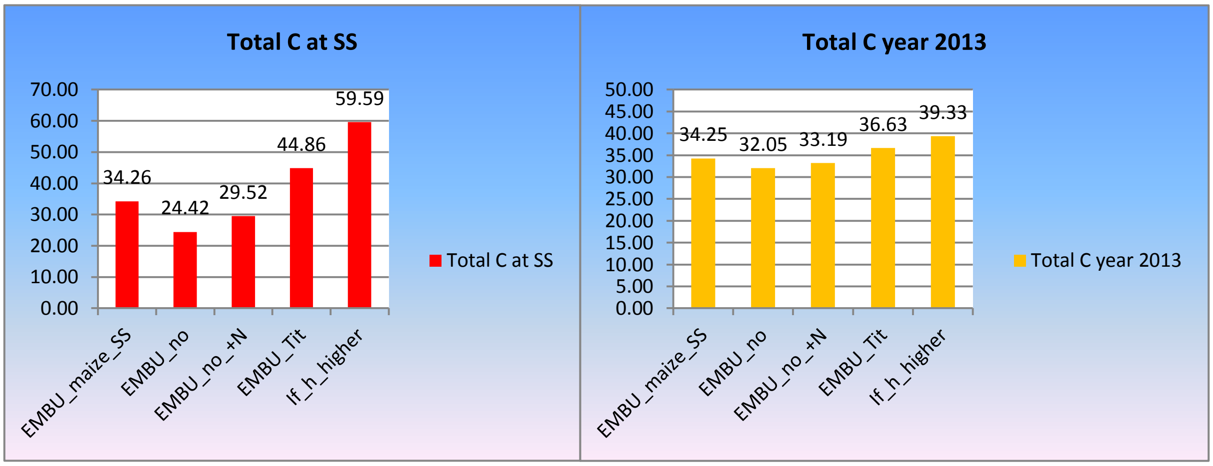
Soil carbon balance calculations and projections

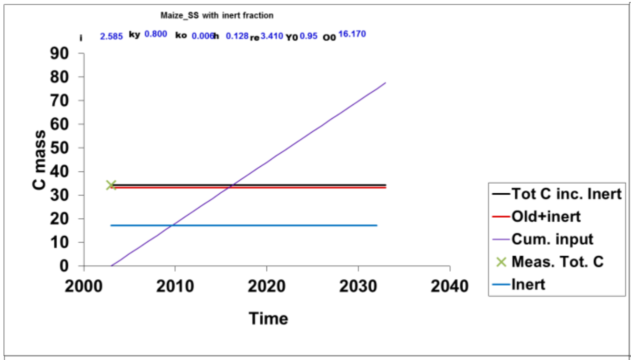
The Embu experiment has annual additions of five different organic materials (cut bush material, manure, sawdust etc.), each at two levels, 1.2 and 4 t C/ha. The crop residues were exported, but we also include a treatment with annual additions of 1.2 t C ha^{-1} maize stover and one with *Tithonia sp.* bush added. The initial soil C mass was 34.3 ton C/ha and we assumed that 50% of this was inert. This is a summary table from *Af_ICBM_1.xlsx* that lists parameters used (compare with fig. on p.1) and summarizes the results. Y_0 and O_0, the initial mass of Young + Old C thus was calculated from 0.5*34.27= 17.13 t/ha when the inert was excluded, and the distribution between them was calculated by the program. This table shows the parameter sets used in the worksheets.

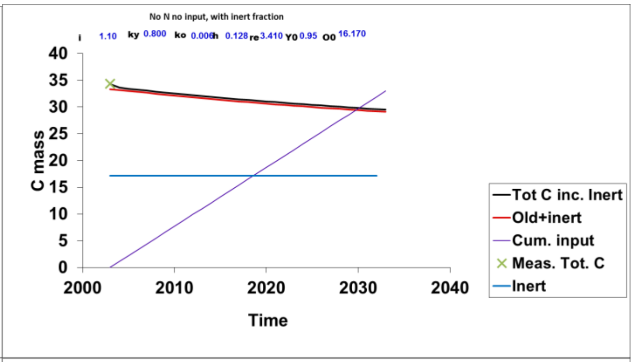
Sheet	**Object**	***i_crop***	***i_add***	***i_tot***	***ky***	***ko***	***h***	**Re_clim**	***Tot C0***	***Y0***	***O0***	***Yss***	***Oss***	***Tss***	***inert***	***Total C at SS***	**Total C year 2013**
EMBU_maize_SS	**No N, 1.2 t C maize**	1.38	1.20	**2.58**	0.80	0.04	0.13	3.41	34.27	0.95	16.17	0.95	16.17	17.12	17.14	34.26	34.25
EMBU_no	**No N, no org input**	1.10		**1.10**	0.80	0.04	0.13	3.41	34.27	0.95	16.17	0.40	6.88	7.28	17.14	24.42	32.05
EMBU_no_+N	**N, no org. Input**	1.87		**1.87**	0.80	0.04	0.13	3.41	34.27	0.95	16.17	0.69	11.70	12.38	17.14	29.52	33.19
EMBU_Tit	**No N,1.2 t C Tithonia**	2.99	1.20	**4.19**	0.80	0.04	0.13	3.41	34.27	0.95	16.17	1.53	26.19	27.72	17.14	44.86	36.63
If_h_higher	**As EMBU_Tit h=0.2**	2.99	1.20	**4.19**	0.80	0.04	0.20	3.41	34.27	0.95	16.17	1.53	40.92	42.45	17.14	59.59	39.33

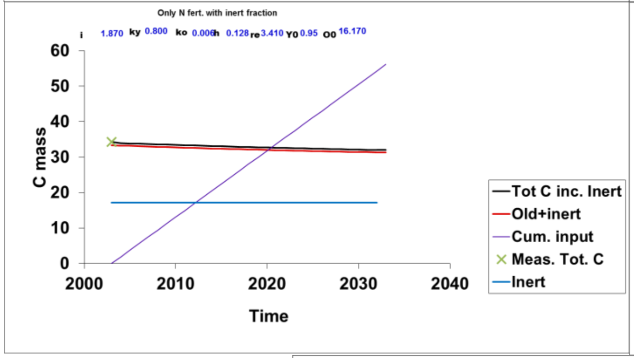
From top to bottom, we assumed that the treatment without N fertilizer and with 1.2 t/ha maize straw C added was similar to the steady-state conditions, and this figure illustrates how the measured initial value (X) remains the same over the years – after adjusting the *h* parameter to 0.128.

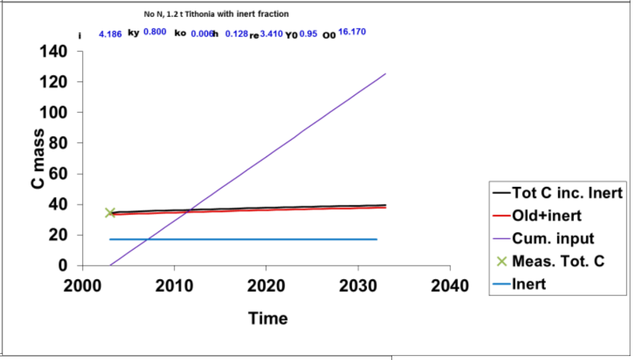
This is close to the default for cereal straw, 0.12, so this can be a start. The following rows show parameters for selected treatments and the bottom row shows parameters for calculating C mass if we assume that the humification quotient *h* for Tithonia is higher, 0.2, than for maize. Inspecting the bar diagrams below reveals a property of the model (and reality!) – what seems to have major effects on the carbon balance at steady-state (after many years…) does not necessarily give significant differences after 10 years or so (Cf. Gentile et al, 2011).

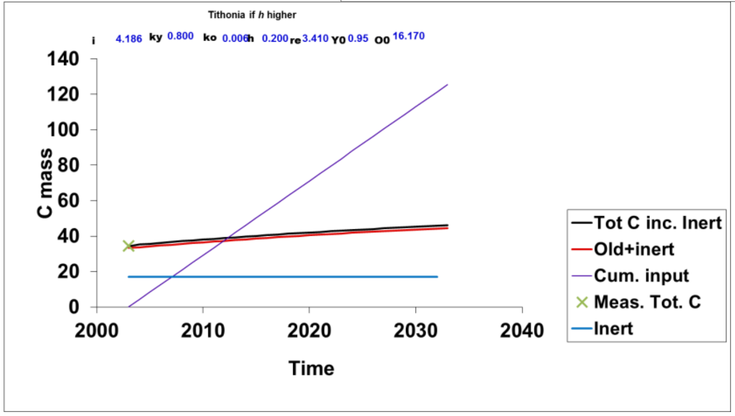












These figures from *Af_ICBM_1* show the projections of C balances using the parameters in the table above. Note the different scales on y-axis. It is obvious that major differences in annual total C input do not necessarily give significant differences in total C after a 10-yr period. Also, it is clear that the fraction of the added material that becomes 'Old', i.e., semi-resistant (described by parameter *h*) of great importance. And, if for example biochar is added, the 'Inert' line would jump up and stay up after just one addition – a much more efficient way of sequestering C.

Now, fire up *Af_ICBM_1* and play with the parameters – why not test much C would be sequestered if the climate was like in central Sweden, i.e., r_{e_clim}=1?

(Answer: Total C at steady state for the first case will be 75.5 ton/ha)

Literature

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