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Communication

The Long-Term Experiment Platform for the Study of Agronomical and Environmental Effects of the Biochar: Methodological Framework

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Abstract: In this communication, a wide overview of historical Long-Term Experimental Platforms (LTEP) regarding changes in soil organic matter is presented for the purpose of networking, data sharing, experience sharing and the coordinated design of experiments in the area of Earth system science. This serves to introduce a specific platform of experiments regarding biochar application to soil (LTEP-BIOCHAR) and its use for agronomic and environmental purposes (e.g., carbon sequestration, soil erosion, soil biodiversity) in real conditions and over a significative timeframe for pedosphere dynamics. The methodological framework, including the goals, geographical scope and eligibility rules of such a new platform, is discussed. Currently, the LTEP-BIOCHAR is the first of its kind, a community-driven resource dedicated to biochar, and displays around 20 long-term experiments from Europe, the Middle East and Africa. The selected field experiments take place under dynamically, meteorologically and biologically different conditions. The purposes of the platform are (1) listing the field experiments that are currently active, (2) uncovering methodological gaps in the current experiments and allowing specific metadata analysis, (3) suggesting the testing of new hypotheses without unnecessary duplications while establishing a minimum standard of analysis and methods to make experiments comparable, (4) creating a network of expert researchers working on the agronomical and environmental effects of biochar, (5) supporting the design of coordinated experiments and (6) promoting the platform at a wider international level.

Keywords: biochar; long-term experiment platform; soils; soil organic matter; design networks; data sharing

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1. Introduction

In their work "Integrated biochar research: a roadmap", Amonette et al. (2021) [1] highlighted the need for the creation of a long-term, integrated, coordinated research and development program to provide the foundational science needed to support the adoption of biochar as a practice to mitigate climate change and to improve soil health and fertility. This can accelerate the adoption of biochar in agriculture and foster regenerative production systems for climate-resilient food and energy [2].

From their viewpoint, Amonette and coworkers, from laboratories and universities in the US, develop and articulate a biochar scope research program for the next two decades. Such a proposition expresses the need for certainties related to the use of biochar as a response option for many of the challenges expected in the coming years. After a

20-year debate on the effects, biochar has indeed emerged as a promising land management technique to mitigate and adapt to climate change and improve soil fertility [3]. Biochar represents a long-term carbon store since (i) it has proven—in the International Panel for Climate Change's (IPCC) words—"relatively" resistant to decomposition compared with fresh organic matter or compost [3] and (ii) it has the potential to stabilize organic matter when added to soil. Having made appropriate distinctions and specifications about feedstock and process temperatures, this statement can be considered almost certain in the IPCC's terms, showing very high confidence [4]. This recalcitrance can be exploited to convert biomass that is less resistant to decomposition into carbon storage pools, co-producing, at the same time, renewable energy. These properties have led to a plethora of studies, applications and initiatives all over the world [5]. Advantages in the use of biochar can go, however, far beyond the production of carbon stock pools. Nonetheless, biochar knowledge showing very high confidence ends here. As reported by Schmidt et al. (2021), due to the absence of long-term experiences, knowledge about biochar degradation is limited [6]. For instance, Wang et al. (2016) [7] estimated the mean residence time of biochar in 556 years. Although statistically significative (128 observations), this work was conducted mainly through laboratory incubation studies, not taking into account the effects of climate (e.g., precipitation, dry spells) and microbiological activity in the pedosphere on biochar persistence. There is "medium evidence" that biochar's stability is influenced by soil properties [3] and biochar can be further stabilized by interactions with clay minerals and native Soil Organic Matter (SOM). However, due to different interactions between the biotic (e.g., microbial communities, flora) and abiotic (e.g., clays, macro-aggregates) components of soil, biochar's mineralization rates can vary within two/three orders of magnitude [7–9]. As a result, it was found that the mean residence time for different forms of biochar in different applications varied from decades to thousands of years [7]. Recently, Pulcher et al. (2022) [10] confirmed the results found in Ventura et al. (2015) showing that the long-term degradation rate of biochar for an 8-year field experiment in a poplar short-rotation coppice plantation was around one order of magnitude less than Wang's results [7] (10–30 years). Notably, Ventura et al. [11] concluded that the presence of plant roots has a crucial effect on biochar's stability and, therefore, laboratory incubations may overestimate the C sequestration potential of biochar.

When combining such uncertainties—those related to the mechanistic behavior of biochar—with those related to biomass availability and the capacity to convert the available biomass into soil and agricultural and technological systems—the IPCC placed the potential carbon removal between 0.03 and 6.6 $GtCO_2eq$ year^{-1} and associated "medium evidence" with this two-orders-of-magnitude range when evaluating biochar's addition to soil. As a result, when compared to geological Carbon Capture and Sequestration, and BioEnergy with Carbon Capture and Storage (CCS, and BECCS), such uncertainty is limiting the massive and widespread economic adoption in repayment/offsetting schemes and opportunities offered by emission trading schemes.

In Table 1, we report the four macro groups of ecosystem services investigated in biochar research, combining the findings associated with each macro group and their knowledge gaps.

Table 1. Ecosystem services affected by biochar, associated with findings and uncertainties.

Ecosystem Services	Finding	Truth Value	Uncertainties
Carbon sequestration	Biochar resistant to decomposition compared with fresh organic matter [5]	Very high confidence	Feedstock and process temperature
	Biochar stability is influenced by soil properties [7]	Medium confidence	Interactions between biotic and abiotic components of soil

Table 1. *Cont.*

Ecosystem Services	Finding	Truth Value	Uncertainties
	Global carbon equivalent removal rate for converting available biomass into biochar is between 0.03 and 6.6 $GtCO_2eq$ $year^{-1}$ by 2050 [3]	Medium confidence	Biomass availability and sink models' interactions between biotic and abiotic components of soil
	Mean residence time is in the order of magnitude of hundreds of years [12]	Low confidence	Feedstock and process temperature, interactions between biotic and abiotic components of soil, priming effect, crops, and soil conditions
Provision of food, fibers, feed, and other biomasses	Increased plant productivity by 10–13% [13]	Medium confidence	Biochar type, biochar and fertilizer agent interactions, application methods, permanence of the effect
Nutrient cycling	Improved nutrient use efficiency and increased availability of phosphorus and potassium in soils; amelioration of soil acidity [14–16]	Medium confidence	Biochar type (ash content) and crop type, soil alkalinity; lack of long-term experiments, permanence of the effect
Storing and purifying water, regulating flows, recharging aquifers	Increased water holding capacity [17]	Medium/high confidence	Specific local conditions may result in increased runoff and lower infiltration rates; soil type

Besides storage and sequestration capacity, biochar can provoke indirect and positive effects to mitigate non-CO_2 Green House Gas (GHG) emissions from soil, such as reduced losses of nitrogen, reduced use of fertilizers, and increased atmospheric CO_2 uptake due to increased plant biomass and yields [3,11–13].

There is a "clear consensus" that biochar can reduce soil nitrous oxide emissions as a result of increased nutrient cycling, as indicated in Table 1 [6]. However, further research is needed since most field studies have measured emission reductions in the first year of application, and only Hagemann et al. (2017) [18,19] showed an N_2O emission reduction in the third year after application. Biochar could also mitigate CH_4 emission for a prolonged period in flooded soils. This has been explained as an effect of methanogens and methanotroph microorganisms stimulated by biochar, which caused the CH_4 reduction in the first year after application [20]. For the subsequent years, biochar seems to inhibit methanogen microorganisms, probably due to increased soil aeration, reducing CH_4 emissions. However, the CH_4 mitigation effectiveness of biochar application lacks a robust number of long-term field experiments that can provide strong evidence on the stable mitigation of soil CH_4 emissions [21].

Additional climate benefits of biochar soil application can arise through reduced nitrogen fertilizer requirements, due to reduced losses of nitrogen. This is explained by Borchard et al. (2019) [22], positing a carrier matrix function for nutrients to reduce leaching. The results are based on 755 observations: 90 from field experiments, and the rest from incubation and pot trials. The IPCC (2019) [23] and Schmidt et al. [6] also reported that biochar has the potential to benefit climate adaptation by improving the resilience of food crop production systems to future climate change by increasing yields and improving water holding capacity in some regions.

When considered in the framework of the mitigation potential of response options in 2020–2050, the addition of biochar to soil offers the largest maximum mitigation potential among agricultural pathways; however, unlike other options, such as reforestation, fire management, natural forest management, and nutrient management, the mitigation potential has not been well demonstrated beyond research settings. Hence, the trade-offs, costs, and feasibility of the large-scale implementation of biochar are poorly understood [24]. Several studies have highlighted the lack of historical databases [25] and limited knowledge about the long-term description of Soil Organic Carbon (SOC) stocks [18]. For example, with reference to the dataset underpinning the work of Gross et al. (2021) [18], the number of field experiments lasting more than 3 and 10 years and focusing on the estimation of SOC increase due to biochar application were respectively 12 and 1. Moreover, none of these studies have estimated biochar stability, since they did not apply any methods to measure the biochar decay rate. All the meta-analyses that investigate the efficacy of biochar to improve ecosystem services cover a limited number of 1–3 years in field experiments, which represents less than 20% of the total [11,17,21,22,26]. In this sense, lab incubation (decomposability of soil organic matter under controlled conditions) and pot experiments (assessing plants' productivity under controlled conditions) largely prevail over field studies.

In line with the lack of a consistent number of long-term experiments, Tammeorg et al. (2017) [27] identified the upscaling of biochar experiments from short-term and laboratory-controlled conditions to long-term and field conditions as a key recommendation to reduce the knowledge gaps regarding biochar soil amendment's interactions with ecosystem services. In fact, biochar undergoes an aging process in soil, wherein its long-term properties develop over a period of years following soil amendments, and these are poorly studied [28]. Indeed, the growth in the biochar literature in the past two decades lacks a coordinated approach between the biochar research groups and long-term, well-designed field studies on the efficacy of biochar in different soil types and agro-climatic zones [29]. A coordinated approach would guide the scientific community towards large-scale, regionally focused, long-term studies of biochar production and application to evaluate the technology cost–benefits and potential impact [1]. In summary, while meta-analyses on the efficacy of biochar are abundant and exhaustive, we call for a coordinated effort to design, measure, and compare long-term experiments (LTEs).

At present, there is no unified knowledge infrastructure to study the long-term effects of biochar application to soil. To mitigate climate change, improve soil health and fertility, and integrate and coordinate research on this topic, this communication intends to propose a community-driven resource for networking, data sharing, experience sharing, and the coordinated design of long-term experiments with biochar. We intend to illustrate the rationale behind it and to discuss the future trajectories of such a platform.

2. State of the Art of Long-Term Experiments Focusing on Soil Carbon Studies: Site Networks, Database, and Data Management

An international group of experts held, at the Institute of Arable Crops Research, Rothamsted, in 1995, a workshop entitled "Evaluation of Soil Organic Matter Models Using Existing Long-Term Datasets", which marked the launch of the Soil Organic Matter Network (SOMNET) [30], a network of SOM model developers and experimentalists working on LTEs that included measurements of soil carbon [31]. The workshop put together the most relevant experiences related to LTEs concerning SOM measurements, and, in this sense, it was and still is a pioneer in methodologies concerning site networks, databases, and data management focusing on SOM. The workshop put together and shared the results of historical LTE sites experiments: the North American site network, led by Paustian; the Australian site network lead by Grace; the long-term data sets from Germany and Eastern Europe led by Körschens; and the European Soil Organic Matter Network (SOMNET) led by Smith.

The main features of the above-mentioned networks and initiatives, together with other worldwide networks, are reported in Table 2.

Table 2. Main features of the LTE networks addressing SOM studies (at the time that the information was published).

LTE Networks	Experiments	Duration Eligibility (Years)	Oldest Experiment (Years)	LTEs Addressing SOM
Australia (1995)	32	10	83	>6
Germany and Eastern Europe (1994)	50	30	116	>13
EuroSOMNET (2002)	110	8	157	>45
North America (1992)	39	10	118	39
BonaRes Germany (2020)	200	20	142	n.a.
Africa (2012)	19	5	52	n.a.
Nordic Research Platform (2008)	38	16	104	>6

LTEs addressing soil carbon studies in Australia considered trials over 25 years, and the three oldest cropping trials in the network ranged from 70 to 83 years, while the latest experiments started 10 years before the workshop. The network structure was composed of 32 living experiments out of 50 experiments developed in Australia, which covered an excess of 10 years. The experiments included different soil types and were aimed at establishing the potential for carbon sequestration in Australian agricultural soils. The Australian network was based on the concept of the meta-analysis, establishing a central database of information for use by researchers. The project became later the Australian Carbon Farming Initiative/Emission, which gathered data for estimating and reporting SOC stock changes for SOC management projects [32].

The long-term data sets from Germany and Eastern Europe did not represent a formal network, but rather a collection of data from 23 German LTEs and 27 in Eastern Europe, including the European part of Russia. This was a selection of a wider set of experiments older than 30 years. The oldest experiment sought to measure carbon sequestration dating back to 1878, and the latest started in 1963. Some of the sites were included later in EuroSOMNET and were inventoried under the BonaRes project, which collected 200 LTEs' data across Germany, with a minimum duration of 20 years or a planned duration of at least 20 years [33].

The North American site network [31] presented a working site network where site information was systematically treated and cross-site sampling using the same protocol was adopted. The goals of the network included the following:

1. assessment of C sequestration potential in agricultural soils;
2. assessment of agricultural ecosystem adaptation to climate and CO_2 changes;
3. regional assessment of C sequestration on U.S. Conservation Reserve Program land;
4. regional assessment of the impacts of conservation tillage on SOM;
5. regional soil quality assessment and monitoring;
6. contribution to IPCC chapter on "Mitigation options in agriculture";
7. process studies of environmental and management impacts on soil structure and SOM dynamics;
8. process studies of tillage effects on microbial community structure and SOM stabilization;
9. carbon dating and $^{12}C/^{13}C$ analyses of SOM turnover;
10. management and soil effects on microorganism biodiversity.

The European SOMNET [30] was a network aimed at the following:

1. collecting and retrieving LTE experimental data;
2. establishing a database system—composed of a metadata database and actual dataset database—as described here below;
3. establishing quality control criteria and protocols;
4. fostering data and model sharing among researchers through an electronic bulletin board and list server—which was made possible through a collaboration agreement preserving the intellectual property rights of data holders and model developers.

For specific experiments, an actual database was established. The network also envisaged establishing common sampling protocols and analysis methods to be used at all network sites. In 1997, Smith et al. (2002) [34] brought the project under the EU-ENRICH program, which aimed to strengthen the European component of SOMNET—thus named EuroSOMNET—with reference to long-term SOM experiments in Eastern Europe and the former Soviet Union. In 2002, most of the datasets were for arable experiments, and only 17 of the 109 experiments contained data on non-arable land use. At that time, the database included 110 LTEs. The experiments ranged in duration from 8 to 157 years (the oldest in the world in 2002): the average duration was 45 years, with a median of 36 years. The details collected for each EuroSOMNET experiment contained the following information:

1. general details (name of the experiment and start year, contact details for data holder/duty person);
2. local condition descriptions (e.g., coordinates, site history, climatic region, rainfall and temperature, soil description);
3. nature of the experiment (e.g., land use, vegetation/crop type, factors, treatments, land management);
4. measurement methods and frequency;
5. experimental design (e.g., plot size, slope, heterogeneity measures, replicates, controls, statistical analysis, etc.);
6. data availability;
7. key references.

It has to be noted that the collected information included the availability of archived samples and the nature of collected data was included.

Besides the mentioned networks and initiatives, it is worth reporting the existence of other initiatives, such as the inventory of LTEs in Africa, which took over from the "tropical long-term experiment" led by Prof. Swift at the Tropical Soil Biology and Fertility Institute, Nairobi [35]. Additionally worth mentioning is the Nordic Long Continued Agricultural Soil Experiments inventory, encompassing experiments initiated before 1992 in Norway, Sweden, Finland, Estonia, and Denmark [36].

All the participants of the mentioned workshop in 1995 reported the need for LTEs to understand the complex and slow changes in soil properties. This was the necessary endeavor to achieve good science and contribute the implementation of the Global Change and Terrestrial Ecosystems (GCTE). This program belongs to the International Geosphere-Biosphere Programme (IGBP). This was instrumental in setting out the basic science of the terrestrial carbon cycle in an IPCC special report on land use, land use change, and forestry and in all the Assessment Reports issued by the IPCC. The workshop and initiatives taken thereafter showed the potential of disclosing the wealth of data and the work of analysis and comparison. For example, Glendining and Powlson, in the section "Interpretation Difficulties with Long-Term Experiments" in Powlson et al. (1996) [31], also revealed many practical issues that could affect the quality of data from LTEs. They especially focused on those experiments that were not originally established to measure changes in soil organic matter (SOM) content—including soil movement between plots, erosion, changes in cropping or sampling practices with time, and changes in analytical methods. One notable conclusion from the workshop was that an LTE's average cost is around USD 10,000 per year. LTEs are therefore valuable under many perspectives and not easily reproducible. The new frontier was the large data exploitation.

As of May 2022, all presented networks and organizations are not curating data or proposing standard formats and cross-sampling protocols anymore. However, individual LTEs and their networks are still used to answer critical questions [37].

3. The Proposal for a Long-Term Experiment Platform for the Study of the Agronomical and Environmental Effects of Biochar (LTEP-BIOCHAR)

We have proposed and developed a long-term experiment platform for the study of the agronomical and environmental effects of biochar (LTEP-BIOCHAR): a platform intended to be a community-driven resource to improve the biochar experiment network, comparing the ways in which experiments have been conducted and organized, highlighting methodological gaps, and delivering recommendations.

To achieve this goal, LTEP-BIOCHAR currently displays selected experiments conducted so far with the following immediate purposes:

1. Taking a census of the current LTEs on biochar's effects on soil;
2. Presenting the objectives, methods, and conditions of the experiments;
3. Displaying the authors and promoters of the experiments.

Scope of the platform. The scope of the platform addresses the agronomical and environmental effects of biochar. Given the scarcity of LTEs in this field, the platform collects data on experiments at this time in agriculture, forestry, and horticulture. The remediation of polluted soils is not within this scope because it would imply a completely different approach. At present, the focus regards what Amonette et al. [1] call mechanist research. In other words, the platform serves to study fundamental processes controlling biochar performance across a variety of soils, plant communities, and climatic zones, using biochar representing common feedstocks and conversion processes.

Conditions to qualify an experiment as LTE. In LTEP-BIOCHAR, an experiment qualifies as an LTE if either its duration is at least three years or in a prospective manner if its duration is at least one year and it will be available for further analysis and experiments for at least 3 years. The measurements must be conducted with a scientific method and compared with initial measurements: replicability and reproducibility must be ensured. A record of all treatments must be reported, and all conditions affecting data quality, such as soil movement between plots, erosion, changes in cropping or sampling practices with time, and changes in analytical methods, must be mentioned.

Currently, the platform holds detailed records of 18 long-term soil biochar experiments (50% of the experiments are ongoing) (Table 3), offering wide geographical coverage of Europe, and includes a few experiments from African (2) and Middle Eastern (1) countries (Figure 1).

Table 3. Long-term experiments currently included in LTEP-BIOCHAR platform. (The abbreviation n/a indicates that the researchers have not confirmed the experiment's continuation.)

Field Name	Location	Ongoing
1. Tebano [38]	Italy	Yes
2. Braccesca [39]	Italy	Yes
3. Poggio Torselli (olive)	Italy	Yes
4. Poggio Torselli (wine)	Italy	Yes
5. Jumilla [40]	Spain	Yes
6. Udine [40]	Italy	Yes
7. Bezek [41]	Polonia	n/a
8. Őrbottyán-Nyírlugos [42]	Hungary	n/a
9. Donndorf-Eckersdorf [43]	Germany	n/a
10. Mashhad [44]	Iran	n/a
11. Siaya-Nyabeda-Kibugu [45]	Kenya	n/a
12. Gartow [46]	Germany	n/a
13. Prato Sesia [11]	Italy	Yes
14. Frescobaldi	Italy	Yes
15. Groß-Gerau [47]	Germany	n/a
16. Cesa	Italy	Yes
17. Dolna-Malanta [48]	Slovakia	n/a
18. Merelbeke [40]	Belgium	n/a

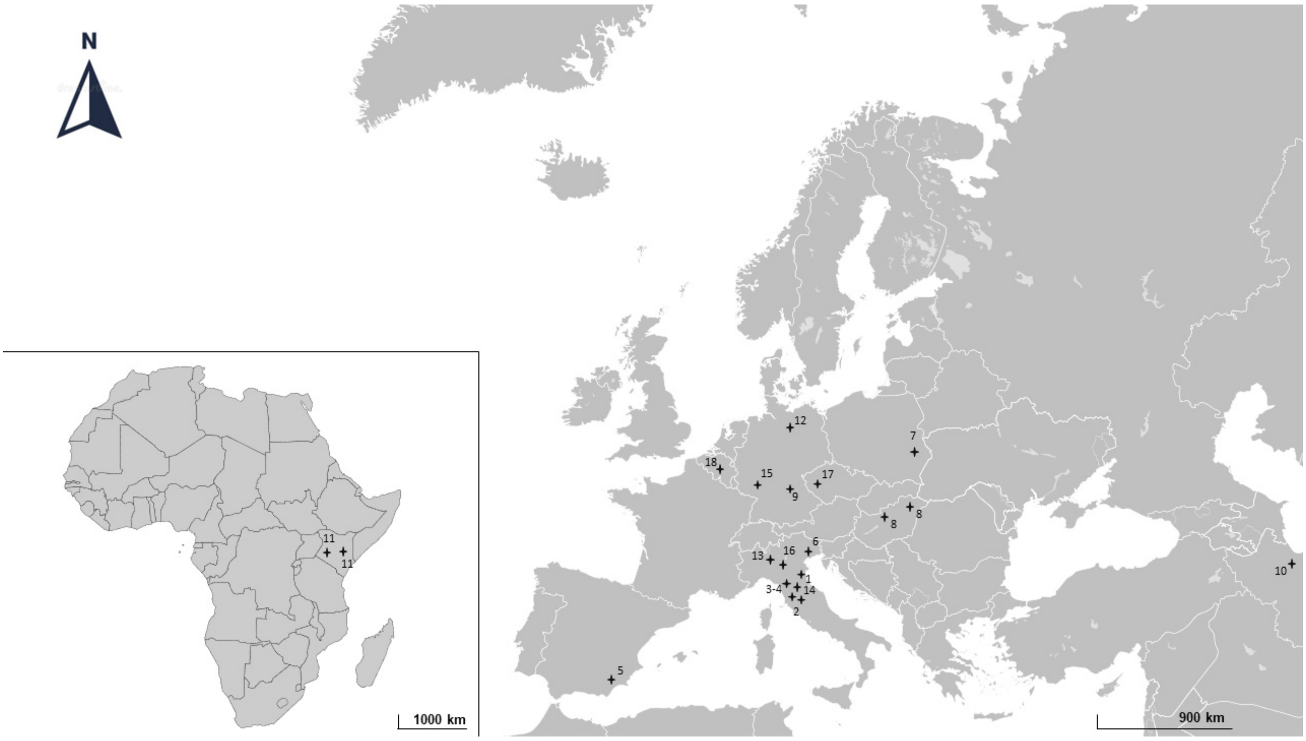

Figure 1. The locations of experiments in Europe, Africa, and the Middle East currently included in LTEP-BIOCHAR. Numbers correspond to the experiments listed in Table 3.

As a general goal, the platform shows the aim of the research and the experimental design. Therefore, by comparison, a further analysis may uncover methodological gaps and suggest new hypotheses to be tested without unnecessary duplications. In this sense, the platform aims to support the design of future experiments by comparing the ways in which experiments are conducted and organized, highlighting methodological gaps, and delivering recommendations, even though the implementation of databases whose datasets will be available for several analyses (e.g., multivariate analysis) and easily attainable for the scientific community. Collected data and metadata need to be in a standard format. Data standardization is the process that ensures datasets' comparability. The use of data standards enables the reusability of data elements and their metadata, which can reduce redundancy between systems, thereby improving reliability.

The results of the individual experiments in the standard format are briefly summarized only to illustrate the objectives and methods of the LTEP-BIOCHAR experiments.

The process of populating the platform and the selection criteria are summarized as follows:

1. engaging new LTEs on biochar (by invitation, literature search, or spontaneous request from the LTEP leader);
2. qualification check from the LTEP board, including minimum duration (3 years), availability to provide all the information requested in the standard format;
3. downloading and completing the "template" entirely, adding all the details of interest and attaching some photos of the site and the materials used, specifying all technical details of the experiment;
4. providing at least one published, peer-reviewed paper as proof of the scientific approach of the experiment, as well as authorship and data property protection;
5. editorial checks and adjustments to fit the standard format;
6. publication on the website [49].

At present, in order to make the data quality check and validation more robust, we accept on the platform only studies published in peer-reviewed papers. Duration and scope requirements are reviewed by the authors of this work, who, at present, serve as the scientific committee of the platform. Published papers, furthermore, guarantee that data/model holders have their authorship and data ownership protected. All additional information is published under the Creative Commons 4.0 [50].

Standard format. The platform is structured as a collection of open field studies, all of which have been standardized to a standard format (Table 4). We have developed a prototype standard metadata format, defined by examining the main variables that influence the agronomic and environmental effects of biochar on soil.

Table 4. Summary of LTEP-BIOCHAR standard format.

Section	Logical Function
Project name and location	Name that identifies the field study in the platform and at geographic level
Experimental purpose	Aim of the study, technical–scientific challenges (e.g., increasing water retention, soil quality improvement, carbon storage, etc.), technical challenges (e.g., increasing quality and production), and relating the quality of the substrate
Geographic position	Geographic location of the experiment
Site description	Accurate description of the main environmental variables that act on soil dynamics: climate, soil type and its physico-chemical characterization, initial field conditions, and agronomic operations
Biochar and its application	Biochar type as well as its physico-chemical and geochemical characterization, biochar application rate, and description of the experimental design: plot size, slope, cultivation, heterogeneity measures
Measured parameters	Parameters periodically measured in relation to the purpose of the experiment, with particular attention to sampling frequency and analytical protocols: vegetation measurement, time zero samples, soil carbon measurements, soil physico-chemical properties, etc.
Planned activities	Description of the planned activities (such as changing the conditions of the soil, agronomic operations, experimental devices, etc.)
Key findings	Scientific results derived from the field study and data
Presentation of the working group	Description of the group that conducts and supports the experiment: collaboration with universities, ministers, and any received funding from private parties, national/EU/Federal projects, etc.

A reference name (internal to LTEP) was given to each experiment and provides a point of reference in reports. Additionally, besides the reference name, it was indicated whether the experiment was still running, marking it with the label "ONGOING". The collection of LTEs is available via a website managed by the University of Bologna [49] and ICHAR [51]. All researchers can submit their experiments through the instructions therein provided.

Collectively, the sites represent an array of different experimental treatments, including biochar (66.6%), biochar and compost (27.8%), and biochar and fertilizers (5.6%). Half of the experiments were performed in arable soil, 22.2% in vineyards, and 27.8% in olive groves. Moreover, 70% investigated the effects of biochar on SOC content, 20% the effect on yield increase, and 10% on soil biology. In terms of financing, 77.8% of the experiments were publicly funded, while the remaining 22.2% instead were self-funded (Table 5). Additionally, it has to be noted that around the half of the site experiments are still ongoing.

Table 5. Sample of key findings from the LTEP-BIOCHAR metadata.

Metadata	Key Findings
Cropping system	50% arable soil, 22.2%vineyard, 27.8% agroforestry (olive groves)
Irrigation	n/a [1]
Treatment	66.6% only biochar, 5.6% biochar and fertilizers, 27.8% biochar and compost
Duration of the experiment	Median = 4 years, average = 5.3 years, longest = 13 years
Main purpose	20% yield increase, 70% SOC content, 10% soil biology
Funding	77.8% funded by programs/entities, 22.2% self-funded

[1] Usually, arable soils are irrigated.

4. Critical Review of the Adopted Choices

Comparison of the minimum duration of LTEs presented in Table 2 with the chosen duration of 3 years should be explained.

The definition of LTE would suggest a much longer experimental length. Smith (2008) [52], considering the measurements necessary for assessing the net ecosystem carbon budget of croplands, suggested at least a decade as a unit to designate an agronomic experiment as long-term. There are many reasons to affirm this:

1. the period for soils in a temperate location to reach a new equilibrium in terms of C sink saturation after a land use change is around 100 years [52];
2. guidelines for greenhouse gas inventories use a figure of 20 years for soil C to approach a new equilibrium: "It is important, in deriving estimates of biomass accumulation rates, to recognize that biomass growth rates will occur primarily during the first 20 years following changes in management, after which time the rates will tend towards a new steady-state level with little or no change occurring unless further changes in management conditions occur" [53];
3. a decade is therefore the minimal timespan to record significative changes.

Biochar has a longer mean residence time in soils compared to conventional organic soil amendments, i.e., in the range of hundreds of years compared to 1–10 years. Robust evidence of biochar's effect on crop yields should be shown over this same time. Moreover, many side effects, involving the ecosystem services presented in Table 1, might manifest only some years after the biochar's addition to the soil, and since it is an irreversible practice, "is it appropriate?" seems a legitimate question. As a minimal requirement, Jeffrey et al. (2017) recommend studying the effects on yield after two or more years of biochar application, and representative simulated aging methodologies are required to investigate relevant long-term effects (tens to hundreds of years) [25].

In response to sensitive objections to the 3-year duration, there are scientific, practical, and necessary considerations that led to this choice. The first reason is the meta-analysis of the positive effects of biochar application to soil on crop production, presented by Jeffery et al. [6], where no studies that had run for more than 2 years were found in the literature. Four years is the longest study duration in this meta-analysis, with most experiments covering one growing season. More than 90% of the studies included in the analysis showed results over one growing season. More generally, from our review, around 80% of data about biochar's effects are gathered from pot trials and incubation experiments. Agegnehu et al. (2017) [29] counted 273 field experiments involving the use of biochar that should be available worldwide. In the areas currently covered by LTEP-BIOCHAR (Europe, Africa, and Middle East), we obtained 30–40 open field experiments longer than 2 years; a 10-year threshold would reduce the number of experiments down to 3–8.

A second reason is that, in the mentioned study conducted by Pulcher et al. (2022) [10], it was shown that—at specific site conditions—the mean residence time of biochar can be one order of magnitude less than what is observed in laboratory experiments (10–30 years). This would justify a minimum duration to study the effects of biochar application on soil.

Another consideration is that the biochar's contribution to the soil is additional with respect to the contribution derived from other inputs and can be easily tracked by existing models, when properly calibrated and validated (Figure 2, [10]). The knowledge of SOC against the studied changes rests on decades of experimental studies and therefore the differences in biochar addition can be revealed in a few years, as recommended by Jefferey et al. [25]. Three years appears a sufficient minimum interval to reveal a significative contribution of biochar to the soil ecosystem.

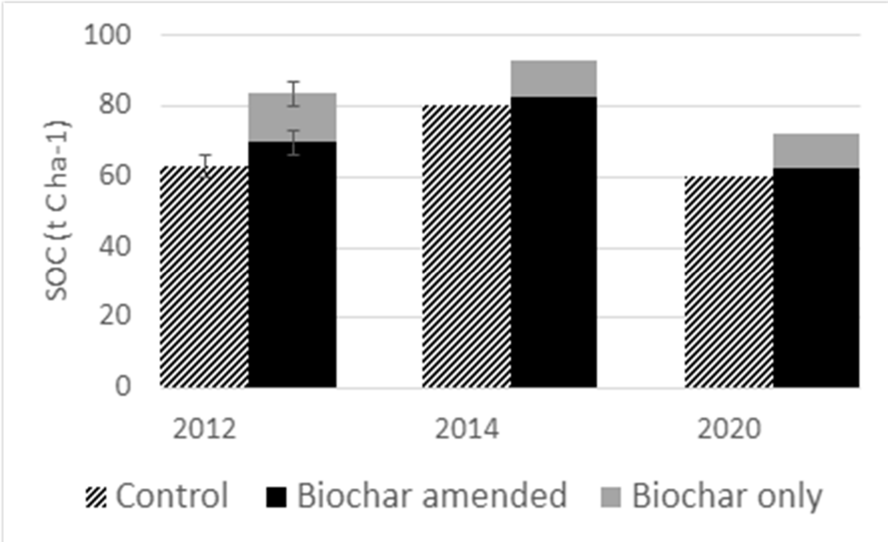

Figure 2. SOC changes in a field experiment simulation in two treatments: control and biochar amended. This figure shows the results of the simulation for a calibrated and validated model that can discriminate between biochar and native SOC degradation (based on data from Pulcher et al. (2022) [10]).

5. Future Directions

At present, the main purpose of the platform has been to put together the most relevant experience in the specific geographic area and to show the potential of a collaborative framework in accordance with a standard format. Work so far has shown that all researchers adopted variable methods and protocols and that only a few specific measurements allow paired comparisons (e.g., soil pH prior to and after application, biochar rate). We qualitatively noted significant differences in terms of the design of experiments. The next immediate step—which is ongoing—is to perform a metadata analysis showing, for each of the sub-categories displayed in Table 4, an index of uniformity/similarities for methods among experiments. With reference to Table 1, the purpose is also to understand to what extent current experiments contribute to reducing the uncertainties related to the most relevant findings. Such an exercise will make it possible to understand what the most urgent actions are to be set in place and how to improve the quality check of the future experiments to include in the platform.

The subsequent step would be to establish a minimum standard of analysis and methods to make experiments more comparable and to deliver recommendations to design new experiments or change the analysis protocols of existing ones. As many platform participants as possible should contribute to defining quality control criteria. Once defined, a quality control checklist or standard protocol should be applied to all datasets in LTEP-BIOCHAR. In such a direction, the most suitable outcome would be to establish a cross-site protocol to be adopted in all the nodes of the network, as was the case in the North American LTE network.

With reference to the latter, the ongoing steps include a review of the standard format and additional questions posed to the data holders. Besides the scientific methodology, we aim at collecting also organizational information, the costs of the experiments, site-ownership, and specific agreements to perform the experiment. This may lead to a better understanding of the workable solutions and conditions to realize valuable LTEs concerning biochar application. The platform, and the results derived from the experiment holders, should encourage the consideration of options to continue the experiment beyond the minimum recommended duration.

As a further step, we aim at expanding the platform to include more experiments, data, and experiences, both geographically (at a global scale) and in scope. We wish to steer the platform towards a "system-oriented perspective" [1]. In this sense, the platform can serve as a model to design experiments exploring interactions among the biochar type, biochar application rate, fertilization rate, and their impact on the ecosystem in which the experimental site is located. These experiments also would include studies that account for regional differences. Examples include site-specific biochar types, water regimes, application technologies, biochar activation technologies, and cropping systems.

Another direction of the network would be to include, in the catalogue of experiments, existing or past LTEs, as proxy data can be useful to understand the potential behavior of biochar after several decades. As an example of this, it must be noted that in many Australian LTE sites, carbon-based materials—derived from slash and burn agricultural practices—were found. Peter Grace, when presenting and discussing the "Australian Site Network" in Powlson et al. (1996) [31], found indeed that most of the organic carbon, physically inert with respect to photo-oxidation determinations, was in the form of charcoal, probably a relic of fires prior to European settlement. In analogy to the most prominent finding in Terra Preta, such a carbon-based material, despite not originally intended as a carbonaceous material used as a soil improver, can be assimilated with biochar [54]; therefore, in such sites where LTEs have been established, it is possible to access and analyze the time series of soils exposed to the action of biochar-like materials for more than a century. At present—to the best of our knowledge—there is no inventory of historical LTEs where charcoal originally derived from biomass was found in soils. In such a direction, the immediate action to take will concern the inclusion of other LTEs from Europe, Africa, and elsewhere. This might also be achieved through a more in-depth investigation into existing data set collections of specific LTEs or initiatives, notably in Africa.

Finally, this is a collaborative effort. At present, the platform relies on the means provided by the researchers and is therefore a self-funded effort. One of the most important next steps will be the promotion of the platform at a wider, international level and fund-seeking activities, together with the expansion of the researchers involved and of the steering and scientific committee.

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