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Supplementary Info

Photosynthetic limits on carbon sequestration in croplands – a Fermi approach

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Detailed description Monte Carlo simulation

The parameters used in our Fermi approach are approximate, with acknowledged margins of error. To demonstrate how these uncertainties affect the distributions of carbon volumes, we simulated the parameters of Equations 2 and 4, where parameter values were allowed to vary randomly, according to a Normal distribution, using the rnorm function in base R (R Core Team 2020) with the following means and standard deviations: P: mean = 5.25, standard deviation (sd) = 0.46; k1: mean = 0.44, sd = 0.04; k2: mean = 0.15, sd = 0.015; H: mean = 140, sd = 14; R = 500, sd = 200. The standard deviation for P was from Wolf et al. (2015) while the others were estimated by the authors. The MonteCarlo function from the MonteCarlo package (Leschinski 2019) handled the generation of loops over the desired parameter grids and the 2 x 500 repetitions of the Monte Carlo experiment for each of the parameter constellations, yielding density patterns of the outputs for Equations 2 and 4. To ensure the reproducibility of the results, the Monte Carlo experiment was performed using the set.seed function (seed = 123).

Table S1: Examples of studies, with emphasis on recent findings, demonstrating the prominent influence of plant-derived carbon inputs on carbon stocks in soil. This compilation is not exhaustive nor necessarily representative, but nevertheless clearly indicates that soil C stocks (and *change* in soil C stocks) are directly dependent on and related to the amount of plant C added

Source	Study type	Excerpt
Amelung et al. 2020 Nat. Comm. 11:5427	Review article	"Considering the general agreement that the most effective way to accumulate SOC is to increase C inputs"
Baethgen et al. 2021 Soil Sci. Soc. Am. J. 85: 423–437	Long-term experiment, Uruguay	"The model and observed data show that soil respiration, N mineralization, soil C, and crop yields increase with increasing plant-derived C inputs caused by increasing the frequency of pastures in the rotations"
Bell et al. 2012 Agric. Ecosyst. Environm. 158:156-163	Two long-term field studies (Canada)	"Due to higher net primary productivity and higher carbon inputs, particularly below ground, SOC stocks (0–120 cm) were 21–65 t C ha^{-1} higher under the re-established grassland than cropping systems at the clay soil site after 18 years, but not at the site with sandy loam soil after 9 years."
Berhane et al. 2020 Glob. Change Biol. 26: 2686-2701	Meta-analysis of long-term field experiments (China)	"the annual soil sequestration rates and annual straw C inputs of the treatments with straw return (NP+S and NPK+S) were significantly positively related."
Bhardwaj et al. 2019. Sci. Rep. 9:9114	10-yr experiment (India)	"Total C input to soil had a direct effect on soil C stock, soil C fractions (maximum in VLc and LLc), yet the responses in terms of biological yield were controlled by the quality of the biomass (C:N ratio, decomposition, etc.) incorporated."
Bitew and Abera. 2019 Ind. J. Ecol. 46: 235-249	review	"Conservation tillage based intercropping (CTBI) … gives higher percentage of organic matter and organic carbon as compared to conventional tillage based mono-cropping due [to] addition of carbon input from the intercropped legumes and residues from conservation tillage."
Börjesson et al. 2018 Biol. Fert. Soils 54: 549–558	Two 35-yr cropping systems experiment (Sweden)	"At both sites, total mean C input from crop residues correlated well with changes in SOC stocks in both the 0- to 20- and 0- to 50-cm layers"
Bruni et al. 2021 Biogeosciences 18: 3981–4004	Modelling study	"We found that, on average among the selected experimental sites, annual C inputs will have to increase by 43.15 ± 5.05 %..., with respect to the initial C inputs in the control treatment."

Buyanovsky and Wager 1998 Glob. Change Biol. 4: 131-141	Long-term cropping system experiment (USA)	“A direct dependence was observed, as one would expect, between amounts of carbon returned to the soil during 100 years and soil organic carbon content”
Cardinael et al. 2018 Biogeosciences 15:297-31	18-yr study including agroforestry and wheat systems (France)	“High organic inputs explain shallow and deep SOC storage in a long-term agroforestry system” [title] “the increased inputs of fresh biomass to soil explained the observed additional SOC storage in the agroforestry plot”
Cole et al. 1993 Wat. Air Soil Poll. 70: 357-371	Literature review	One important result of the steady-state analysis is that total C at steady-state (= maximum soil C level)is shown to be directly proportional to the rate of C input (Paustian et al., in press). This has important implications for C sequestration potential
Dalal et al. 2018 Soil Res. 56: 429–440	12-yr cropping systems study (Australia)	“We found a significant relationship between soil organic C and root biomass at depths of 0-0.1 and 0-1.2 m…”
Deng et al. 2019. Sc. Rep 9:3090	Field experiment (China)	“Increased root residue and extra external carbon input to soil under RFFSM directly contributed to SOC recovery.”
Engel et al. 2017 Soil Sci. Soc. Am. J. 81: 404-413	10-yr field study, with various tillage and cropping treatments (USA)	“Among the cropping systems, [change in soil organic carbon adjusted for equivalent mass] was directly related to net primary productivity (NPP; $r^2 = 0.73$) and total C (TC; shoot + root + rhizodeposit) inputs ($r^2 = 0.86$).
Fan et al. 2018 Field Crop Res. 219: 14-23	Long-term maize experiment (China)	“Stover retention rather than no-till decreases the global warming potential of rainfed continuous maize cropland” [title] “Our results highlight the importance of C input from crop residues for increasing SOC stocks and mitigating GHG emissions.”
Ferreira et al. 2018. Sci. Tot. Envir. 622:735-742	Long term field study (Brazil)	“The processes that drove SOC recovery in the studied sites were soil fertility management allied with high C input through intense crop rotation.”
Franko and Ruehlmann 2018 Geoderma 321: 15-21	Long-term experiment (Germany)	“The prediction of future SOC sequestration rates has to be based on the characterization of the carbon input considering the amount and quality of the fresh organic matter, as well as on the description of the initial conditions, where not only the actual amount of SOC is relevant but also its distance to a possible equilibrium as determined by the previous management.”
Fujisaki et al. 2018 Agric. Ecosyst. Env. 259: 147-158	Meta-analysis of tropical cropping studies, including 214 cases in 48 studies (13 countries)	“The SOC accumulation rates increased linearly with C inputs, and the conversion rate of C inputs to SOC was 8.2□±□0.8%.”
Guo et al. 2021 Land Degrad Dev. 32: 1274–1286	Long-term field experiment (China)	“The SOC sequestration in the IMsoil increased by 15.4 Mg C/ha at a rate of 2.20 Mg C ha^{-1} yr through large C inputs and high SOC transfer efficiencies compared with the beginning of this experiment.”

Han et al. 2018. Glob. Change Biol. 24: 987-1000	Extensive regional soil sampling in the 1980s and 2010s (China)	"Successful desalinization and the subsequent increases in carbon (C) inputs, induced by agricultural projects and policies intended to support crop production…, combined with improved cultivation practices (i.e. fertilization and straw return) since the early 1980s were the main drivers for the SOC stock increase.
He et al. 2021. Plant Soil Environ 67: 1-7.	Long-term experiment (China)	"The SSR [SOC sequestration rate] of all treatments ranged from 0.11 to 0.40 t/ha/year, and there was a significant correlation between SSR and the average C-input"
Hobley et al. 2017 Glob. Change Biol. 23: 955-965	Study of organic C in 12 sites under different land-uses and climates (Australia).	"Our results indicate that organic carbon storage in soils is input driven down the whole profile,…"
Huang et al. 2020 Plant Soil 454: 299–310	Meta-analysis	"Although our findings require additional confirmation from long-term field experiments, our analysis provides isotopic evidence that N addition stimulates soil C storage both by increasing soil C input and (at high N rates) by decreasing decomposition of old soil C."
Huang et al. 2020 Agr. For. Meteor. 291: 108090	Modelling/field study (USA)	"Simulation results for 1970–2018 show that NT, relative to conventional tillage (CT), led to carbon gains (0.22 Mg C ha^{-1} yr^{-1}) in the topsoil in a CC-inclusive continuing maize system; however, NT per se brought minor net carbon gains. This well captures the field observations. Model factorial analyses reveal that soil carbon sequestration was highly correlated with biomass carbon inputs from both the winter cereal CC and the summer maize."
Jiang et al. 2017 Soil Till. Res. 170:77-84.	Field study with treatments varying in straw amendment (China)	"a significantly linear relationship (SOC sequestration rate=0.29×annualC input–0.57, R^2=0.99, P<0.05) was detected between annual straw C input and SOC sequestration rate over the 5-year cycles"
Karimi et al. 2018. Can. J. Soil Sci. 98: 580–583	Long-term experiment (Canada)	"Analysis of archived samples from a site established on grassland in 1911 showed that SOC, under wheat systems, approached steady state after several decades, and that its amount reflected the inputs of residue C."
Kauer et al. 2019. Agric. Ecosyst. Env. 283: 106562	Long-term field experiment (Estonia)	"SOC changes were highly correlated with estimated C inputs"
Keel et al. 2019. Agric. Ecosyst. Env. 286: 106654	Eleven long-term field experiments on cropland and permanent grassland (Switzerland)	"Based on a linear mixed effects model we showed that SOC change rates (ΔSOC) were driven by C inputs to soil (harvest residues and organic fertilizer), soil cover and initial SOC stocks."
King and Blesh 2018 Ecol. Appl. 28: 249-261	Meta-analysis 27 cropping system sites and 169 cropping systems)	"Our results show that increasing the functional diversity of crop rotations is more likely to increase SOC concentrations if it is accompanied by an increase in C input." "Crop rotations with functional groups of crops that increased total C input (cover cropped and perennial cropped rotations) increased SOC concentrations relative to a control"

Kong et al. 2005 Soil Sci. Soc. Am. J. 69: 1078-1085	Long-term field study (USA)	“We found a strong linear relationship (r2 = 0.70, p = 0.003) between SOC sequestration and cumulative C input, with a residue-C conversion to SOC rate of 7.6%”
Lal 2018 Glob. Change Biol. 24: 3285-3301	Research review	“A positive soil C budget is created by increasing the input of biomass-C to exceed the SOC losses by erosion and mineralization”
Larson et al. 1972 Agron. J. 64:204-209	11-yr field study with various amendments (USA)	“Organic C, N, S, and P contents of the soils increased in proportion to the amount of plant residues added”
Le-Noë et al. 2019. Env. Sci. Pol. 93: 53-65	Modelling study, 1852 to 2014 (France)	“Our results emphasize the role of crop net primary production (NPP) as the main driver of changes in SOC stocks through the input of crop residues.”
Liang et al. 2018 Nat. Comm. 9: 3175	Literature review of incubation studies using isotopes	“More replenishment than priming loss of soil organic carbon with additional carbon input” [title] “our findings suggest that increasing C input to soils likely promote SOC accumulation despite the enhanced decomposition of old C via priming.”
Li et al. 2019 Soil Till. Res. 195: 104428	Field study, paddy rice (China)	“No significant correlation was found between SOC content and yearly carbon inputs.”
Li et al. 2021. Agron. J. 113: 2118–2131	Long-term experiment, straw mulching (China)	“Principal component analysis (PCA) indicated that organic C input was the key to improving SOC sequestration, SOC lability, and soil macro-aggregation rather than N input,…” “The increases in SOC stock were primarily attributed to large C inputs across different treatments,” “We also observed a positive correlation between SOC sequestration and cumulative C input”
Li et al. 2021 Agron. J. 113: 2150–2164	Short-term field experiment (China)	“Positive relationships (P < .05) existed between the SOC sequestration and cumulative C input in both [conventional wheat monoculture and green manure–winter wheat]”
Liu et al. 2021 Soil Sci. Soc. Am. J. 85: 829–846	Field experiment (USA)	“After 8 yr, total C inputs were positively correlated with total soil organic C, the proportion of macroaggregates in the whole soil, and the mean weight diameter of soil aggregates.”
Luo et al. 2017 Glob. Change Biol. 23: 4430-4439	Review of cropping experiments (90 field trials, 28 sites) (Australia)	“we found that the most influential variables on [SOC change rate] were the average C input amount and annual precipitation, and the total SOC stock at the beginning of the trials.”
Martin et al. 2021 Glob. Change Biol. 27: 2458–2477	Reverse modelling analysis (France)	“Results showed that a 30%–40% increase in C inputs to soil would be needed to obtain a 4‰ increase per year over a 30-year period.”
Mary et al. 2020 Agric. Ecosyst. Env. 299:106972	Long-term field experiment (France)	“Soil carbon storage and mineralization rates are affected by carbon inputs rather than physical disturbance: Evidence from a 47-year tillage experiment” [Title]
Matsumoto et al. 2021; Soil Sci. Plant Nutr. 67: 190-196	Long-term experiment (Thailand)	“Rice straw mulch increased SOC stock change, which was caused by an increase in the amount of organic matter input into the soil”
Nash et al. 2018	Modelling study	Intensifying crop rotations was predicted to have a greater impact on SOC stocks than tillage

J. Env. Qual. 47: 654-662		(minimum tillage [MT], no-till [NT]) during 2013 to 2032, as SOC was highly correlated to biomass input (= 0.91, = 0.00053)."
Orgill et al. 2017 Geoderma 285: 151-163.	Long-term laboratory incubation study	"This study demonstrated that with sustained C and nutrient inputs, the stable fraction of OC can increase linearly.
Pareja-Sánchez et al. 2020 Soil Sci. Soc. Am. J. 84: 1219-1232	Long-term field experiment (Spain)	"In P1-R and P3-I [selected treatments], C-input explained 70% of the variability of ΔSOC_{rate}."
Paustian et al. 1992 Soil Sci. Soc. Am. J. 56: 476-488	30-yr field experiment with various amendments (Sweden)	"Most of the treatment differences in SOM could be explained by the rate of organic-matter input, its lignin content, and C/N ratio, plus the effect of N fertilizer on belowground C inputs."
Poeplau and Don. 2015. Agr. Ecosyst. Env. 200: 33-41	Meta-analysis and modelling study	"the C input driven SOC sequestration with the introduction of cover crops proved to be highly efficient."
Poffenbarger et al. 2020 Agr. Ecosyst. Env. 291: 106810	Long-term field trials (USA)	"We conclude that adoption of cropping systems with enhanced belowground C inputs may increase total profile SOC, but the effect is minimal and inconsistent"
Qaswar et al. 2020 Soil Till. Res. 198: 104569	Long-term field experiment (China)	"Path analysis showed that long-term fertilizer inputs increased soil nutrient contents and C input directly affected soil OC."
Rasmussen et al. 1980. Soil Sci. Soc. Am. J. 44: 596-600.	Long-term cropping systems experiment (USA)	"Changes in soil C correlated highly with the amount of organic C supplied by each treatment, regardless of the different kinds of residue applied. Thus, changes in soil organic matter levels were controlled primarily by the amount of organic C supplied in crop residue."
Rasmussen and Collins. 1991. Adv. Agron. 45: 93-134	Literature review	"It now appears that residue input plays an important role in setting a new organic matter equilibrium level in soil. The effect of crop residue on soil organic matter content is highly related to the amount and only weakly related to the type of residue applied"
Rasmussen and Parton 1994 Soil Sci. Soc. Am. J. 85:523-530.	Long-term cropping systems experiment (USA)	"The change in soil C and N with time is nearly linear for all treatments, and highly correlated with residue input."
Rasmussen et al. 1998. Soil Till. Res. 47: 197-205	Review of long-term experiments (USA)	"The major factors influencing changes in organic C and N were the frequency of summer-fallow and the amount of c input by crop residue."
Riggers et al. 2021 Plant Soil 460:417–433	Modelling study (Germany)	"Depending on the climate scenario, we estimated that the OC input to the soil in 2099 needs to be between 51% (+ 1.3 Mg ha^{-1}) and 93% (+ 2.3 Mg ha^{-1}) higher than today to preserve current SOC stock levels.
Rosenzweig et al. 2018 Agr. Ecosyst. Env. 258: 14-22	Model, based on analysis of 96 dryland, no-till fields (USA)	"Overall, the model suggests that cropping system intensity increases SOC both directly, through greater C inputs to soil, and indirectly, by increasing fungal biomass and aggregation"
Sandermann et al. 2017. Soil 3:1-5	Long-term crop rotation trial (Australia)	"After > 40 years under consistent management, topsoil carbon stocks ranged from 14 to 33 Mg C ha^{-1} and were linearly related to the mean productivity of each treatment."

Sarker et al. 2018. Soil Till. Res. 178: 209-223	Analysis of soils from long-term (16–46 years) systems (Australia)	"These findings suggest that reducing soil disturbance and enhancing crop residue input in farming systems are important for SOC and nutrient storage, particularly in finer aggregate fractions."
Smith et al. 1997. Glob. Change Biol. 3: 67-79	Review article	"These yearly percentage changes in SOC content were then plotted against the amount of organic manure added per year…. Despite very different soil types, rotations, climatic conditions and durations of experiment, a highly significant linear relationship was found…."
Tao et al. 2019 Soil Till. Res. 186: 70-78	Literature review of croplands (China)	"The increase of the SOC stock was attributed to substantial increase in organic inputs, resulted from increased crop productivity, the amendments of crop residues and organic manure, the increases in synthetic fertilizer application and the optimal combination of nutrients, as well as adopting no-tillage practice."
Virto et al. 2012 Biogeochemistry 108: 17–26	Meta-analysis of soil organic carbon (0-30 cm) of 92 no-till vs inversion tillage pairs (37 studies) in diverse conditions	"Crop C inputs differences was the only factor significantly and positively related to SOC stock differences between [no-till] and [inversion tillage], explaining 30% of their variability."
Veloso et al. 2018. Agr. Ecosyst. Env. 268: 15-23	Long-term field experiment (Brazil)	"Overall, the variation in SOC stocks was explained largely by plant carbon input (R^2 = 80%) which varied with N fertilization and cropping system."
Wang et al. 2017 Atm. Chem. Phys. 17: 11849-11859	Global modelling study	"We found that SOC change was significantly influenced by the crop residue retention rate (linearly positive), and the edaphic variable of initial SOC content (linearly negative)."
Wang et al. 2018. Biol. Fert. Soils 54: 423-436	Field experiment with wheat (China)	"All C fractions at most depths were correlated with the estimated wheat root residue returned to the soil"
Wei et al. 2020 Arch. Agron. Soil Sci. 66: 1520-1531	Long-term field experiment (China)	"A significantly positive correlation was observed between the annual SOC sequestration rate and annual carbon input (R 2 = 0.94)…"
Weyers et al. 2018. Soil Sci. Soc. Am. J. 82: 878-888	Field experiment (USA)	"Animal manure, particularly in combination with high residue inputs, had a positive impact for maintaining SOC." "These findings support the need to develop integrated management strategies that increase residue inputs through amendments as well as yield improvements, particularly for organic production systems in the upper Midwest region."
Wijesekara et al. 2021. J. Env. Man. 284: 112008	Global meta-analysis	"A meta-regression of 297 treatments found four variables with a relationship with SOC stocks: cumulative biosolids carbon (C) input rate, time after application, soil depth and type of biosolids. The cumulative biosolids C input rate was the most influencing driver."
Witing et al. 2019 J. Env. Man. 237: 272-280	Regional study (Germany)	"Both the increase in carbon inputs to soil (+8%) and the reduction of carbon turnover rates (−10%) had positive effects on SOC storage."

Xie et al. 2019 J. Plant Nutr. Fert. 25: 1073-1083	Long-term field experiment (China)	" OC contents of all macroaggreagte [sic] fractions were significantly and positively correlated with cumulative C input, especially for the iPOC content."
Xie et al. 2021 Soil Till. Res. 205: 104763	Large scale field study (China)	"Land use changes and carbon inputs were the main factors for temporal changes of SOC." [Highlights]
Xu et al. 2019. Geoderma 337: 622-629	Field experiment, (China)	"These results demonstrate that soil type, fertilizer application, and a threshold amount of maize straw input are needed to drive net SOC sequestration."
Xu et al. 2020 Carb. Balance Man. 15:2	Meta-analysis	"We propose that natural ecosystems have the capacity to buffer soil C changes and that increasing C inputs is one of the best measures to sequester C."
Xu et al. 2021 Glob. Change Biol. 27: 1170–1180.	Meta-analysis, SOC response to N fertilizer; 369 sites worldwide	"Our findings suggest that SOC increases [with N addition] largely resulted from the enhanced plant C input to soils coupled with reduced C loss from decomposition and amplification was associated with reduced microbial biomass and respiration under long-term N addition. Our study suggests that N addition will enhance SOC sequestration over time and contribute to future climate change mitigation.
Zhang et al. 2018. Geoderma 330: 204-211	12-yr field study, with rotation and tillage systems (China)	"Returning residue to the soil significantly increased SOC storage in all tillage/cropping systems…"
Zhao et al. 2018 Proc. Nat. Acad. Sci. USA 115: 4045-4050.	extensive survey of croplands (4,060 soil samples) (China)	"The SOC sequestration was largely attributed to increased organic inputs driven by economics and policy:…"
Zhu et al. 2020 Eur. J. Soil Biol. 96: 103146	Eight-year field study (China)	"This study demonstrates the non-linear relationship between carbon inputs and SOC content, and suggests the importance of the trade-off effects between microbial catabolism and anabolism."

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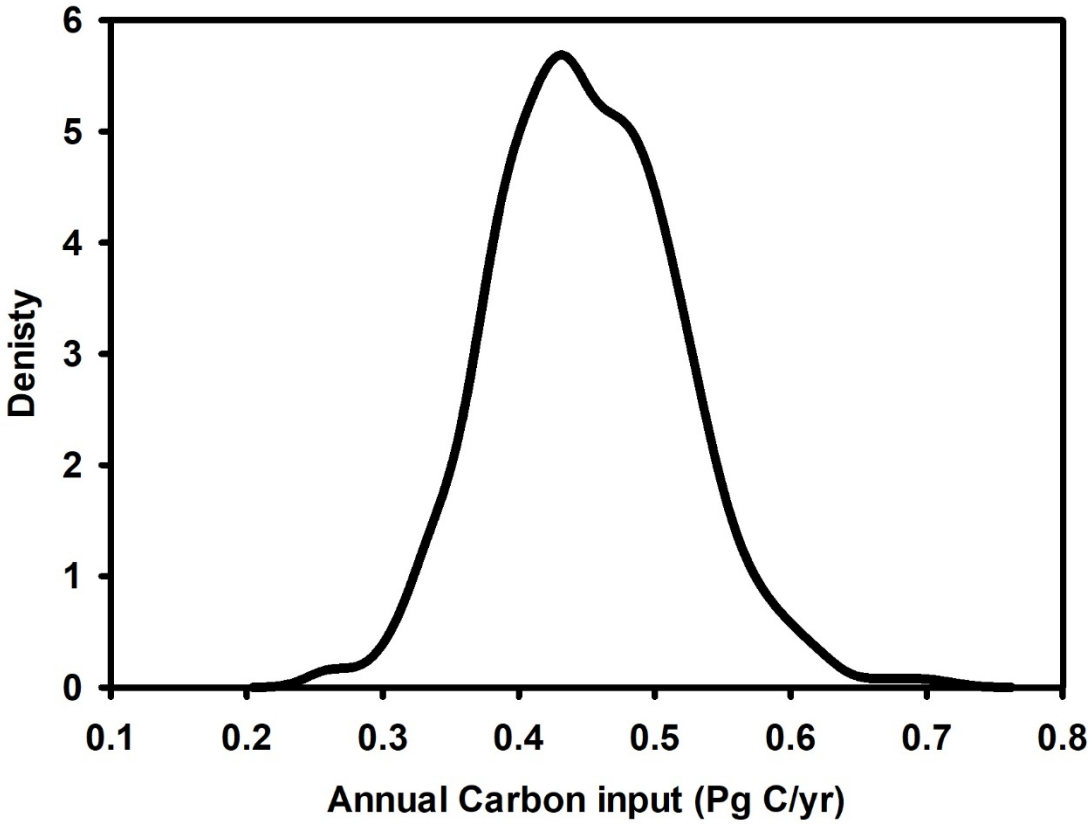

Figure S1. Distribution of annual carbon input (C_i) estimates from Monte Carlo analysis (n = 1000) of Equation [2]. Parameter estimates are detailed in Table 2.

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