Modelling long-term impacts of novel biobased fertilizers on soil C storage from laboratory short-term mineralization

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INTRODUCTION

The growing emphasis on circular food economies and sustainable agriculture is driving the recycling of exogenous organic matter (EOM) through the production of **biobased fertilizers** (**BBF**). While this provides an opportunity to reduce reliance on mineral and synthetic fertilizers, uncertainty exists regarding the **long term impact of BBF application** on soil organic matter dynamics.

This study aims to model the impact of novel BBFs — such as microbial biomass, insect biomass, insect frass, biochar, and derived blends, produced in the framework of H2020 project RUSTICA — on long term soil C storage.

For this purpose, we used a **modified version of the RothC** model encompassing additional EOM pools. We calibrated EOM pools' parameters, specifically pools' size and decay rates, through inverse modelling of BBF and derived blend mineralization rates measured with a gas chromatography system (*Fig. 1*) from amended soil.

Figure 1. *Automated gas chromatography system for GHG analyses of amended soils incubated in laboratory.*

METHOD 1: Incubation and respiration signals of blends

- Mineralization rates of 50 g (over-dried bases) preconditioned soil, amended with a dose of 0.5% (w:w) of diverse BBF (*Fig. 2*) and derived blends, where recorded during a 30 days aerobic incubation under controlled conditions of humidity (about 40% of soil water holding capacity) and temperature (20°C). Among the amendments we also included compost, as it was utilized in the formulation of the blends.

- Samples were incubated in sealed plastic jars (*Fig. 1*) continuously aerated at a constant flow rate (15 ml min^{-1}) for determination of CO_2 evolution every 4 h (in triplicate) with a continuous gas sampling and analysis system.

- Mineralization rates of amendments (*Fig. 3*) were isolated from the contribution of the soil CO_2 efflux by subtracting the efflux of a control (untreated soil).

Figure 2. *Some of the BBF used for the laboratory experiments before drying, grinding, and sieving at 1 mm.*

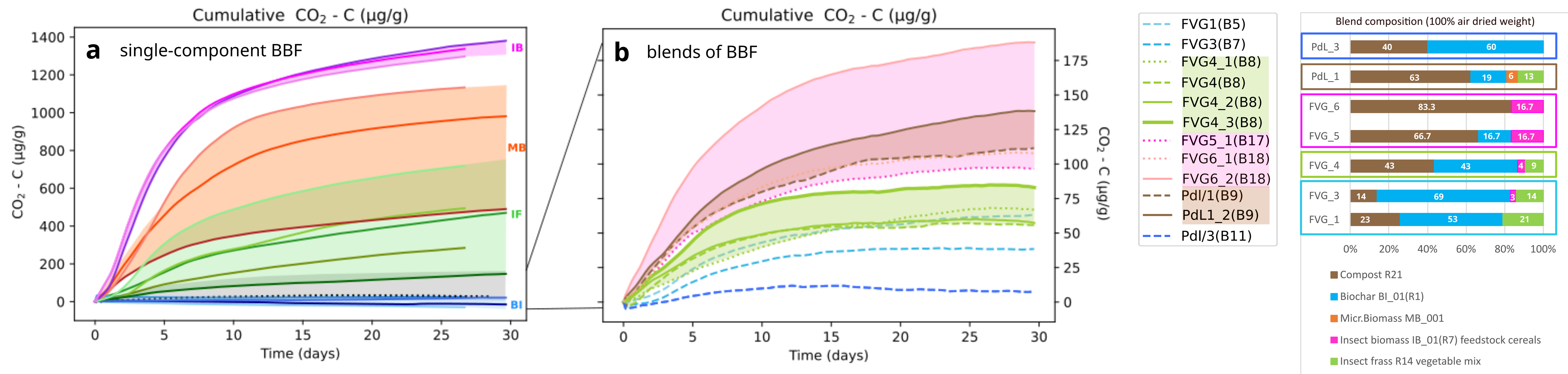


Figure 3. CO_2 *emissions. Cumulative respiration curves during the 30-day incubation. Each curve is the result of outliers removal and averaging of three signals from three replicates for: (a) single-component BBF and (b) blends of BBFs. Colors as in Fig. 7 and Fig. 9, respectively.*

METHOD 2: INVERSION of GC signals provides the KINETIC PARAMETERS FOR EACH BIO-BASED FERTILIZER and BLEND

NEW function for ROTHC model with EOM

DREAM DiffeRential Adaptive Metropolis

- Inverse modelling of mineralization rates is based on a modified Rothamsted carbon model (ROTHC) (Coleman and Jenkinson, 1996) to deconvolute the CO_2 efflux of amendments into EOM C-pools specific decay rates and size.
- A new R function of modified ROTHC, according to Mondini et al. (2017), foresees three additional EOM C pools (decomposable (DEOM), resistant (REOM), and humified (HEOM), with specific partition coefficients. It is also possible to assign specific decomposition rates to DEOM and REOM, while HEOM has a fixed decomposition rate of 0.02 y^{-1}.

- The simulations of soil respiration are run under the same incubation conditions.
- For the estimation of optimal kinetic parameters of BBF and blends, we perform an inversion of the measured mineralization rates of the incubations (*Fig. 3*) with a Bayesian approach using the DiffeRential Adaptive Metropolis (DREAM) algorithm (Scharnagl et al. 2010 and references therein, Joseph and Guillaume, 2011 and 2013). This allows us to infer the probability density functions of the values for C-pools size and their C-pool-specific decay rates (*Fig. 4*).

- Working with novel BBF, little is known about their kinetic parameters. Therefore, constraining the search of parameter estimates within a predefined space of solutions is a way to guide the search without starting from a specific (unknown) value. The search space for each parameter is defined by bounds taken from literature of similar products (from Woolf et al. (2023) for the biochar, and from Mondini et al. (2017) for the other BBF) and expanded to broaden the search and reach a more robust solution, when necessary.

- The RothC condition that forces the sum of all EOM pools to 1, allows to describe the size of the resistant pool (f.REOM) and humified organic matter pool (f.HEOM) in function of the size of a repartition factor between them (rep.f.REOM.HEOM) and the size of the decomposable pool (f.DEOM):

f.REOM = (1-f.DEOM)*rep.f.REOM.HEOM
f.HEOM = (1-f.DEOM)*(1-rep.f.REOM.HEOM)

- This reduces the search of optimal values to 4 parameters (DEOM pool size, the repartition factor, and the C-pool-specific decay rates k.DEOM and k.REOM)

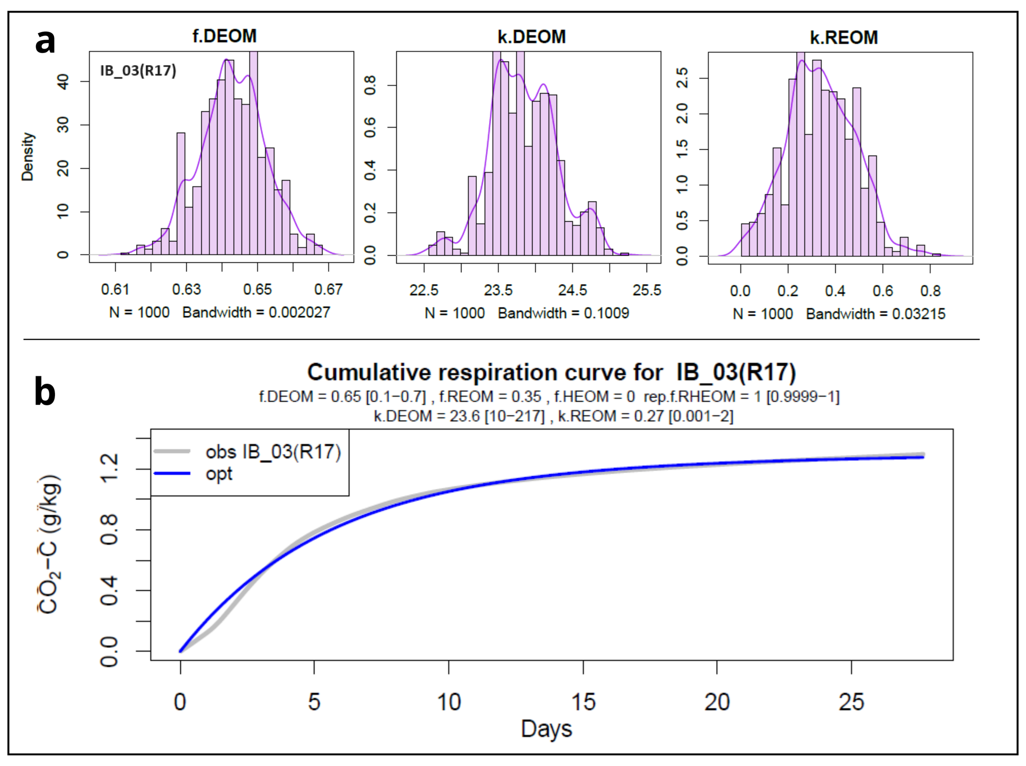
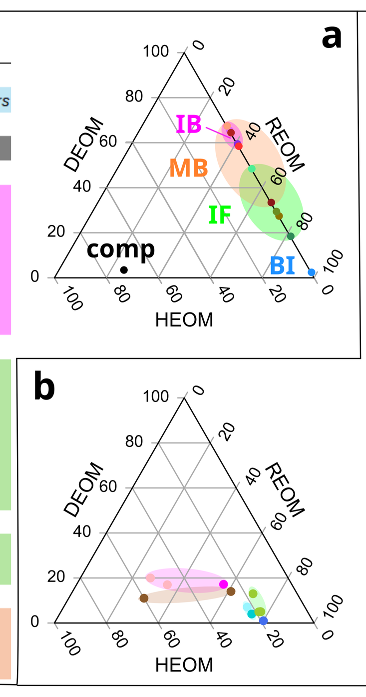


Figure 4. *Example of simultaneous estimation of kinetic parameters and respiration fitting. (a) marginal posterior probability distributions of 3 EOM pools of ROTHC. Histograms are constructed using a subset of the 50% most represented sample values generated with DREAM after convergence, (b) fit of the respiration curve.*

RESULTS: calibration of kinetic parameters and long-term predictions of SOC in soil amended with BBF and BBF blends

Calibration of kinetic parameters

group	type	BBF	C added (µg/g)	f.DEOM	f.REOM	f.HEOM	k.DEOM	k.REOM	feedstock
				[0.001-0.2]	rep.f [0.9999-1.]		[2.55-250]	[0.0001-2.52]	
BI	*biochar*	BI_02r(R2)	2278	0.02	0.98	0	5	0.0002	*willow wood and peppers*
				[0.01-0.1]	[0.2626−0.808]		[10-200]	[0.1-2]	
comp	*compost*	Comp(R21)	1055	0.03	0.25	0.71	29	0.10	*urban compost*
				[0.1-0.7]	rep.f [0.9999-1.]		[10-217]	[0.001-2]	
IB	*insect larvae biomass*	IB_01(R7)	2832	0.59	0.41	0	19	0.03	*cereals*
IB	*insect larvae biomass*	IB_02(R16)	2345	0.67	0.33	0	23	0.31	*cereals*
IB	*insect larvae biomass*	IB_03(R17)	2367	0.65	0.35	0	24	0.26	*cereals*
				[0.01-0.3]	rep.f [0.9999-1.]		[0-80]	[0.01-1]	
IF	*hermetia insect frass*	IF_02(R5)	2235	*0.18*	*0.82*	*0*	*12*	*0.44*	*Bear bagasse*
IF	*hermetia insect frass*	IF_04(R13)	1369	*0.27*	*0.73*	*0*	*7*	*0.24*	*Broccoli plant*
IF	*hermetia insect frass*	IF_05(R14)	1488	*0.29*	*0.71*	*0*	*12*	*0.97*	*Vegetables mix*
				[0.1-0.7]	rep.f [0.9999-1.]		[0-80]	[0.01-1]	
IF	*hermetia insect frass*	IF_06(R15)	1972	*0.48*	*0.52*		*12*	*0.02*	*cereal*
				[0.2-1.]	rep.f [0.9999-1.]		[10-217]	[0.010-2]	
MB	*microbial biomass*	MB_1.5(R9)	1208	0.33	0.67	0	27.54	1.211	*Paprika*
MB	*microbial biomass*	MB_4.1(R10_	2129	0.64	0.36	0	16.18	0.022	*market waste*
MB	*microbial biomass*	MB_4.2(R18)	2211	0.67	0.33	0	15.83	0.087	*market waste: carrots*



blend composition	BBF	C added (µg/g)	f.DEOM	f.REOM	f.HEOM	k.DEOM	k.REOM
			[0.001-0.2]	rep.f [0.32−0.81]		[5−60]	[0.0005−2.52]
23% comp (R21), 53% BI(R1), 21% IF(R14)	FVG1(B5)	1125	0.07	0.70	0.22	12.85	0.0007
14% comp (R21), 69% BI(R1), 3% IB_01(R7), 14% IF(R14)	FVG3(B7)	1403	0.04	0.74	0.22	15.30	0.0010
43% comp (R21), 43% BI(R1), 4% IB_01(R7), 9% IF(R14)	FVG4_1(B8)	756	*0.13*	*0.70*	*0.17*	*8.66*	*0.0005*
	FVG4(B8)	1375	*0.05*	*0.76*	*0.18*	*23.20*	*0.0005*
	FVG4_2(B8)	1512	*0.05*	*0.77*	*0.18*	*20.98*	*0.0006*
	FVG4_3(B8)	2268	*0.05*	*0.77*	*0.19*	*20.22*	*0.0007*
66.7% comp (R21), 16.7% BI(R1), 16.7% IB_01(R7)	FVG5_1(B17)	687	0.17	0.56	0.26	16.42	0.0220
83.3% comp (R21), 16.7%	FVG6_1(B18)	573	0.20	0.27	0.53	19.84	0.5633
	FVG6_2(B18)	1145	0.17	0.35	0.48	20.61	0.3978
63% comp (R21), 19% BI(R1), 6% MB, 13% IF(R14)	Pdl1(B9)	1218	0.11	0.29	0.60	18.46	0.0978
	Pdl1_2(B9)	1173	0.14	0.61	0.25	14.17	0.0285
40% comp (R21), 60% BI(R1)	Pdl3(B11)	1915	0.01	0.80	0.19	33.86	0.0005

Figure 5. *Tables with the information of the BBF composition and estimates for EOM C-pools size and C-pool-specific decay rates from DREAM for (a) single-component BBFs and (b) blends of BBF. In brackets are the upper and lower bounds that define the search space for each parameter. Ternary plots: distribution of BBF groups based on their optimized C-pool size.*

Long-term predictions of SOC in soils amended with BBF and BBF blends

Before running the long—term simulation of C storage in soil amended with different BBF and blend, we used the spin—up phase (*Fig. 6*) of the RothC model to compute the size of soil organic C pools at the equilibrium for a specific vineyard soil (Corno di Rosazzo, Italy). We used monthly averaged climate data (temperature, precipitation, and PET) of 30 years (1990-2010) and information about land management and soil coverage to take into account the conditions of typical vineyard in NE Italy. We hypothesized two long—term (100 years) scenarios of soil amendment: (a) single initial addition of 10 ton C/ha (*Fig. 7a* and *Fig. 8a*) and (b) annual addition at a rate of 1 ton C/ha/y (b) (*Fig. 7b* and *Fig. 8b*)

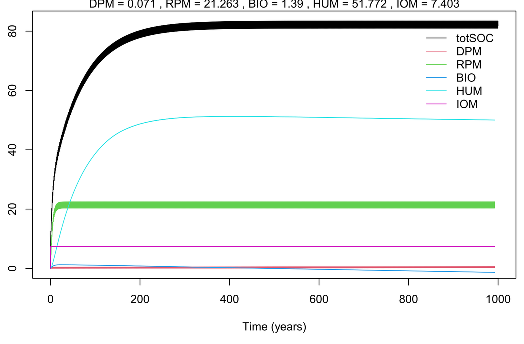


Figure 6. *Soil C pools size at equilibrium: DPM = 0.071, RPM = 21.263, BIO = 1.39, HUM = 51.772, IOM = 7.403.*

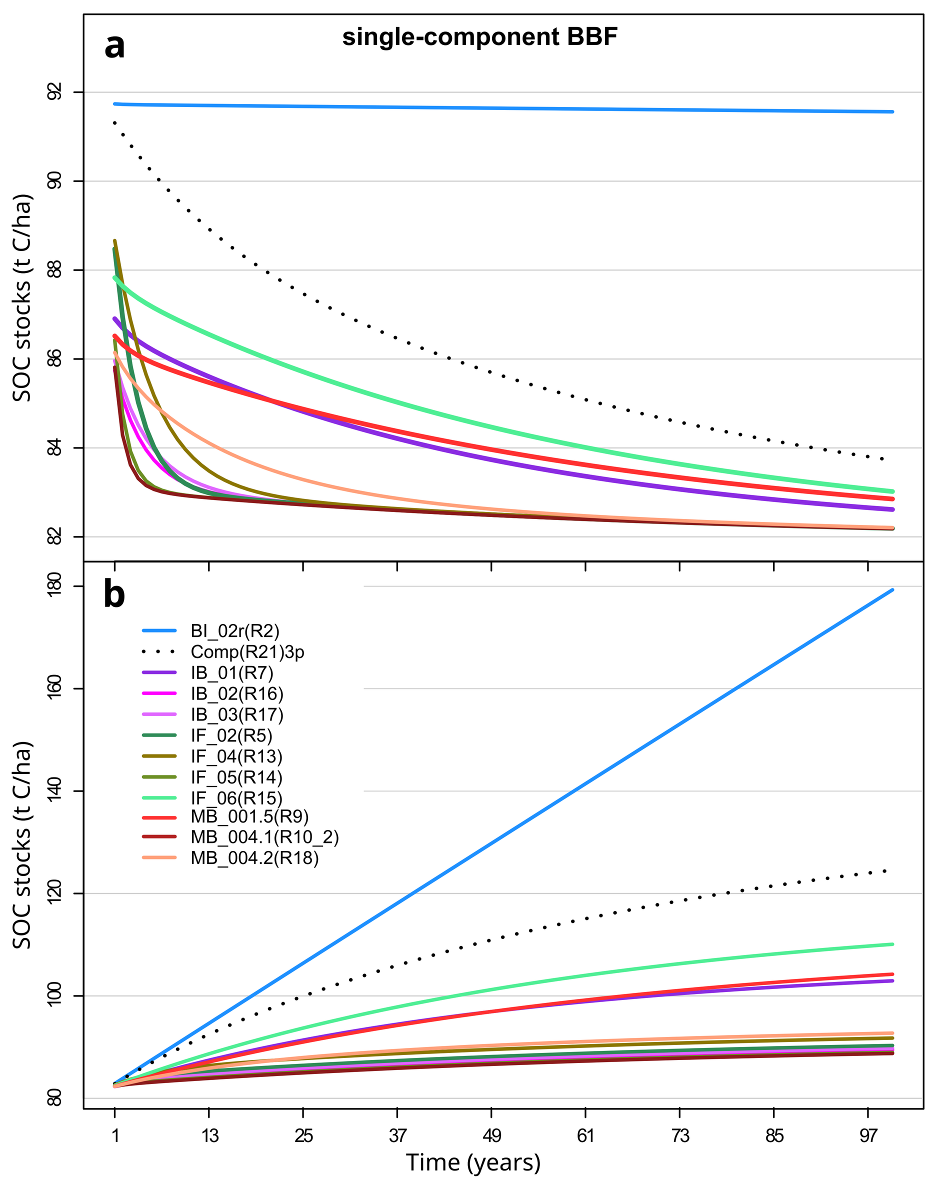


Figure 7. *Long-term prediction of SOC for the single-component BBF. (a) Single initial addition of 10 ton C/ha, and (b) Annual addition at a rate of 1 ton C /ha/y.*

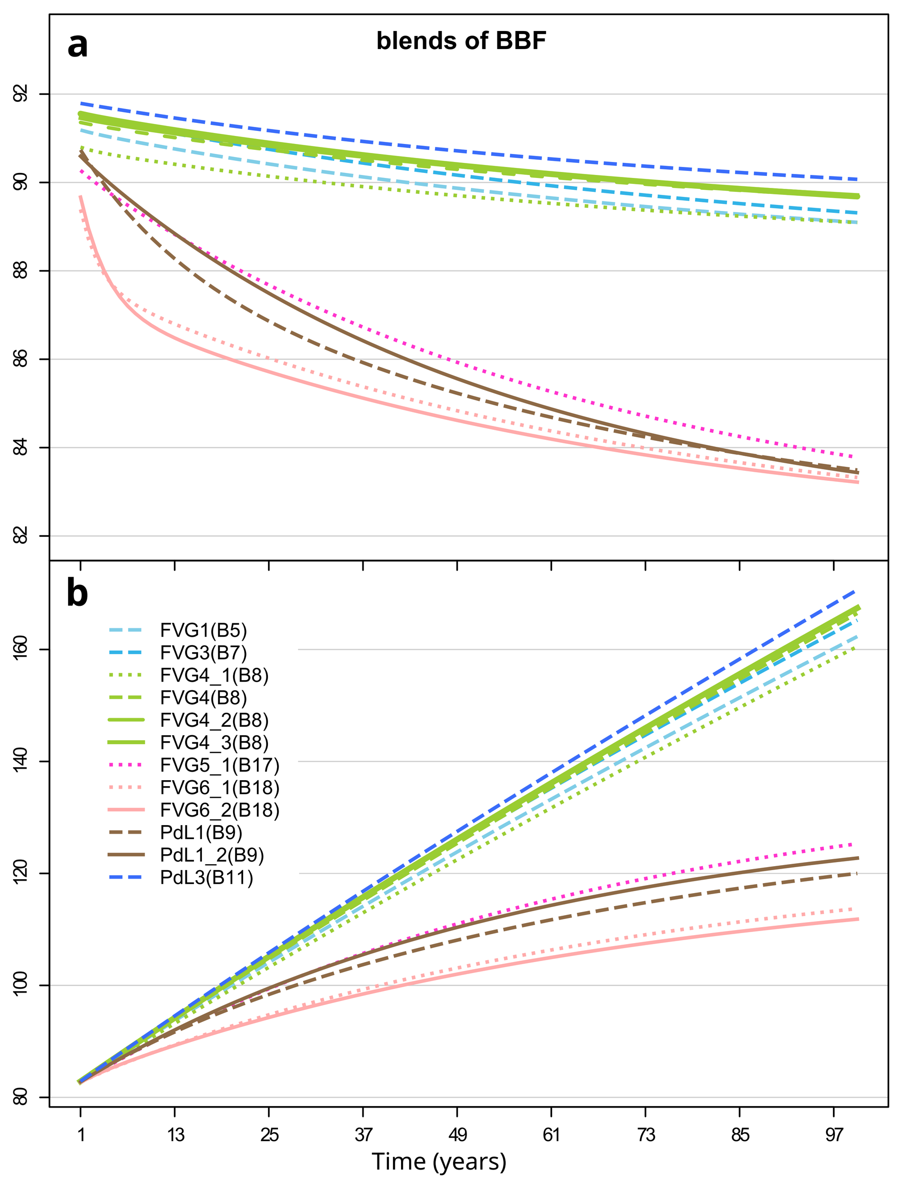


Figure 8. *Long-term prediction of SOC for blends of BBF. (a) Single initial addition of 10 ton C/ha, and (b) Annual addition at a rate of 1 ton C /ha/y.*

DISCUSSION AND CONCLUSIONS

Single-component BBF

Single initial addition results show the stability of each BBF. Biochar stands out with 96.6% C remaining after 100 years, indicating its stability and effectiveness in soil C sequestration. Compost, insect biomass, insect frass and microbial biomass (18.2, 4.3, 5.0 and 4.7 %, respectively) degrade faster. Continuous annual amendment simulations reveal biochar significantly increases SOC stocks by 119%, while compost contributes 52%. Other BBF contribute less to long-term sequestration, with annual rate of C sequestration around 0.13 ton C/ha/y, but offer other soil benefits.

Blends of BBF

Blends with biochar show varied C retention (13.1% to 82%) after 100 years, depending on biochar content (0% to 60%). Biochar stabilizes more degradable materials in blends, such as insect and microbial biomass, impacting SOC accrual. Blend FVG4 (41% biochar) and FVG3 and PdL3 (69 and 60% biochar, respectively)
show similar values of remaining C (*Fig. 9*).
For continuous amendment, SOC stocks increase by 36% to 108% over 100 years, correlating with biochar content ($r = 0.91$; $p < 0.05$).
The blends show a significant C sequestration potential with annual rate in the range 0.30-0.89 ton C/ha/y.

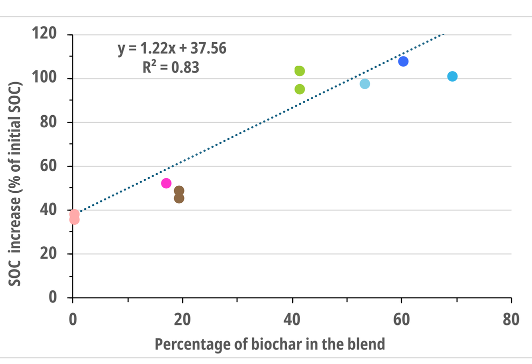


Figure 9. *SOC increase as a function of the percentage of biochar in the blend (colors as in Fig. 8)*

Results should be cautiously interpreted due to lab-based short-term parameterization, which is different from field conditions. However, they classify BBF and blends by their stability and C sequestration potential. The study's inversion procedure can be easily applied to data from amendments under field conditions for more robust assessment of EOM pools parameters. This enhances reliability of SOC simulation, a prerequisite for the implementation of measures favoring SOC conservation and increase. Overall, it offers insights into BBF complex dynamics for sustainable soil management.

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