



Re-Livestock
RESILIENT FARMING SYSTEMS

DELIVERABLE 13:

**Guidelines for manure management
aimed to promote C sequestration
and nutrient recycling**





Contents

Executive Summary	3
1. Introduction.....	4
1.1. Manure management at housing phase	7
1.1.1. Biochar-supplemented bedding	7
1.1.2. Compost bedded pack (CBP) housing systems	7
1.2. Manure management at storage phase	9
1.2.1. Addition of Biochar	9
1.2.2. Slurry acidification in dairy systems	9
1.3. Manure management at field phase.....	10
1.3.1. Biochar can reinforce soil functioning and plant productivity.....	10
1.3.2. Biochar can reinforce soil carbon stocks	10
1.3.3. Biochar can reduce GHG emission	11
1.3.4. The lack of knowledge on the effect of biochar on grasslands.....	12
2. Objectives	12
3. Methods.....	13
3.1. Trial 1: Biochar for bedding	14
3.2. Trial 2: Biochar added to the manure pile stock	16
3.3. Trial 3: Fertilization with biochar-enriched manure	17
3.4. Trial 4: Compost bedded pack	20
3.5. Trial 5: Slurry acidification.....	20
4. Results and Key findings	21
4.1. Biochar-supplemented bedding.....	21
4.2. Biochar added to manure-pile stock.....	29
4.3. Fertilization with biochar-enriched manure	34
4.4. Compost bedded pack	40
4.5. Acidification of slurry	40
5. Conclusions and Recommendations	41
6. References	42
Appendix 1. Biochar production of farms	49
Appendix 2. The multiple functions of biochar on livestock farms	52
Appendix 3. Potential production of biohar in dehesas	54





Project Number:	101059609
Project:	Re-Livestock - Facilitating Innovations for Resilient Livestock Farming Systems
Duration:	60 months
Start date of Project:	1 September 2022
Project management:	CSIC - AGENCIA ESTATAL CONSEJO SUPERIOR DE INVESTIGACIONES CIENTIFICAS
Deliverable:	DELIVERABLE 13: Guidelines for manure management aimed to promote C sequestration and nutrient recycling
Due date of deliverable:	M36 (August 2025)
Actual submission date:	19 December 2025
Work package:	4
Leader:	Fernando Estellés (UPV)
Person in charge:	Gerardo Moreno (UEX)
Author(s):	Gerardo Moreno and Fernando Estellés
Contributor(s):	Víctor Rolo, Xavier Diaz de Otalara, Guadalupe Navazo
Communication level:	PU (Public)
Version:	1.0



Executive Summary

This deliverable focuses on a selected set of manure management strategies that have been tested or are currently under evaluation within Work Package 4: the use of biochar, the implementation of compost bedded pack (CBP) housing systems, and the acidification of slurry. These practices have been prioritised because they are already being applied on commercial farms involved in the project and/or have been experimentally assessed by the WP4 partners for their potential to improve carbon retention, reduce gaseous nitrogen losses, enhance nutrient recycling and, where relevant, contribute to animal health and welfare. It should be noted, however, that a much wider portfolio of mitigation and nutrient-recycling approaches exists across the manure management chain—including housing design, frequent manure removal, solid–liquid separation, composting optimisation, slurry covers, anaerobic digestion, nitrification inhibitors or low-emission spreading techniques—which may also contribute to carbon sequestration and circular nutrient use. These complementary options fall outside the scope of this document and are therefore not analysed in detail here, as the present deliverable is restricted to reporting experimental evidence generated within WP4 and to illustrating its practical relevance for farm-scale transition towards climate-smart manure management.

The objective is to search for the best practices to reduce the emission of greenhouse gases (GHG) from manure during the whole manure management chain, together with optimization in terms of soil carbon sequestration and nutrient cycling. This report compiles the results of five trials that test low-cost practices to reduce the emission of GHG (CO₂, CH₄, N₂O) and NH₃ from the manure, along three phases, (i) the production in the stables, (ii) storage either in solid manure piles or slurry ponds, and (iii) application in field fodder crops.

The study combines both lab and real farm experiments, with measurements of gases emissions and manure and soil analysis. Specifically, the biochar produced with the waste of the pruning of the trees on a *dehesa* farm is used as supplement of the straw bedding, and the emission of gases are monitored successively in the barns, manure pile and soil, once applied to the soil pastures, all in the same *dehesa* farm. Two additional experiments were run to test the effect of the ventilation of composted bedded packs and the acidification of slurry ponds on the nitrogen and carbon conservation. Complementary, information on livestock welfare and health is reported.

Results show that biochar produced in *dehesa* is effective in reducing GHG and NH₃ emissions in the bedding phase. Besides, the bed remained drier, young animals performed better and the farmer saved money (straw). Biochar applied directly as a cover on the manure pile also contributes to reducing GHG and NH₃ emissions, but not as much as biochar that is already incorporated during the bedding phase. And finally, the biochar as a pasture amendment had positive effects in terms of grass production, soil fertility, and soil carbon sequestration. Contrary to expectations, no negative effect was observed in low-fertility soils due to the immobilization of available nutrients. Biochar also contributed to reducing emissions of the three GHGs analyzed. When biochar was incorporated into manure, the effect on soil fertility and forage production was, as expected, even more beneficial. It also helped to ensure that GHG emissions did not increase after manure application, keeping emissions below the control soil without amendment.

Beyond the use of biochar, improving the ventilation of stables, reduce the volatilization of Nitrogen from the compost bedded pack, obtaining a more rich and equilibrated manure (lower C/N ratio). Similarly, the acidification of slurry contributes largely to the conservation of nitrogen and carbon conservation during storage, reducing in this way the emission of NH₃ and CH₄.

In summary, including best management practices for manure at the successive phase, from the production to the application in the field, reduces greatly the emission of GHG and NH₃ and produce a higher-quality manure. Specifically, converting biomass waste into biochar and using then the biochar in animal bedding is an investment that improves animal comfort and health, optimises waste management, reduces GHG emissions at farm level (in stables, manure pile stocks and farmed soils) and produces a valuable by-product for agriculture, closing a sustainable nutrient cycle and providing a good example of green and circular economy. In the near future, this biochar could be also marketed as carbon credit, providing an additional income to farmers.

1. Introduction

Manure is a waste product from livestock farms that is responsible for a large part of their GHG emissions (carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O)), as well as other polluting molecules such as ammonia (NH₃) and nitrates (leachate), among others. Anaerobic digestion (without oxygen) during decomposition generates CH₄, and nitrogen volatilisation produces NH₃ and CH₄. These emissions contribute to global warming and air pollution, making management key to meeting climate targets. The leaching of nitrates (and other nutrients) not only constitutes a loss of a valuable resource but also increases the risk of contamination of surface and groundwater bodies.

Good manure management should not only reduce gas emissions (GHG and NH₃) and leachates, but also optimise nutrient recycling (e.g., reducing nitrogen losses) and transform it into a valuable resource, such as manure or compost. Good manure management not only reduces the carbon footprint of the farm but can also contribute to increasing its productivity and improving animal welfare and health (e.g., reducing NH₃ levels). Good management must take into account the three phases: manure production, storage and field application, given that all three phases produce gas emissions, leachates and, therefore, nutrient losses, and there are practices for all three phases that can reduce these losses.

Manure is produced in stables and pens. To reduce emissions, it is recommended to remove it frequently from the stable, store it on impermeable surfaces, and incorporate it quickly into the soil (within 4 hours) after application to avoid nitrogen loss, or use techniques such as composting to stabilise it before using it as fertiliser in the field, minimising contamination. As immediate or frequent removal is not always possible, it is very common for it to accumulate in the animal housing (deep litter).

Gas emissions from animal bedding are a dynamic process in which manure interacts with absorbent material (straw, sawdust, etc.). Unlike liquid slurry systems, solid bedding favours certain specific chemical processes. The main gases emitted are:

- **NH₃:** This is the most immediate emission. It is produced when the urease enzyme in faeces comes into contact with urea in urine. In bedding systems, the emission rate can be higher than in slatted floors if there is not enough absorbent material to “sequester” the nitrogen.
- **N₂O:** Litter systems emit significantly more than liquid systems. This occurs because the porous material creates areas with and without oxygen (aerobic and anaerobic), facilitating nitrification and denitrification processes.
- **CH₄:** This is generated in the deep, compact layers of the litter where oxygen cannot reach. Although the main source in ruminants is enteric fermentation (belching), accumulated bedding contributes to the farm's total emissions.
- **CO₂:** This comes from the aerobic decomposition of organic matter (natural composting) in the bedding itself.

The factors that increase emissions are:

- **Temperature and Humidity:** Heat promotes microbial activity and volatilisation. Very damp and warm bedding accelerates the release of NH₃.
- **Animal Diet:** Diets with excess protein increase nitrogen in urine, dramatically raising (up to 4.5 times more) NH₃ emissions from straw.
- **Animal Density:** A higher number of animals per square metre increases the accumulation of manure and the compaction of bedding, promoting anaerobic conditions for CH₄.

Some mitigation measures in the barn can be:

- **Bedding management:** Keeping bedding dry by regularly adding absorbent material reduces the surface area from which NH₃ is emitted.
- **Cleaning frequency:** Frequent removal of solid manure from the barn to controlled storage areas reduces the accumulation of harmful gases in the animal living area.
- **Ventilation:** Proper barn design helps disperse NH₃, improving animal welfare and preventing dangerous concentrations.

Gas emissions from livestock manure storage vary significantly depending on its physical state (solid or liquid), affecting climate change and air quality in different ways.

In solid manure piles, natural aeration facilitates both aerobic and anaerobic processes, generating a complex mixture of gases:

- **N₂O:** This is the most critical gas in solid manure. It is produced by the alternation of areas with and without oxygen in the pile, which favours nitrification and denitrification processes.
- **NH₃:** It is continuously released from the surface. Priority should be given to reducing the ratio between the emission surface and the volume of the pile in order to minimise these losses.
- **CH₄:** Although lower than in slurry, it is generated in the compact, oxygen-free core of the pile.

Liquid storage (slurry ponds) is predominantly anaerobic, which defines its emissions profile:

- **CH₄:** Accounts for approximately 60% of the gases generated in the anaerobic digestion of slurry. It is a potent GHG (25 times more than CO₂).
- **CO₂:** Accounts for about 39% of emissions in these systems.
- **NH₃:** Volatilisation occurs at the air-liquid interface. It is recommended frequent emptying into outdoor ponds or treatment plants to reduce these emissions in the barn.

Covering slurry ponds and acidification of the liquid is recommended, a technique that can drastically reduce NH₃ volatilisation by keeping nitrogen in ammonium form. To reduce leachates, manure piles must have leachate collection systems to prevent nitrate contamination in the environment. Equally important is the transformation of slurry into biomethane, capturing CH₄ emissions for energy use in transport or industry, but the latter is beyond the objectives and capabilities of the RELIVESTOCK project.

The most traditional use of manure is its application to the soil to improve its structure and fertility by providing organic matter and nutrients, and also by strengthening the biomass and activity of the soil microbiota. However, its application also generates GHG emissions such as N₂O and CH₄, and can contaminate groundwater if used excessively or incorrectly, affecting biodiversity. To minimise risks, it is crucial to compost it properly, bury it quickly to avoid nitrogen losses, control doses, and combine it with sustainable practices, as good management transforms this 'problem' into an opportunity for healthier soils and more sustainable production.

This study explores the potential of some of these techniques applied to the three phases of manure production and management (bedding, storage and soil application), based primarily on the application of biochar in an agroforestry livestock system, such as the Iberian pastureland,



where there is great potential for producing biochar at low cost, using biomass residues that are currently disposed of by open burning. In addition to the use of biochar, other practices are explored, such as the deep litter aeration model and slurry acidification. Each of the practices evaluated is introduced below.



1.1. Manure management at housing phase

1.1.1. Biochar-supplemented bedding

Generally applied by mixing the biochar with straw or sawdust, the application is simple and easily integrated into animal bedding management routines: After the initial dose, at a typical ratio of 5% to 10% by volume, additional biochar can be sprinkled in damp or high-traffic areas as needed during the bedding cycle. When biochar is added as bedding material in stables or feedlots produces similar results to those describe for biochar added to manure or composting piles. But in this case, some additional benefits can be achieved in terms of animal welfare, health and abatements of GHG emissions (Schmidt et al., 2019; Shin et al., 2025).

- i. **Odour and NH₃ Emission Control: Gas Absorption:** Biochar is highly porous and has a large surface area, allowing it to adsorb volatile compounds that cause unpleasant odours and, crucially, NH₃, a respiratory irritant. An environment with less NH₃ reduces respiratory health problems in animals and workers. By retaining NH₃, biochar not only improves air quality, but also prevents the loss of nitrogen, a valuable nutrient that would otherwise volatilise (Pires, 2025).
- ii. **Methane Emission Control:** The use of biochar in animal bedding contributes significantly to the reduction of CH₄ emissions, and this effect occurs from the whole period and not only during the later phase of manure management and composting (Schmidt et al, 2019; Pereira et al., 2024).
- iii. **Disease Prevention:** Biochar is hygroscopic and helps keep bedding drier for longer by absorbing excess moisture (urine and spilled water), which inhibits the growth of pathogenic bacteria and fungi. A drier environment significantly reduces the incidence of foot problems (pododermatitis) in poultry and livestock and improves the overall health of the herd (Kazemi, 2025). Guerreiro et al. (2025) also observed that biochar led to a decrease in the levels of several mastitis-causing agents (Enterobacteriaceae, Streptococci, Enterococci and Staphylococci), and in the levels of Salmonella spp. and gram-positive bacilli. Nevertheless, they also that some pathogenic groups such as Brucella could be reinforced, an aspect that requires further study to ensure the future safe and sustainable use of this environmental-friendly resource in animal production (Guerreiro et al., 2025).

1.1.2. Compost bedded pack (CBP) housing systems

System description and functioning

Compost bedded pack (CBP) housing systems are based on the use of a deep organic bedding layer where manure and urine are deposited directly by dairy cows and subsequently incorporated into the bedding matrix through mechanical aeration.

The primary objective of aeration is to introduce oxygen into the upper layers of the pack, thereby promoting aerobic microbial processes that drive organic matter decomposition, heat generation and moisture evaporation (Black et al., 2013; Leso et al., 2020).

Under optimal conditions, the aerated layer of the pack functions as an in-barn composting system. However, the scientific literature shows that CBP systems operate along a continuum, ranging from actively composting packs to deep-bedded systems with limited biological activity. This variability reflects differences in climate, ventilation, bedding supply and aeration intensity (Oliveira et al., 2023).

Beyond manure management, CBP systems are widely recognised for their positive effects on dairy cow health and welfare, which indirectly influence manure characteristics and management outcomes. Compared with conventional freestall systems, CBP barns provide a larger, more deformable lying surface that facilitates natural resting postures and reduces competition for

resting space (Tucker et al., 2021). Multiple studies report longer lying times, improved comfort scores and fewer hock lesions in CBP systems relative to freestalls (Barberg et al., 2007; Black et al., 2013). Improvements in locomotion and reduced lameness prevalence have also been documented, likely due to softer flooring and reduced contact with hard surfaces (Leso et al., 2020).

The relationship between CBP systems and udder health is more nuanced. While some studies report comparable or lower somatic cell counts relative to freestalls, others highlight the importance of maintaining dry and well-aerated pack surfaces to limit exposure to mastitis-causing pathogens (Barberg et al., 2007; Oliveira et al., 2023). These findings underline that welfare benefits are closely linked to adequate aeration, bedding management and hygiene.

Key operational parameters

CBP systems reported in the literature exhibit wide variation in design and management. Bedding materials include fine sawdust and wood shavings, which provide high absorbency and surface area, as well as coarser forest biomass residues or chopped straw, which increase porosity and air diffusion but may require more frequent replenishment (Llonch et al., 2020; Llonch et al., 2021). Aeration regimes vary substantially across studies. Mechanical aeration is reported from once daily up to three times per day, with typical aeration depths between 15 and 30 cm. Deeper aeration has been described in some systems to enhance oxygen penetration and heat distribution, although this may also increase nitrogen losses under unfavourable conditions (Black et al., 2014; Damasceno et al., 2022). Pack depth, space allowance per cow and clean-out frequency further differentiate CBP implementations (Leso et al., 2020).

A consistent outcome of CBP research is the identification of a limited number of key parameters controlling system performance. Pack moisture is widely recognised as critical, with values around 40–60% reported as favourable for aerobic microbial activity and heat generation, while excessive moisture promotes anaerobic microsites and hygienic deterioration (Oliveira et al., 2023). Pack temperature is frequently used as an indicator of biological activity. Internal temperatures above 40 °C have been reported under favourable conditions, although sustained thermophilic temperatures are not always achieved in commercial barns, particularly in cool or humid climates (Black et al., 2013).

The availability of carbon through bedding addition is essential to maintain porosity and to buffer nitrogen transformations. Insufficient C supply or low C:N ratios have been associated with increased NH₃ odour and higher risk of NH₃ volatilisation (Misselbrook et al., 2005; Chadwick et al., 2011).

Impacts on carbon and nitrogen conservation and manure composition

From a carbon perspective, CBP systems promote aerobic respiration and therefore higher CO₂ emissions during the housing phase compared with liquid manure systems (Sommer et al., 2004). However, CBP systems also involve substantial inputs of lignocellulosic carbon via bedding. The material removed from CBP barns typically shows high organic matter content and partial stabilisation due to composting processes, which can enhance its value as a soil amendment after land application (Bernal et al., 2009).

Chemical characterisation of CBP-derived material illustrates strong variability. Studies report total organic carbon contents commonly ranging from approximately 30 to 47% (dry matter basis), while total nitrogen contents typically range from 0.5 to 2.5%, depending on bedding type, aeration regime and pack age (Llonch et al., 2021; Oliveira et al., 2023). These ranges reflect both dilution by C-rich bedding and partial nitrogen losses during the housing period.

1.2. Manure management at storage phase

1.2.1. Addition of Biochar

When biochar is added to manure, it increases aeration and absorbs moisture, preventing the conditions that facilitate methane-producing bacteria. Besides, the large surface area of biochar adsorbs gases and promotes the activity of methanotrophic bacteria, which are microorganisms that oxidise CH₄ into CO₂ (a less potent GHG). Zou et al. (2025) reported a reduction in CH₄ emissions by between 27% and 51% by adding biochar to manure composting. The application not only reduces GHG emissions but also helps manage manure more effectively, minimizing odours and enhancing its potential as a soil amendment (Chen et al., 2017; Holly et al., 2017; Meirikhani et al., 2020; Harrison et al., 2024).

By incorporating biochar (10-12%) into composting processes or directly applying it to manure (manure pile or slurry ponds), farmers can thus accelerate the decomposition of organic waste. This not only reduces the environmental impact of manure but also converts waste into a valuable resource that can be used to enrich soil, promoting circular farming practices. Mixing biochar with manure or slurry accelerates the composting process, retains valuable nutrients (nitrogen) and minimises GHG emissions. The result is a higher quality organic fertiliser with a balanced C/N ratio and superior nutrient retention capacity, ready for application to crop fields (biochar-rich manure ~ activated biochar).

1.2.2. Slurry acidification in dairy systems

System description

Slurry acidification is a manure management technique based on reducing slurry pH through the addition of acid, most commonly sulphuric acid, to shift the equilibrium between ammonium (NH₄⁺) and NH₃ towards the non-volatile NH₄⁺ form (Sommer & Hutchings, 2001; Kai et al., 2008). The technique can be implemented in-barn, during storage or at land application, with each option targeting different emission hotspots along the manure management chain (Petersen et al., 2012; Fangueiro et al., 2015). Most commercial systems rely on sulphuric acid due to its cost-effectiveness and buffering capacity, although hydrochloric, nitric and organic acids have also been tested experimentally (Fangueiro et al., 2015; Overmeyer et al., 2021). Target pH values typically range from 5.5 to 6.4, with lower pH values providing stronger NH₃ mitigation but increasing acid demand and safety requirements. Acidification strategies include single-dose acidification early in storage and repeated dosing to counteract pH rebound caused by fresh slurry inflow and microbial activity (Petersen et al., 2012; Lemes et al., 2022).

Impacts on carbon and nitrogen conservation and slurry composition

The effect of slurry acidification on nitrogen conservation is robustly documented. NH₃ emission reductions exceeding 50–70% are commonly reported when target pH values are achieved and maintained, leading to higher total nitrogen retention and increased fertiliser value of slurry (Kai et al., 2008; Webb et al., 2014; Misselbrook et al., 2016). Slurry acidification also affects carbon dynamics by inhibiting methanogenic activity. Experimental and full-scale studies report CH₄ emission reductions of 67–87% during storage when slurry is acidified to around pH 5.5, with particularly strong effects following early single-dose acidification (Petersen et al., 2012; Lemes et al., 2022). In terms of slurry composition, acidification does not substantially alter total carbon content but preserves nitrogen by limiting gaseous losses. The choice of acid influences nutrient balance, notably through sulphate-S addition when sulphuric acid is used, which must be accounted for in nutrient management planning (Fangueiro et al., 2015; Overmeyer et al., 2021).

1.3. Manure management at field phase

1.3.1. Biochar can reinforce soil functioning and plant productivity

Biochar 'loads' its pores with nutrients from manure and urine, producing thus a high-quality fertilizer. When the used bedding is removed and composted or applied directly to the field, a higher quality fertiliser is obtained. Biochar acts as a 'nutrient bank' that slowly releases minerals to plants when applied to the soil (Wang et al., 2022). This high-quality fertilizer can be used to produce fodder on farms, event to fertilize grazing pastures (Biederman et al 2017; Brown et al, 2023). Nevertheless, under certain conditions, biochar can have detrimental effects on plant productivity, deserving more specific studies (Brtnicky et al., 2021). Biochar can improve soil physical, chemical, and biological properties of the soil, offering direct advantages such as nutrient enrichment, pH buffering/elevation, reduction of bulk density, augmentation of water retention, and enhancement of nutrient preservation (Gao et al., 2016; Ali et al., 2017; Glab et al., 2020; Alkharabsheh et al. 2021). All together may subsequently change the soil microbiota structure and functioning and the fate of soil nutrients, overall increasing plant productivity (Jeffery et al., 2022, Brown et al., 2023). Different studies also highlight the ability of biochar to reduce nutrient leachate, improve water quality, and reduce the need for irrigation, as well as fertilization, with the environmental costs that are avoided. Biochar has been reported to have multiple environmental benefits in mineral fertilizer (Gul and Whalen, 2016; Dari et al., 2016; Fonseca et al., 2020), reduced risk of nutrient leaching (Lu et al., 2020). Biochar is particularly effective in increasing yields when applied to low fertility or degraded soil, but the effects seen on more fertile or healthier soil could be little and/or transient (El-Naggar et al. 2019a; Gao & DeLuca, 2020).

The multiple benefits of biochar for soil functioning and plant growth are due to its extremely porous nature. There are some consensus that biochars produced from ligno-cellulosic feedstocks and/or at high production temperatures tend to retain soil inorganic N and P through adsorption and immobilization, (Brtnicky et al. 2021; El-Naggar et al. 2019b), with negative consequences for crop performance unless co-applied with inorganic fertilizers, manure, or crop residue feedstocks (named activated or charged biochar) (Cayuela et al., 2013; Gul & Whalen, 2016). That is, if biochar is incorporated pure and unactivated into the soil, its high adsorption capacity will result in the absorption and fixation of available nutrients and water in the soil, transiently reducing its availability to plants. This in turn can lead to inhibition of plant growth, at least in the beginning (several months to a year) and depending on the nutrient content of the soil. To avoid this, before applying biochar, it must be activated (Joseph et al, 2021). A very effective and efficient form of activation is mixing with manure or composting material, so that the nutrients released are fixed on the surfaces and pores of the biochar, while it is colonized by the microorganisms in the manure. Once activated, it is recommended to apply to the soil in doses of 1 to 10 tons per hectare, depending on the needs of the soil and the crop.

1.3.2. Biochar can reinforce soil carbon stocks

Carbon sequestration in biochar enhances soil carbon storage time in comparison with other terrestrial sequestration approaches like afforestation or reforestation (Vijay et al., 2021). Biochar applied to soil is in a highly stabilized form and can store carbon over hundreds to thousands of years, converting soil into a major carbon sink (Bai & Cotrufo 2022). Half of the emission reductions and the majority of CO₂ removal result from the one to two orders of magnitude longer persistence of biochar than the biomass it is made from (Lehmann et al, 2021). Field experiments of durations between 1 and 10 years with biochar application amounts between 1 and 100 Mg ha⁻¹, showed a mean increase in soil organic carbon (SOC) stocks by 13.0 Mg ha⁻¹, on average, corresponding to 29% (Gross et al., 2021). Likewise, the stability of biochar in the soil is of great importance. Although it is difficult to predict what its long-term behaviour will be, experiments that

have been carried out in laboratory and fields conditions indicate that it can last between hundreds and thousands of years, since it is only a small fraction of it that degrades in a short period of time. A meta-analysis (128 studies) on the stability of biochar in soils estimated the mean residence time of biochar labile and recalcitrant fraction, pool size = 3% and pool size = 97% as 108 days and 556 years, respectively, indicating that the major part of biochar (97%) contributes to long-term carbon sequestration in soil (Wang et al., 2016). In short, biochar amendment can thus play a significant role in carbon removal from the atmosphere and simultaneous reduction of GHG emissions such as CH₄ and N₂O (Cayuela et al., 2013; Lorenz & Lal, 2014).

1.3.3. Biochar can reduce GHG emission

Biochar has also drawn interest because of its perceived potential to reduce GHG emissions in farmlands. Microbial activity, specifically through the processes of nitrification and denitrification, is responsible for the primary soil processes leading to the emissions of N₂O (Kuyppers et al., 2018). The key step of denitrification is the reduction of soluble nitrogen (nitrite) into a gaseous form (NO) catalysed by the nitrite reductase encoded either by the *nirK* or *nirS* genes. The last step of denitrification, which is the only known sink of N₂O in the biosphere as it reduces N₂O into N₂ (Hallin et al., 2018), is catalysed by the N₂O reductase encoded by the *nosZ* gene. Different environmental factors influence denitrification such as soil pH, moisture, temperature, aeration, water-filled pore space and soil carbon (e.g., Brenzinger et al., 2017; Mehnaz et al., 2019; Zurovec et al., 2021). Additionally, physicochemical properties shape soil microbial communities and, thus, indirectly influence the N₂O emissions (Samad et al., 2016).

Biochar can reduce N₂O production through various mechanisms, including 1) enhancing nitrate immobilisation in microbial biomass and uptake by plants, 2) increasing soil pH, 3) promoting soil aeration by reducing bulk density and increasing porosity, and 4) controlling N cycling functional genes, including *amoA*, *nirS*, *nirK* and *nosZ* (Gul and Whalen 2016; Lyu et al. 2022). For instance, Wang et al., (2013) demonstrated that biochar amendment lowered the total N₂O emissions from pig manure composting, especially during the later stages, mostly explained by the abundance of *nosZ*, *nirK*, and *nirS* genes. Biochar-amended pig manure had a higher pH, lower moisture content, less N₂O-producing and more N₂O-consuming bacteria. Similarly, Yuan et al. (2017) reported that the addition to soil of chicken manure compost, either alone or co-composted with biochar, significantly enhanced the abundance of N₂O-producing bacteria and fungi, and gas emissions of N₂O and CO₂, reduced soil CO₂ and N₂O emissions by 35% and 27%, respectively, over the experimental period. Yet, there is still little insight into how biochar may mitigate N₂O emissions from manure and crop fields, where considerable spatial heterogeneity and temporal fluctuations in denitrification are expected (Lu et al., 2020; Cayuela et al., 2014; Brown et al 2023).

Many authors have also reported that biochar can reduce CH₄ emissions from manure and soil. For instance, Harrison et al. (2024) found that biochar-composting substantially reduces CH₄ and air pollutant emissions from dairy manure. Specifically, they reported that amending compost with biochar reduced total CH₄ emissions by 58% (±22%) and H₂S, VOCs, and NO_x emissions by 67% (±24%), 61% (±19%) and 70% (±22%), respectively. These reductions in emissions were attributed to improved oxygen diffusion from the porous biochar and the adsorption of gas precursors to the biochar surface.

Well-aerated soils typically function as net sinks for atmospheric CH₄ due to the consumption of CH₄ by methanotrophic bacteria (Kolb, 2009; Le Mer & Roger, 2001; Tate, 2015). However, the dual role of soil as both a source and sink for CH₄, and the shifting balance between these two entities with land management, are not well understood (Tate, 2015). Key physical soil characteristics such as porosity, aggregation, moisture, and chemical parameters such as soil

pH, nitrogen, and metal oxides are confirmed to be altered by the biochar, with consequences for the regulation of methanotrophs (Zhao et al 2021). According to these authors, both conventional methanotrophs and atmospheric CH₄ oxidation bacteria respond to biochar amendments in grassland and forests, where the effects on nitrite dependent anaerobic CH₄ oxidation is less probable. Lyu et al. (2022) stated that the most responsive were related with the abundance of functional genes such as mcrA (a methanogen) and pmoA (a methanotroph). Their meta-analysis showed that the overall suppression effect was very significant for N₂O and moderate for CH₄. However, when applied to soil with manure, biochar could be inefficient to reduce N₂O emissions but bears the risk of CH₄ release (Efosa et al., 2023). Therefore, more information is needed to assess the effect of biochar on GHG emissions along the whole cycle, from its application to manure until the application in agriculture soils.

1.3.4. The lack of knowledge on the effect of biochar on grasslands

Most studies with biochar have been conducted in laboratory and mesocosm conditions, which are suitable for mechanistic investigations, and the scientific community is claiming more field validation (Gul and Whalen 2016; Li et al., 2018; Lu et al., 2020; Ghodszad et al., 2021; Jeffery et al., 2022; Brown et al., 2023). Moreover, the majority of biochar studies have been conducted in agricultural systems that rely on tillage, burial of biochar, and fertilization of annual crops (Glab et al 2020). Few studies have evaluated the influence of biochar in grassland ecosystems (~ 2%; Brown et al., 2023) that feature more complex plant communities and have relatively few external nutrient inputs (Gao & DeLuca, 2020). Furthermore, the incorporation of biochar into the soil is much more difficult in grasslands than in cultivated soils. Therefore, soil properties and microbial activities in grasslands may be different from those described in previous studies on farmland ecosystems (Li et al., 2023).

Some recent studies have showed positive results on projects of grasslands restoration by adding 1-50 Mg biochar/ha (Bai et al. 2020; Gao and DeLuca 2020; Glab et al 2020; Lu et al 2020; Garbuz et al 2021; Jeffery et al 2022; Brown et al 2023; Li et al 2023). In general, these studies showed that biochar enhanced soil water retention capacity, soil fertility and grassland productivity. But the impact of biochar on GHG fluxes in grasslands remains poorly understood (Jeffery et al., 2022). At present, there is insufficient understanding to provide technical recommendations regarding the utilisation of biochar for enhancing pastures through the integration of soil fertility, carbon sequestration, GHG emissions, and productivity.

2. Objectives

The objective of this work is to search for the best practices to reduce the emission of GHG from manure during the whole manure management chain, together with optimization in terms of soil carbon sequestration and nutrient cycling.

The specific objectives for the housing phase are:

- To evaluate the potential of adding biochar to livestock bed to reduce GHG;
- To assess the effects of adding biochar to livestock bed on animal welfare, tested through the NH₃ emissions, bed wetness and animal infections;
- To assess the effects of different ventilation strategies on manure quality and dairy cow behaviour and welfare.

The specific objectives for the manure storage phase are:

- To evaluate the potential of adding biochar manure pile stock to reduce GHG;
- To evaluate the potential of slurry acidification for the conservation of nitrogen and carbon during storage.

The specific objectives for the field application phase are:

- To compare the benefits of biochar-rich manure respect to manure or biochar alone, in terms of grass productivity and soil carbon sequestration;
- To evaluate the soil emissions of GHG from soils fertilized either with biochar-rich manure or with manure or biochar alone.

Taking the chain of three consecutive applications of biochar on the farm tested in this study, that is, the three phases, bedding, storage and field application, in which in which the product from one phase is useful in the next, and taking the potential of dehesa farms to produce a low-cost biochar, the integration the practices here tested is analysed as an example of circular economy to gain carbon neutrality of the dehesa livestock. The ultimate goal is to be able to apply this comprehensive model for the revaluation of waste, manure and wood to other types of agroforestry livestock systems. The incorporation of lessons learnt in indoor-systems, such as the efficient ventilation of the stables and the acidification of slurries, where applicable, would contribute to this objective.

3. Methods

Different types of livestock (cattle, sheep, goats, pigs, horses) are common in dehesas, with some seasonal differences, to obtain an optimum yield from its varied structure (San Miguel 1994). Briefly, sheep are the most suited species for exploitation of most dehesas. Cattle are found in the most humid dehesas, while goats are often used as a complement to make better use of woody fodder. Finally, pigs are introduced in the dehesa during October-January to take advantage of the abundance of acorns (San Miguel 1994).

To test the potential of biochar produced in Iberian dehesas to reduce the net balance of GHG emissions of the livestock farming carried out in the same dehesa, the UEX team performed a sequence of trials developed in stables (animal bedding), manure pile stock and field pastures. In all cases, the rate of GHG emissions was measured, together with grass production and carbon soil carbon stocks sequestration in the field experiment, in which the biochar-enriched manure produced in the bedding experiments was used to fertilized pastures. In this way, the two main types of waste produced on dehesa farms (pruned branches and manure) are integrated for their revaluation and use within the same farm, thus setting an example of green and circular economy applied to the pursuit of climate neutrality in agroforestry livestock husbandry. The series of tests was as follows:

- * Application of biochar to the livestock bedding;
- * Application of biochar to the manure pile stock;
- * Application of biochar-enriched manure to natural pastures.

For this sequence of trials, biochar produced on the farm itself from the branches of holm oak pruning was used, produced in kon-tiki kilns by a specialized company (Vida negra: <https://www.vidanegra.com/>).



Figure 1 - The production of biochar in the dehesa farms in four stages. A: oak pruning; B: livestock browsing the branches pruned; C: carbonization of fine branches in a kon-tiki kilns; D: spreading biochar for drying at the sun.

The trials were conducted at the Valverdejo dehesa farm, located in Oliva de Plasencia, Extremadura (40.1154°N; 6.1101°W), where a herd of dairy goat graze on natural pastures. The goats are kept in their stables overnight but have also free access during the day. The temporal dynamic of GHG emissions measurements were done with with a portable gas analyzer (Gaser One Pulse, Finland), a photoacoustic multi-gas analyzer platform, that simultaneously measure CO₂, CH₄, N₂O, NH₃ and H₂O. Close chambers, 20 cm of diameter and 20 cm height (6.3 L) were used. Each measure until getting a robust trend (slope = emission rate) took around 20 minutes. In all cases (dates and treatments), a minimum of four repetitions were measured.

Complementary, the UPV team run two additional trials, one for the housing phase, testing the compost bedded pack (CBP), and the other for the storage phase, testing the acidification of slurry.

3.1. Trial 1. Biochar for bedding

Biochar was added to straw layer for bedding in the stable pens for a herd of 21 goats, with a control pen without biochar, with 21 other goats. The trial was repeated twice, in winter and summer, measuring the emission of CO₂, CH₄, N₂O and NH₃ every week for around 2.5 months.

The first round was conducted in winter. Two pens of approximately 28 m² with identical characteristics were used. The stables were cleaned beforehand and the experiment began the 13 December 2023, 10 days after cleaning. The treated pen received 3.5 kg/m² of biochar (a layer of 2 cm; ~ 5% vol. at the end of the trial) between two straw layers, and the control barn received only straw. Because the differences in the bed moisture, the second application of straw in the control was only 5 days after the start of the trial, and in the case of biochar was after 12 days. Along the 10 weeks of the trial, it was necessary to apply straw 11 times in the control and 6 times in the trial, according to the differences in moisture. After two months, the manure was

removed. The height (volume) of the control manure layer was 38-43 cm, while the height in the biochar stable was 27-32 cm.

The second round was conducted in summer (15 July to 30 September 2025) in two pens where the animals could move freely between them. During this period, the animals received the supplementary feed inside the stable to encourage them to enter. In this occasion, only straw was applied initially, with no further applications necessary due to low humidity. The volume of manure generated was similar in both cases.



Figure 2 - Image of the trial: A: biochar application over straw layer; B: a second layer of straw applied over the biochar; C: goats in the pens; D: measuring GHG emission in the pens.



Figure 3 - Livestock bed after two months. A and B: Bed without a with biochar, respectively; C and D: two images of the manure with biochar.

3.2. Trial 2: Biochar added to the manure pile stock

Manure removed on 1st of March 2024 (first round) from both stables, with and without biochar, was used for the second trial. Three treatments were monitored:

- Biochar-rich manure;
- Control manure;
- Control Manure covered with Biochar.

Comparisons were performed following two different approaches.

- Biochar-rich vs pure manure: The manure was always kept outdoors in the sun. Several measurements of GHG emissions were taken from March 2024 until autumn 2024, when the manure was applied to pasture (third trial described below).
- Pure manure alone vs covered with biochar: The test was carried out using 18 cm plastic pots, sealed at the bottom. In each pot, 1.2 kg (6 cm height) of manure was added. In the half of the pots, a layer of biochar (2 cm height) was added. In this trial, measures were taken over seven consecutive days.



Figure 4 - Image of the biochar-rich manure; B: Measuring GHG emissions from manure pile stock.



Figure 5 - Image of the collar ring over, respectively, the pot with pure manure (left) and with manure cover with a layer of biochar (right).

3.3. Trial 3: Fertilization with biochar-enriched manure

In general, uncertainties of CH₄ and N₂O fluxes in wood-pastures are high due to coexisting grass and tree (Shvaleva et al., 2015) and the CH₄ oxidation potential of soil is highly dependent on soil moisture (Fest et al., 2017). However, there is little knowledge on the spatial and temporal dynamics of CH₄ and N₂O fluxes and how they are modified by biochar application. Similarly, the knowledge about the nature and magnitude of changes in forage productivity and quality, and in plant community after biochar application in *dehesas* is still poor.

Taking advantage of the biochar-rich manure produced in the bedding trial, a field trial was initiated to test the effects of biochar-rich manure on grass production, soil GHG emissions and on soil carbon storage. The field fertilization experiment was initiated in autumn 2024, and will last until the spring 2027, including in this report the short-term results (1st year). The experiment was done on the same farm, in an area with native pastures with scattered oak trees. In this trial, four different treatments were compared: (i) manure, (ii) biochar, (iii) biochar-rich manure, and (iv) nothing (control). The material was applied directly onto the grass and slightly incorporated using a rake. Four trees were used in a block-replicated design. The experiment consists of 64 quadrats measuring 1.5 × 1.5 m, grouped into 4 blocks, which are in turn split into 2 microhabitats: open pasture and beneath tree pasture. Each quadrat was virtually divided into four quarts. In one quart, a permanent ring collar was installed at the beginning and left for the whole period of the experiment.

On 6 April, soil samples were taken from each experimental plot, and soil carbon was analysed in an elemental analyser based on Duma's combustion method. Other basic soil parameters such as bulk density, pH, electrical conductivity and N content were also analysed. Grass samples were taken on three occasions along the spring to estimate production, and on two of those occasions, the species collected were recorded. The grass was cut in a 25 x 25 cm square. Biochar, manure and biochar-rich manure were applied directly in the same volumetric quantity, 20 L/m², which in terms of mass varies with each application (Table 1).



Figure 6 - Image of biochar, manure and biochar-rich manure used in the trial. Manure in both case was composted for 6 months before the application.

Table 1 – Application doses of three alternative amendments added to the soil

TYPE	Dose, volumen (L/m ²)	Dose, mass (tn/ha)
Biochar-rich manure	20	110
Manure	20	112
Biochar	20	40

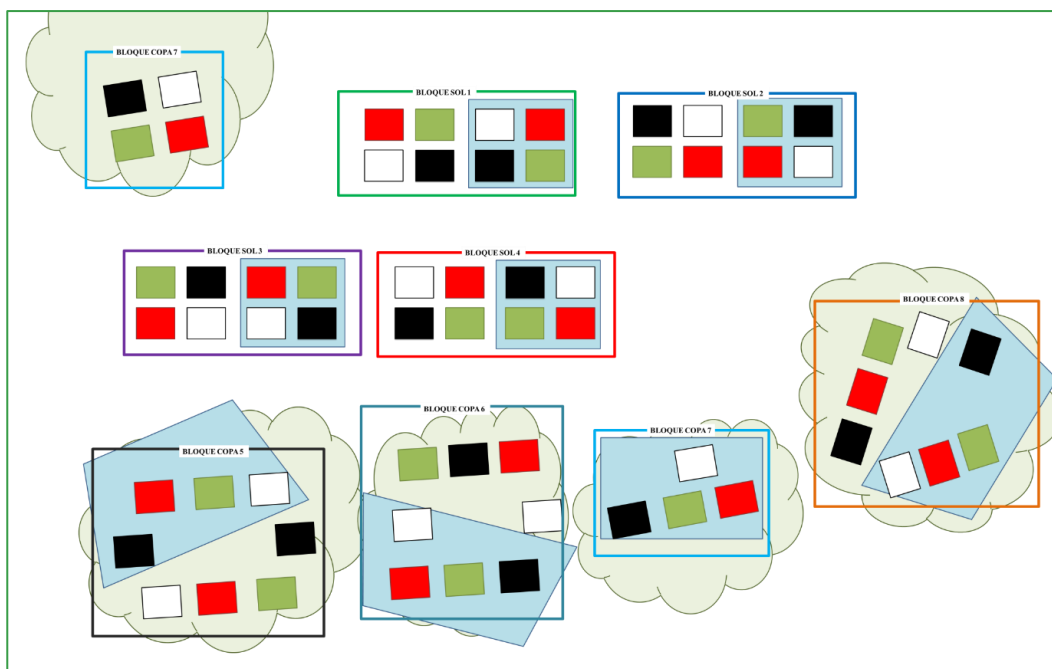


Figure 7 - Scheme of treatments and repetitions in four block.s Then half of the quadrats are beneath a tree canopy and the other half in the open pasture without tree shade. Black: biochar; Green: biochar-rich manure; Red: manure; White: control.



Figure 8 - Image of the trial, with quadrats that received biochar, manure, biochar-rich manure or nothing (control), either beneath tree canopy (up) or in the open pasture (down). Picture was taken immediately after the application of the material.



Figure 9 - Image of the trial, with quadrats that received biochar, manure, biochar-rich manure or nothing (control), either beneath tree canopy (up) or in the open pasture (down). Picture was taken 5 months after the application of the material.



Figure 10 - Image of grass 3 moths after the application of biochar, manure or biochar-rich manure.



Figure 11 - Image of the field trail in spring, during pasture sampling campaign, and in summer during the field campaign to measure GHG emissions.

3.4. Trial 4: Compost bedded pack

A twelve-week on-farm experimental study was conducted by UPV team in a commercial farm located in Bétera (Valencia, Spain) to assess the effects of different ventilation strategies on compost bedded pack quality and dairy cow behaviour and welfare. Compost bedded pack quality was evaluated under three ventilation regimes at four pens with approximately 150 dairy cows each:

- i) two pens with continuous ventilation operating 24 h per day with power modulated according to a temperature set-point;
- ii) one pen with intermittent ventilation operating at full capacity between 11:00 and 15:00;
- iii) one pen without any ventilation.



Figure 12 – Litter aeration to produce CBP in a dairy farm in Valencia (Spain).

Compost bed samples were collected weekly following a zigzag sampling pattern, with eleven subsamples per barn area taken at the surface and at 20–30 cm depth, yielding approximately 1 kg of material per composite sample. Pack temperature was measured at both surface and depth using a thermometer, and samples were analysed for dry matter, carbon and nitrogen content.

3.5. Trial 5: Slurry acidification

UPV team has conducted several trials on slurry acidification. As an example, samples from a nutritional experiment developed by Animal Data Analytics (ADA) were placed in individual containers under uniform environmental conditions (Figure 13).

Slurry composition was characterized at the beginning and end of the experimental period, including dry matter, organic matter, total nitrogen, ammoniacal nitrogen, pH and electrical conductivity. Gaseous emissions were quantified using dynamic chamber methodology, whereby each container was fitted with a controlled airflow system. Emission rates of NH₃, CH₄ and CO₂ were calculated from the difference between outlet and inlet gas concentrations multiplied by the known airflow.



Figure 13 - Experimental set-up to monitor gaseous emissions from acidified slurry samples.

4. Results and Key findings

4.1. Biochar-supplemented bedding

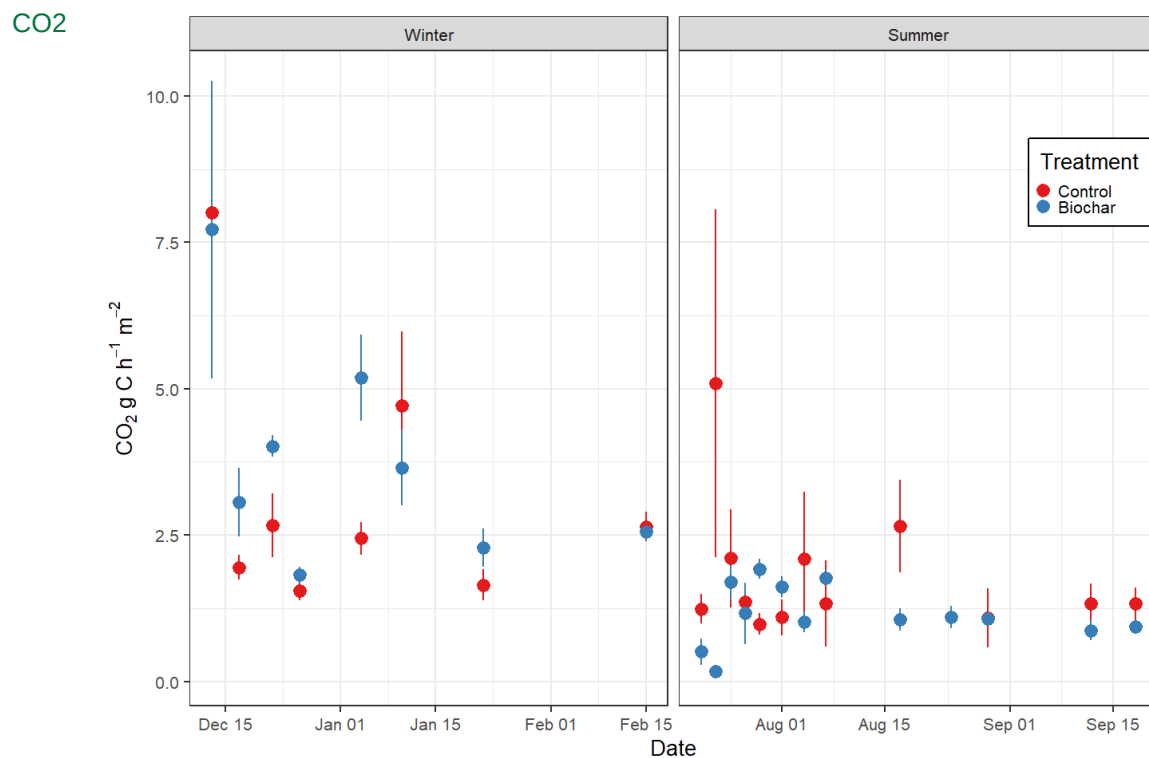


Figure 14 - Time series of CO₂ emissions in the two rounds of biochar application (winter and summer) into the goats bed, compared to the control pen that did not received biochar.

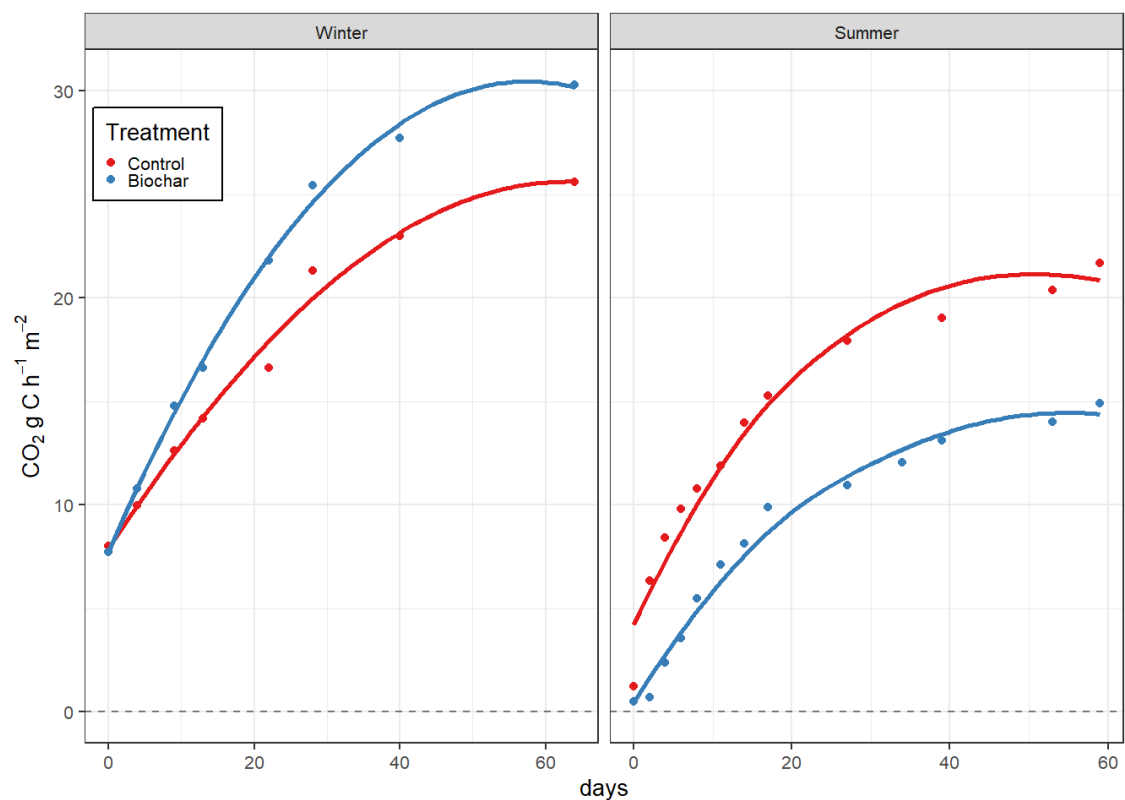


Figure 15 - Accumulation curve of CO₂ emitted along the two rounds of biochar application (winter and summer) into the goats bed, compared to the control pen that did not received biochar.

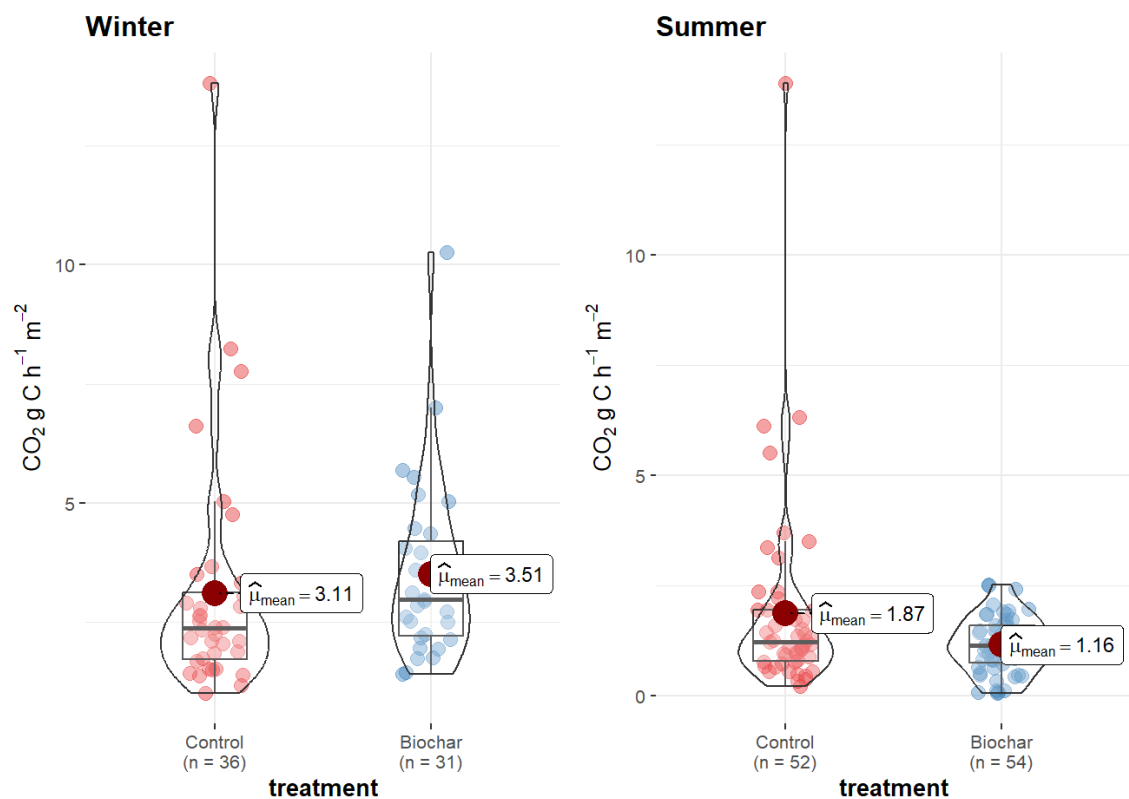


Figure 16 - Violin plots with mean values of CO₂ emission rate from goats bedding along the two rounds of biochar application (winter and summer), compared to the control pen that did not received biochar.



CH₄

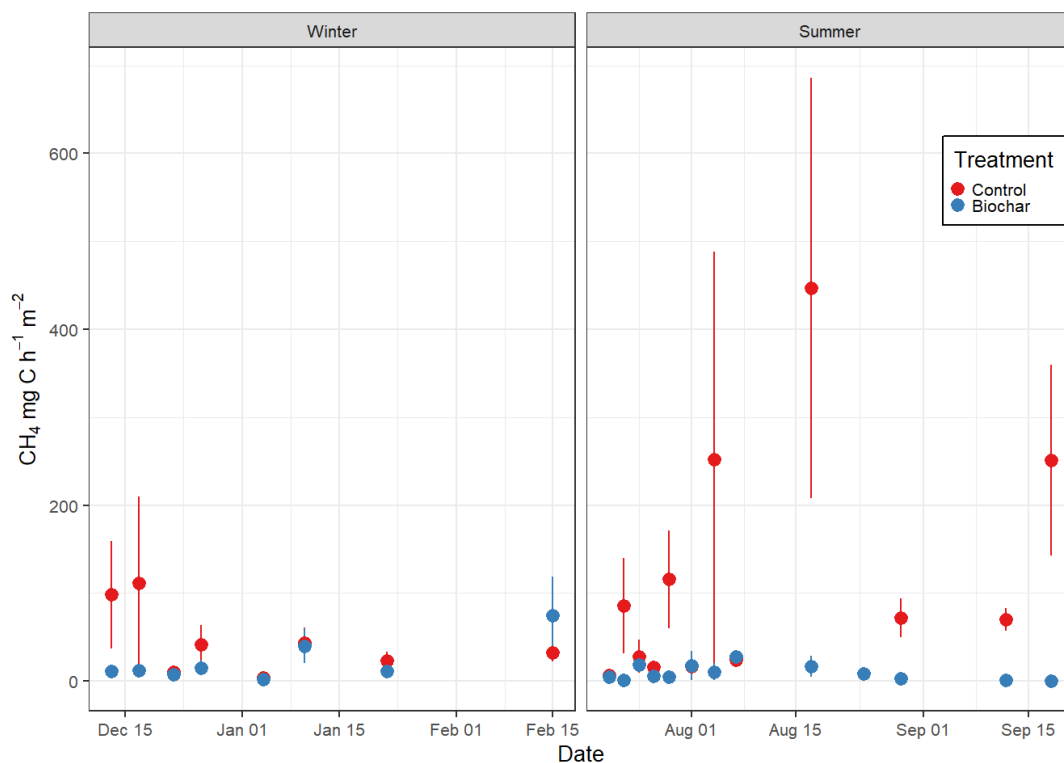


Figure 17 - Time series of CH₄ emissions in the two rounds of biochar application (winter and summer) into the goats bed, compared to the control pen that did not received biochar.

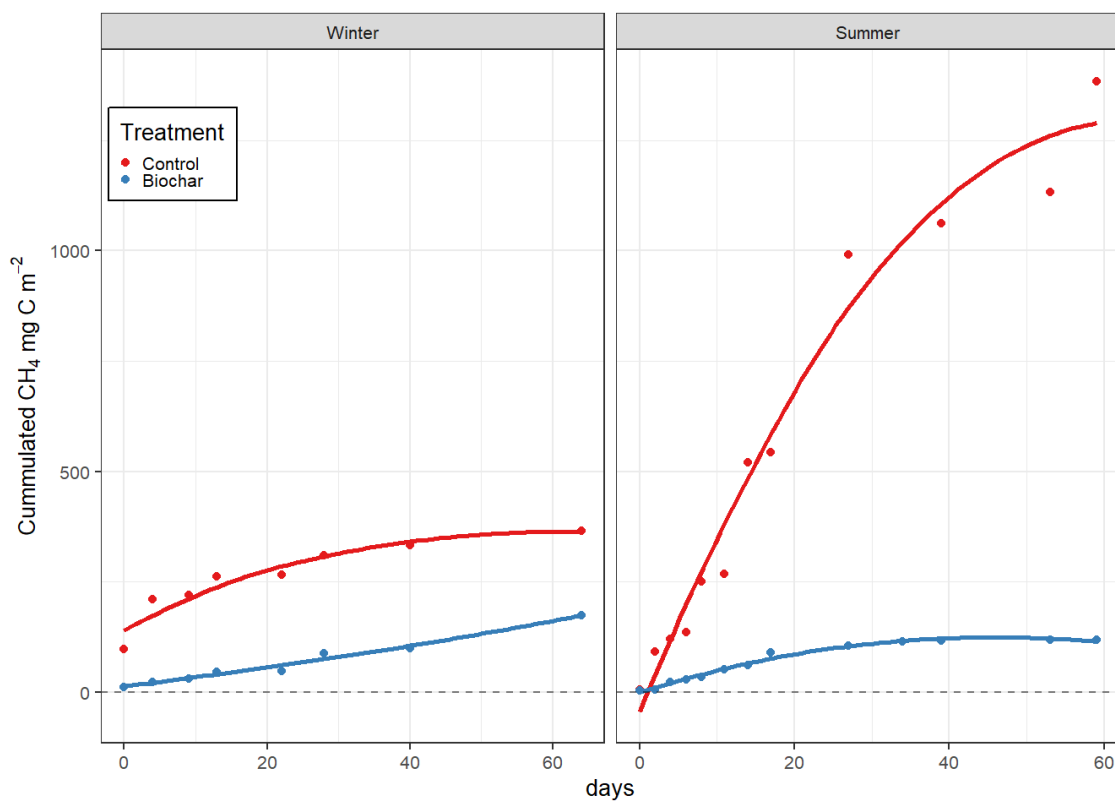


Figure 18 - Accumulation curve of CH₄ emitted along the two rounds of biochar application (winter and summer) into the goats bed, compared to the control pen that did not received biochar.



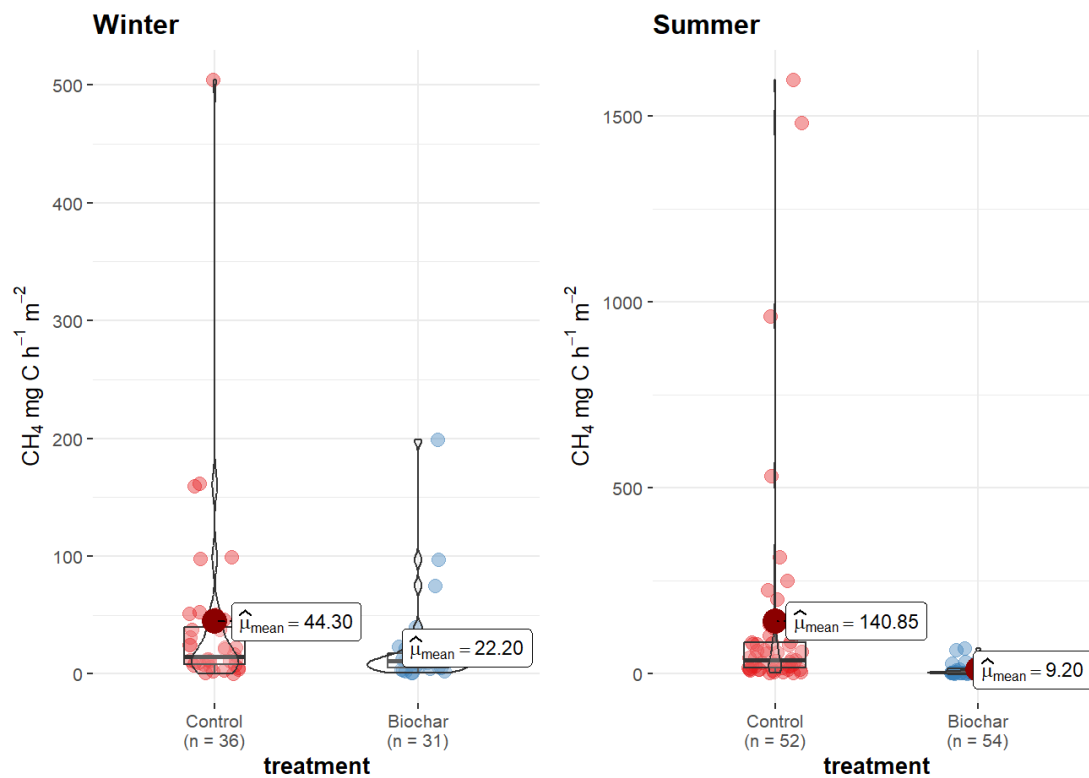


Figure 19 - Violin plots with mean values of CH_4 emission rate from goats bedding along the two rounds of biochar application (winter and summer), compared to the control pen that did not received biochar.

N₂O

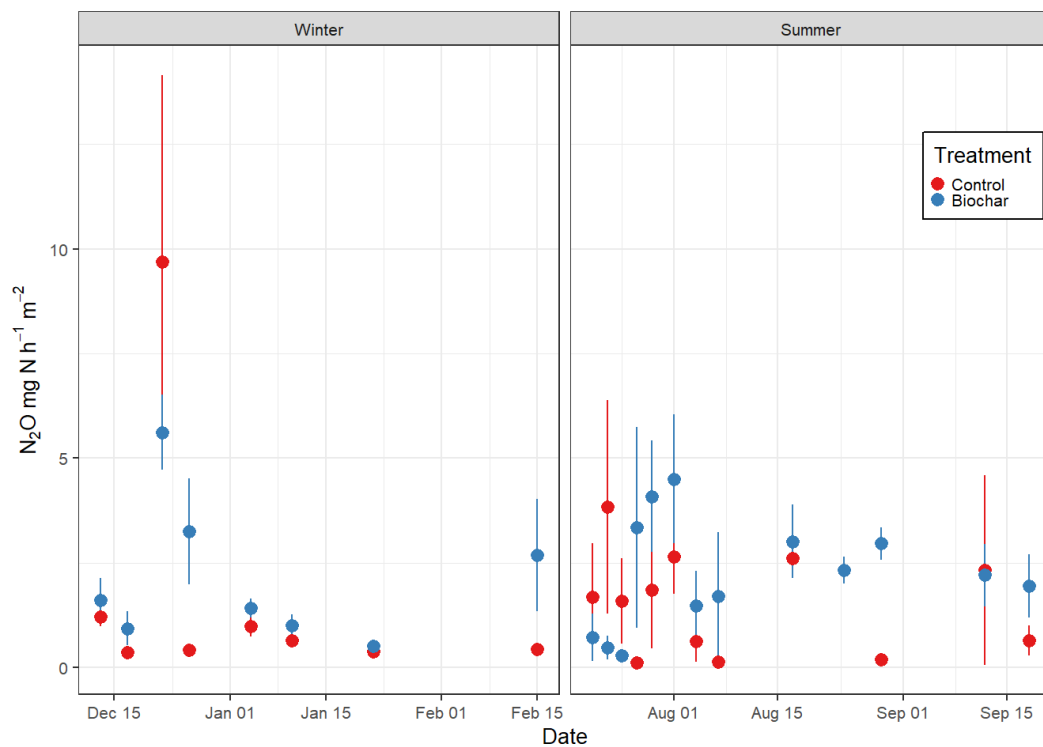


Figure 20 - Time series of N_2O emissions in the two rounds of biochar application (winter and summer) into the goats bed, compared to the control pen that did not received biochar.

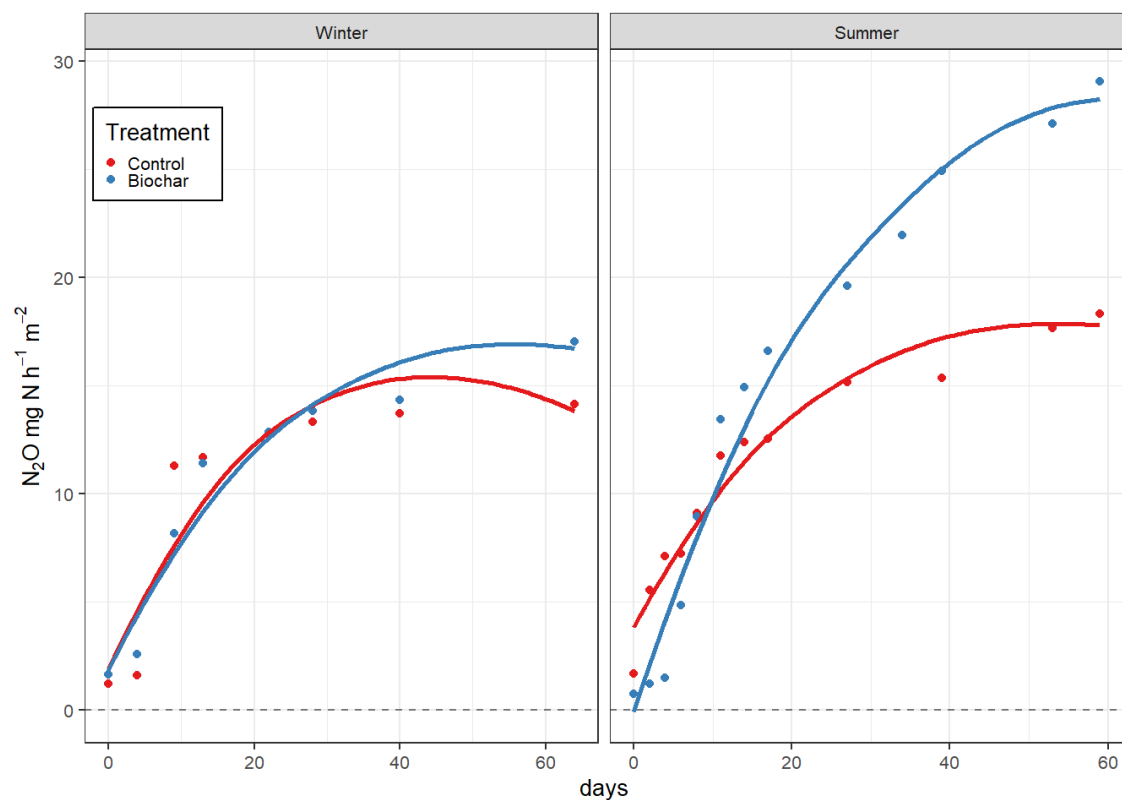


Figure 21 - Accumulation curve of N_2O emitted along the two rounds of biochar application (winter and summer) into the goats bed, compared to the control pen that did not received biochar.

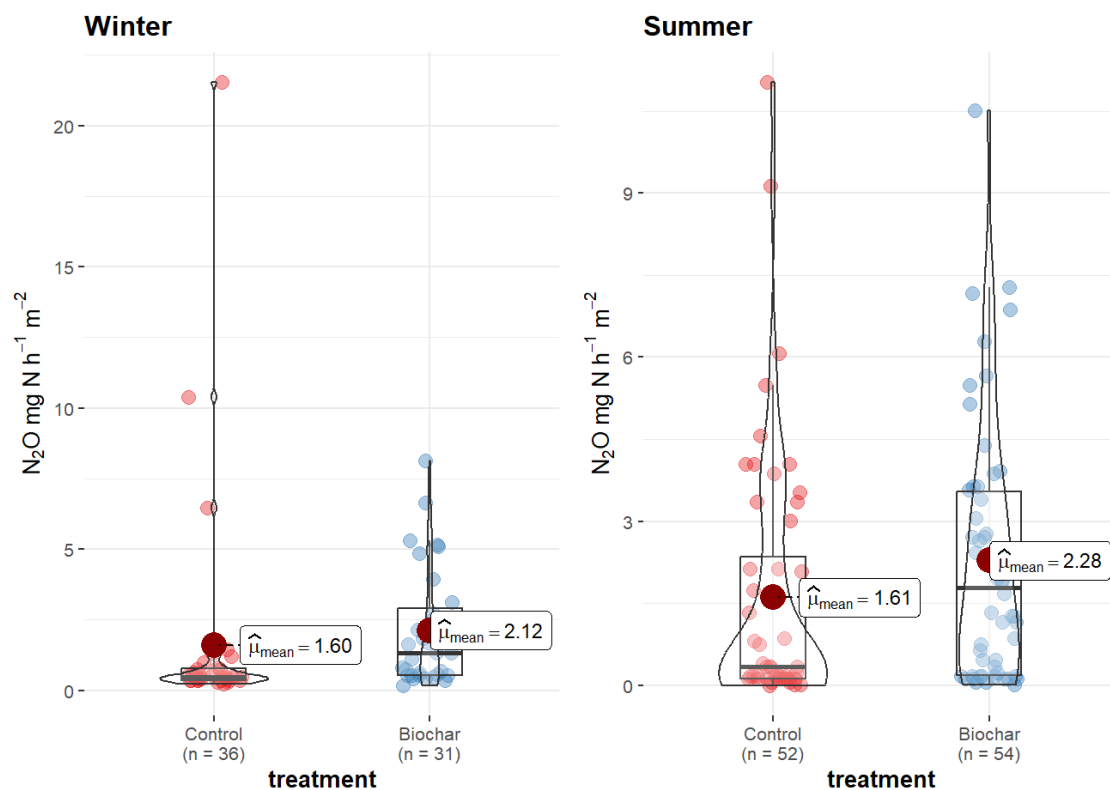


Figure 22 - Violin plots with mean values of N_2O emission rate from goats bedding along the two rounds of biochar application (winter and summer), compared to the control pen that did not received biochar.



NH₃

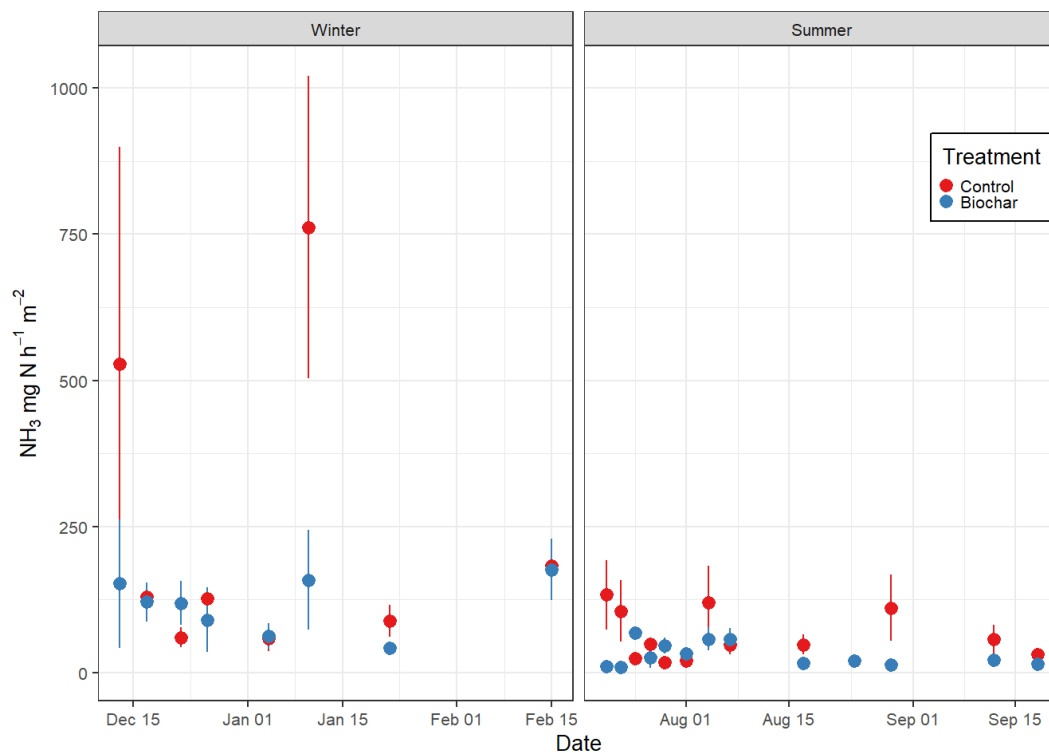


Figure 23 - Time series of NH₃ emissions in the two rounds of biochar application (winter and summer) into the goats bed, compared to the control pen that did not received biochar.

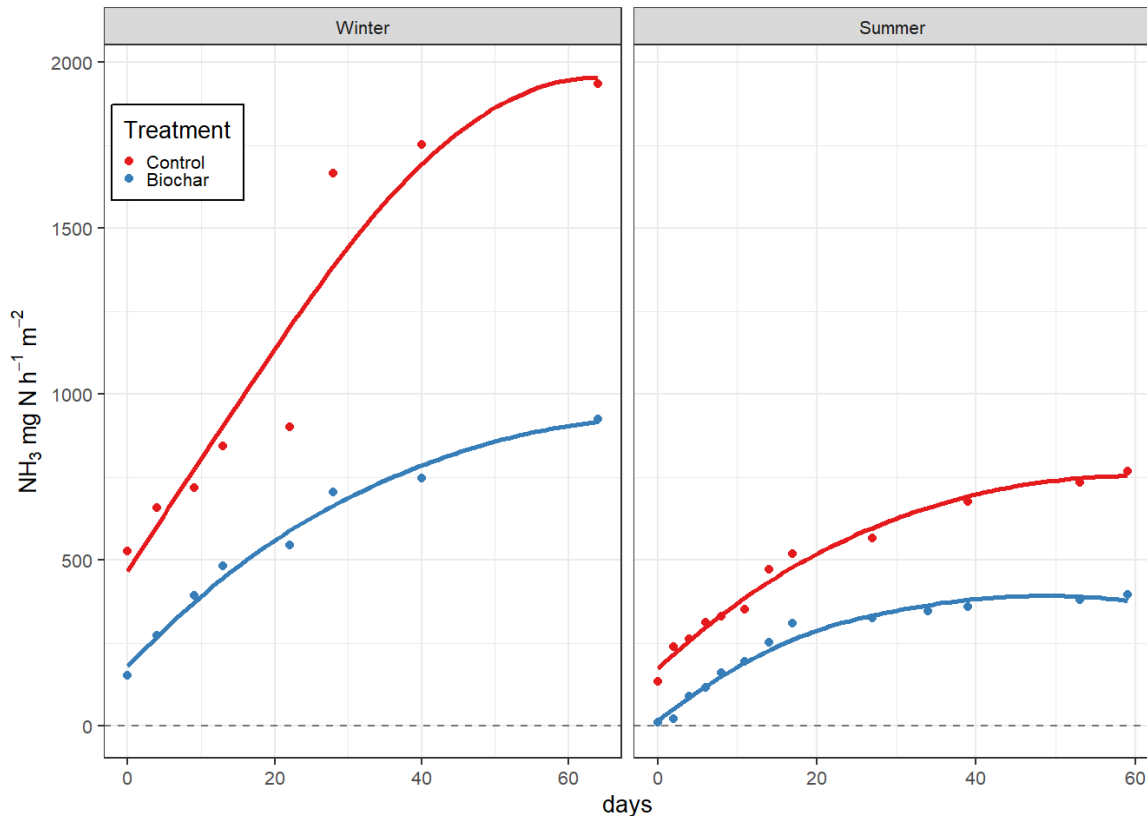


Figure 24 - Accumulation curve of NH₃ emitted along the two rounds of biochar application (winter and summer) into the goats bed, compared to the control pen that did not received biochar.



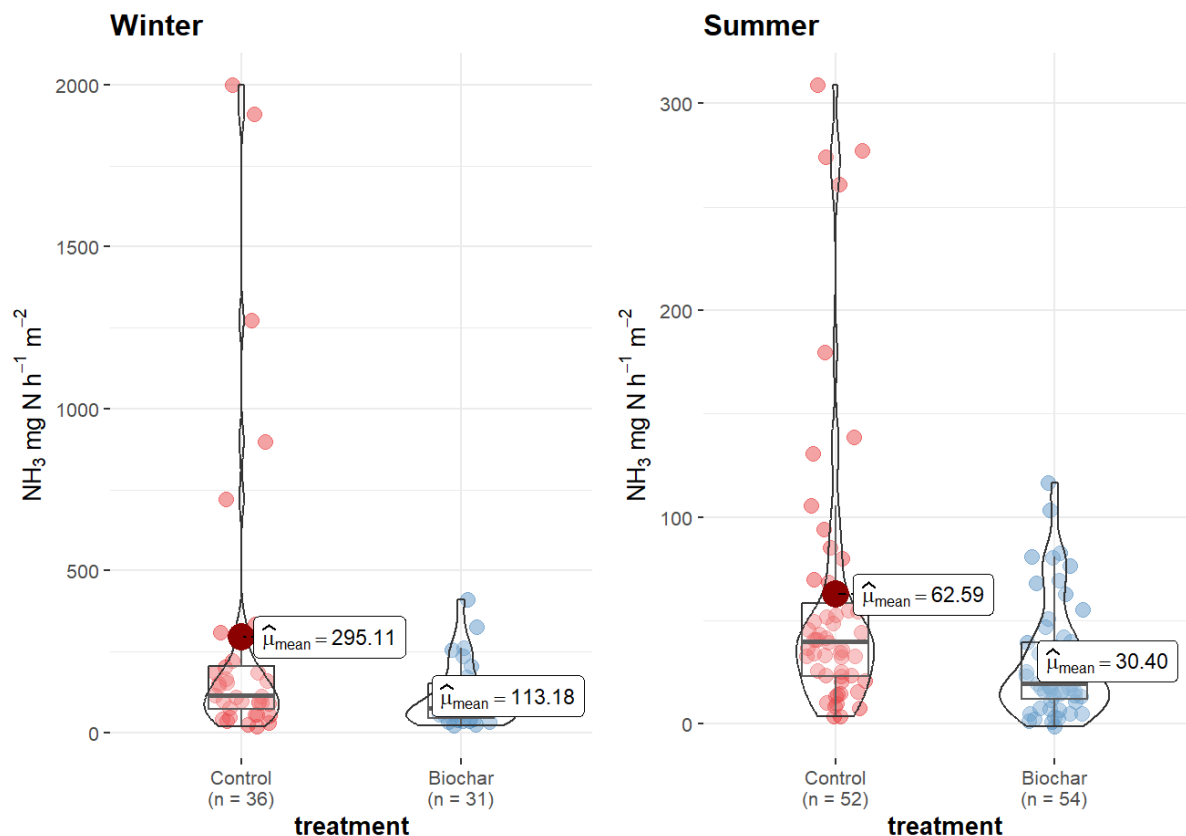


Figure 25 - Violin plots with mean values of NH_3 emission rate from goats bedding along the two rounds of biochar application (winter and summer), compared to the control pen that did not received biochar.

Summary of results:

Table 2. Mean values ($\pm$ S.D.) of GHG and NH_3 emission rates from goats bedding along the two rounds of biochar application (winter and summer), compared to the control pen that did not received biochar.

Season	Treatment	CO_2 $\text{g h}^{-1} \text{m}^{-2}$	CH_4 $\text{mg h}^{-1} \text{m}^{-2}$	N_2O $\text{mg h}^{-1} \text{m}^{-2}$	NH_3 $\text{mg h}^{-1} \text{m}^{-2}$
Winter	Control	3.11 (± 0.42)	44.30 (± 14.72)	1.60 (± 0.65)	295.11 (± 80.35)
Winter	Biochar	3.51 (± 0.33)	22.20 (± 6.97)	2.12 (± 0.38)	113.18 (± 17.48)
Summer	Control	1.87 (± 0.30)	140.85 (± 44.70)	1.61 (± 0.33)	62.59 (± 10.05)
Summer	Biochar	1.16 (± 0.09)	9.20 (± 2.08)	2.28 (± 0.32)	30.40 (± 3.77)

Key findings:

The trial of adding biochar to animal bedding in pens has shown very consistent results in both rounds of testing. In both winter and summer, CH₄ and NH₃ emissions were significantly reduced, but N₂O emissions increased.

- In both seasons, NH₃ emissions were reduced by more than half in the presence of biochar. While in pens with biochar, the emission rate always remained moderate to low, in pens without biochar there were several episodes of very high emissions. The positive effect of the biochar was is longer lasting.
- CH₄ reduction with the presence of biochar was much more intense in summer (less than 10%) than in winter (50%), presumably because in winter the biochar was insufficient to keep the bedding dry. With a higher volume of biochar (10% instead of 5%), better results could have been achieved. In fact, in winter, the presence of biochar only had a significant effect in the first two weeks, soon becoming ineffective. This loss of effectiveness over time was hardly noticeable in summer.
- The increase in N₂O emissions in both seasons is presumably due to the fact that biochar retains much more urine in the substrate, compared to the control where some of the urine is likely to be lost through leaching (the trial was conducted in pens with earthen floors).
- The CO₂ emission results varied between the two seasons and also showed a somewhat erratic temporal pattern, with high variability between dates, not just between seasons. While higher CO₂ emissions were recorded in the biochar pen than in the control pen in winter, the trend was reversed in summer. In winter, with high bedding moisture, presumably the increased aeration of the manure with biochar allowed for better oxidation of the organic matter, releasing more CO₂ and less CH₄.

Other findings (reported by the farmer):

- It was also observed that during the 10 weeks of the winter trial, the biochar pen maintained lower humidity levels, requiring less straw (11 vs 6 straw inputs) to maintain the animals' welfare.
- Compared to other pens, it was observed that the animals preferred to rest indoors in the biochar area.
- A lower percentage of umbilical infections was observed in the goats on the biochar bedding.



4.2. Biochar added to manure-pile stock

CO₂

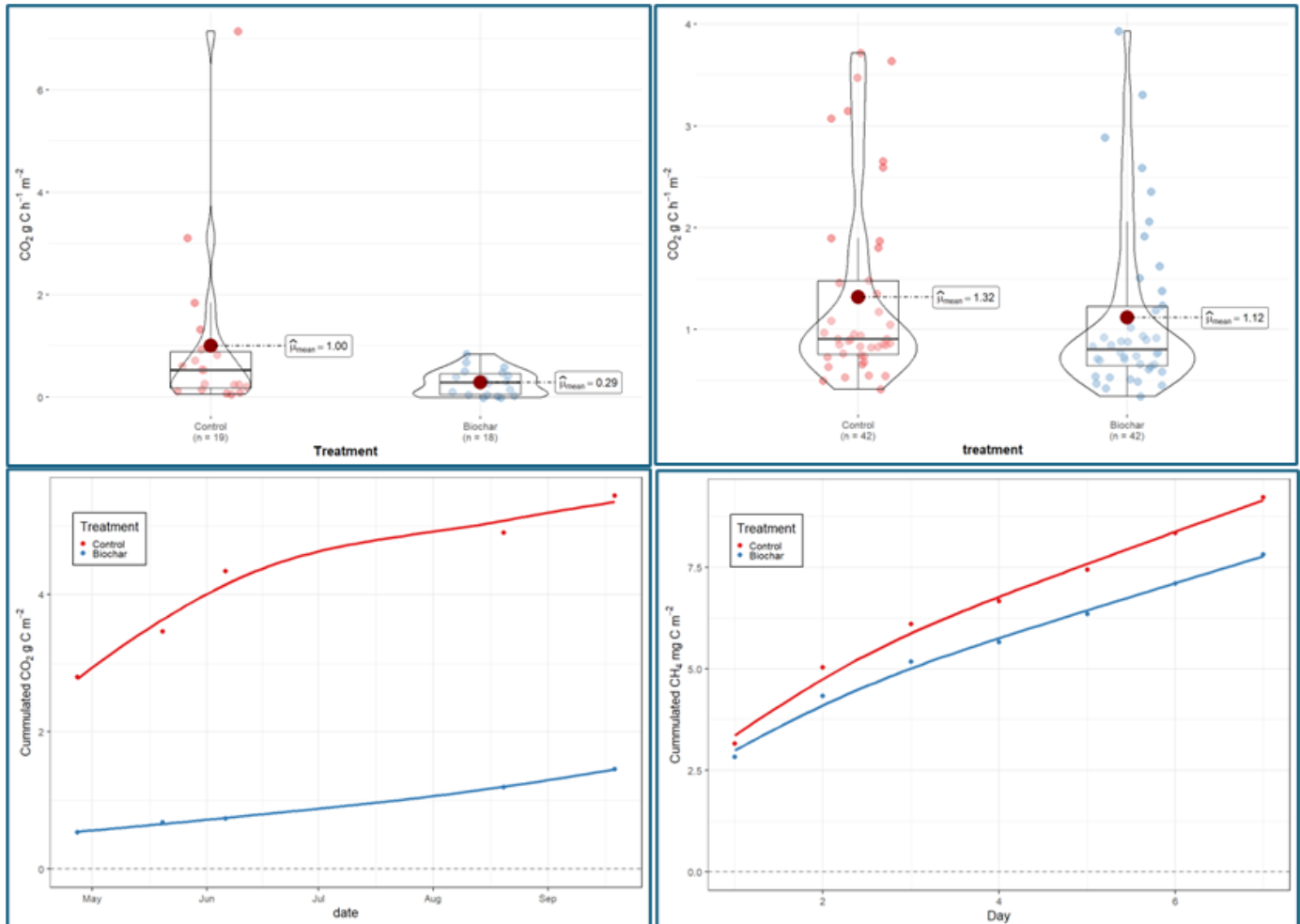


Figure 26 - Violin plots with mean values (up) and accumulated curves (down) of CO₂ emission from manure piles in two different trials: (i) biochar was mixed with the straw in the pen bedding (left); (ii) biochar was only applied over the manure pile stock. Control did not received biochar at any stage.



CH₄

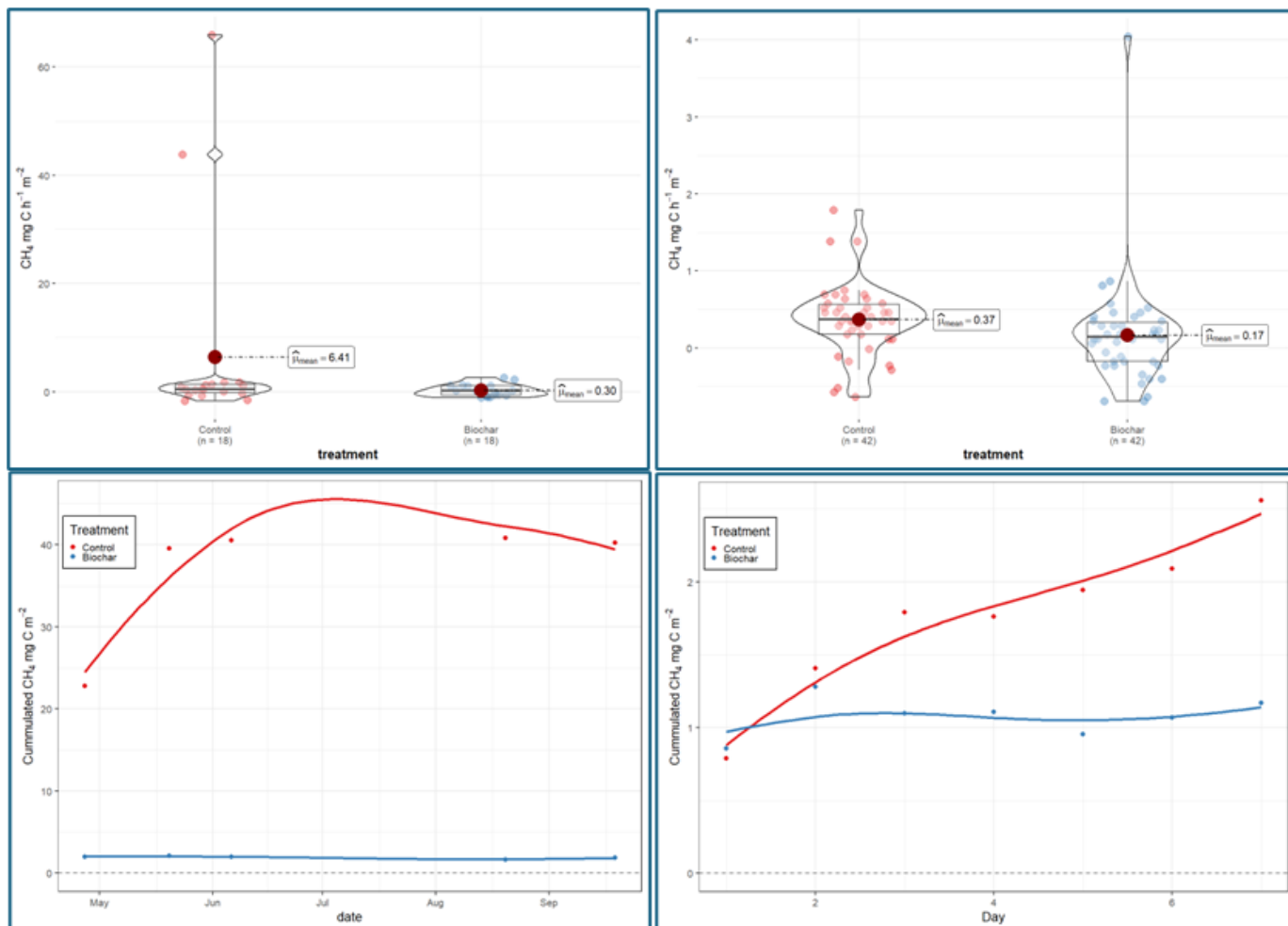


Figure 27 - Violin plots with mean values (up) and accumulated curves (down) of CH₄ emission from manure piles in two different trials: (i) biochar was mixed with the straw in the pen bedding (left); (ii) biochar was only applied over the manure pile stock. Control did not received biochar at any stage.



N2O

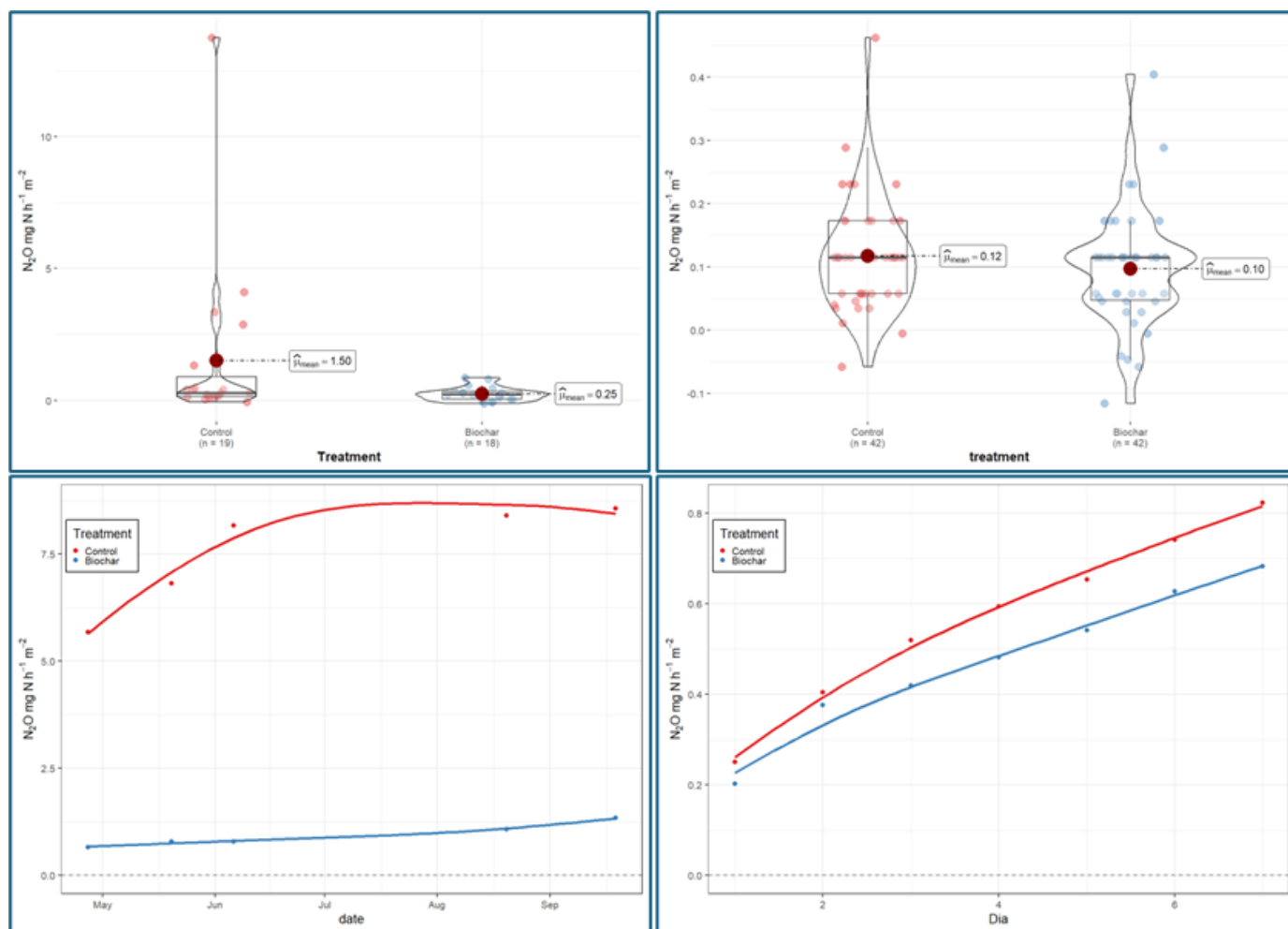


Figure 28 - Violin plots with mean values (up) and accumulated curves (down) of N₂O emission from manure piles in two different trials: (i) biochar was mixed with the straw in the pen bedding (left); (ii) biochar was only applied over the manure pile stock. Control did not received biochar at any stage.



NH₃

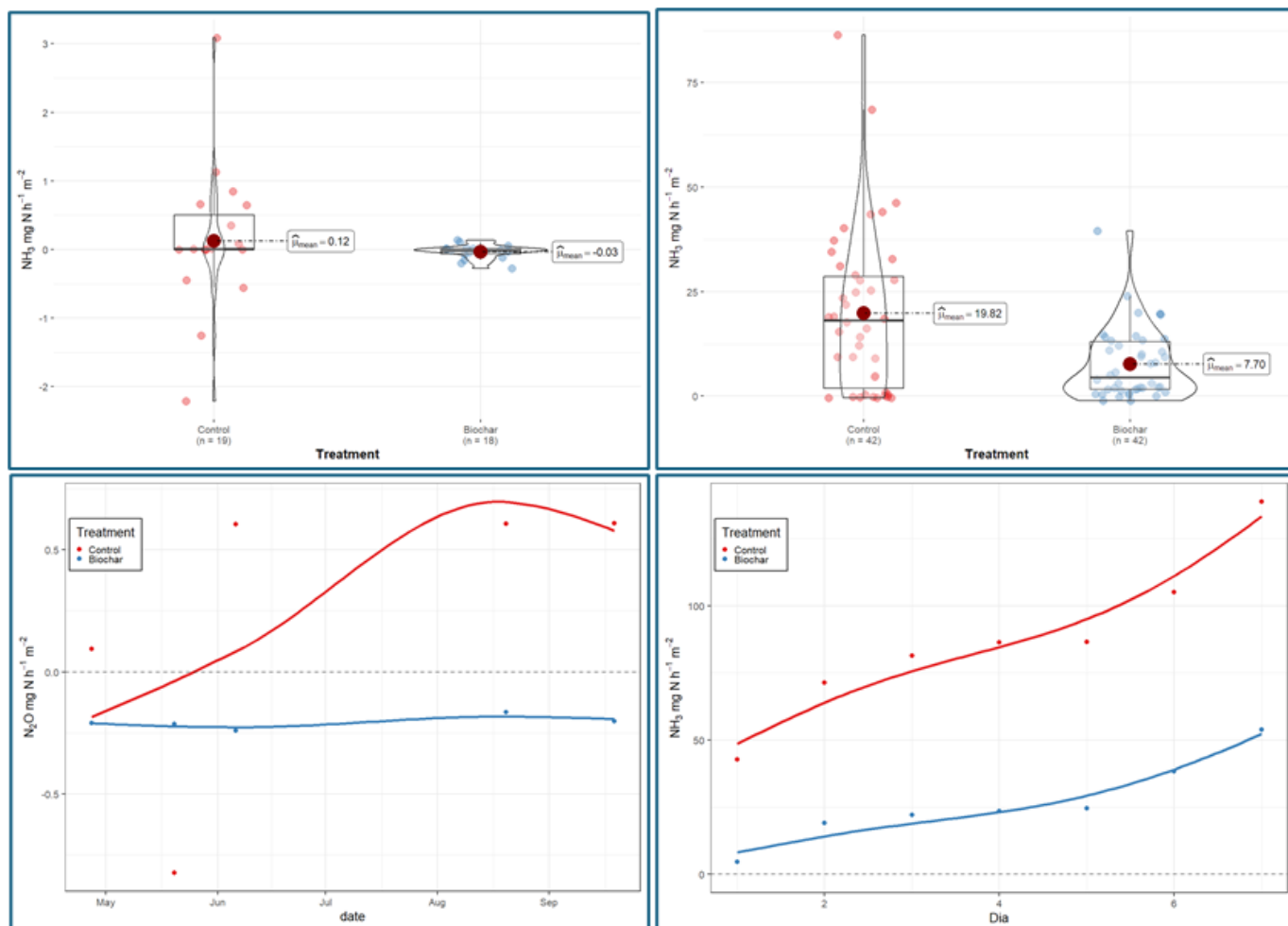


Figure 29 - Violin plots with mean values (up) and accumulated curves (down) of NH₃ emission from manure piles in two different trials: (i) biochar was mixed with the straw in the pen bedding (left); (ii) biochar was only applied over the manure pile stock. Control did not received biochar at any stage.

Summary of results

Table 3 - Mean values ($\pm$ S.D.) of GHG and NH₃ emission rates from from manure piles in two different trials: (i) biochar was mixed with the straw in the pen bedding (left); (ii) biochar was only applied over the manure pile stock. Control did not received biochar at any stage.

Season	Treatment	CO ₂ g h ⁻¹ m ⁻²	CH ₄ mg h ⁻¹ m ⁻²	N ₂ O mg h ⁻¹ m ⁻²	NH ₃ mg h ⁻¹ m ⁻²
At Bedding	Control	1.00 ($\pm$ 0.38)	30.13 ($\pm$ 24.06)	1.50 ($\pm$ 0.74)	0.12 ($\pm$ 0.24)
	Biochar	0.29 ($\pm$ 0.06)	0.30 ($\pm$ 0.25)	0.25 ($\pm$ 0.07)	-0.03 ($\pm$ 0.02)
At pile	Control	1.32 ($\pm$ 0.14)	0.37 ($\pm$ 0.07)	0.12 ($\pm$ 0.01)	19.82 ($\pm$ 2.99)
	Biochar	1.12 ($\pm$ 0.13)	0.17 ($\pm$ 0.11)	0.10 ($\pm$ 0.01)	7.70 ($\pm$ 1.30)



Key findings:

The results of the emissions readings differ widely between the two trials in terms of intensity, although they maintain some common patterns, despite the fact that the first (biochar added to the animal bedding) is long-term (months) and the second (biochar added to the manure pile once removed from the pens) is short-term. Another difference is that in the first trial, with biochar added during bedding, the control is a manure with a much higher share of straw compared to the biochar-rich manure. This difference does not happen in the second trial, in which biochar cover a manure similar to the control pile.

- In all cases, for the four gases and the two trials, less was emitted in the manure with biochar than in the control manure. And for the four gases, it seems more effective when the biochar is already incorporated into the manure because it was added during the bedding phase.
- Manure with biochar released less CO₂, despite being more aerated and therefore more susceptible to complete oxidation of organic matter. CH₄ emissions were significantly reduced in the manure pile that had received biochar during the bedding phase, while they remained high in the manure piles that had not received biochar.
- Adding biochar to the manure pile also reduced CH₄ emissions by more than half, even though they were already low in the control pile.
- Similar to CH₄, N₂O emissions were significantly reduced in the manure pile that had received biochar during the bedding phase, while they remained high in the manure piles that had not received biochar.
- Adding biochar to the manure pile barely reduced N₂O emissions, as they were already very low.
- NH₃ emissions were completely eliminated in the manure pile that had received biochar during the bedding phase. The final average value was even negative, indicating some NH₃ absorption. Adding biochar to the manure pile also reduced NH₃ emissions by more than half but did not eliminate them completely.

4.3. Fertilization with biochar-enriched manure

Emission of CO₂

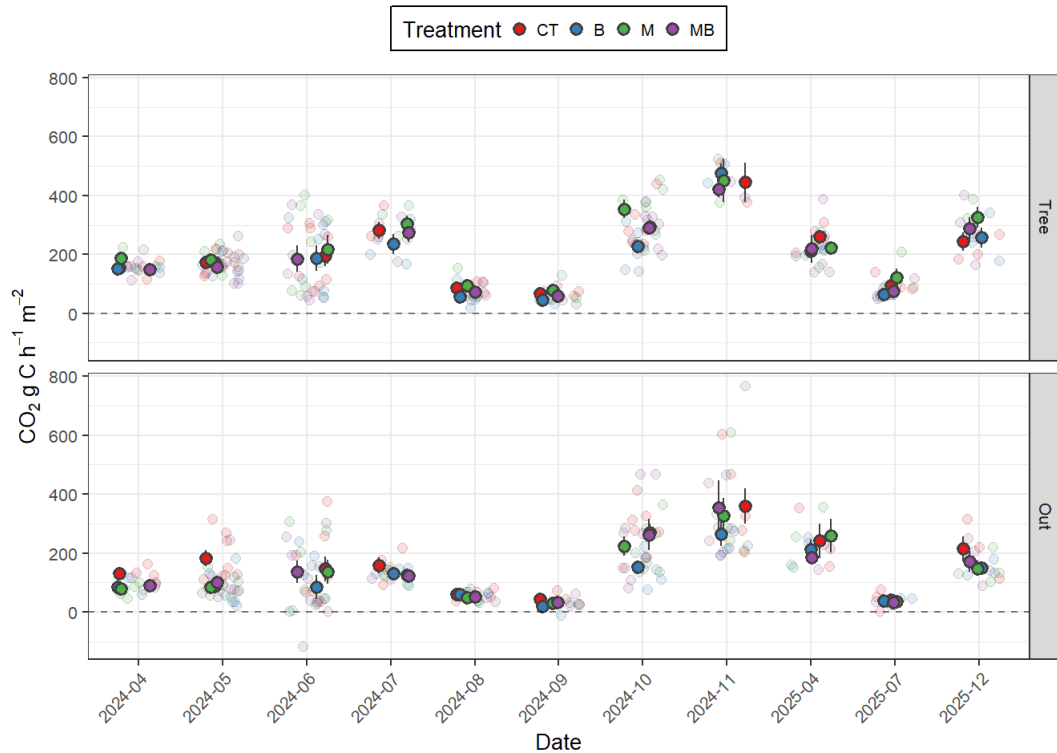


Figure 30 - Time series of soil CO₂ emission recorded in two dehesa microhabitats (open pasture (out) and beneath tree canopies (tree)) after the addition of biochar, manure or manure enriched with biochar, plus the control that did not receive any amendment.

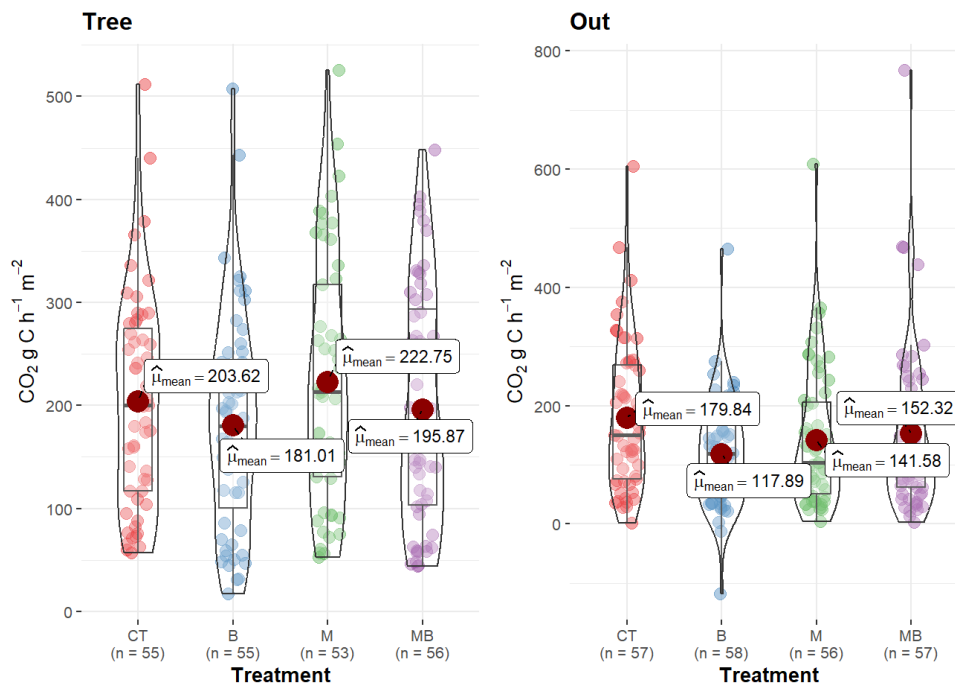


Figure 31 - Violin plots with mean values of soil CO₂ emission recorded in two dehesa microhabitats (open pasture (out) and beneath tree canopies (tree)) after the addition of biochar, manure or manure enriched with biochar, plus the control that did not receive any amendment.

Emission of CH₄

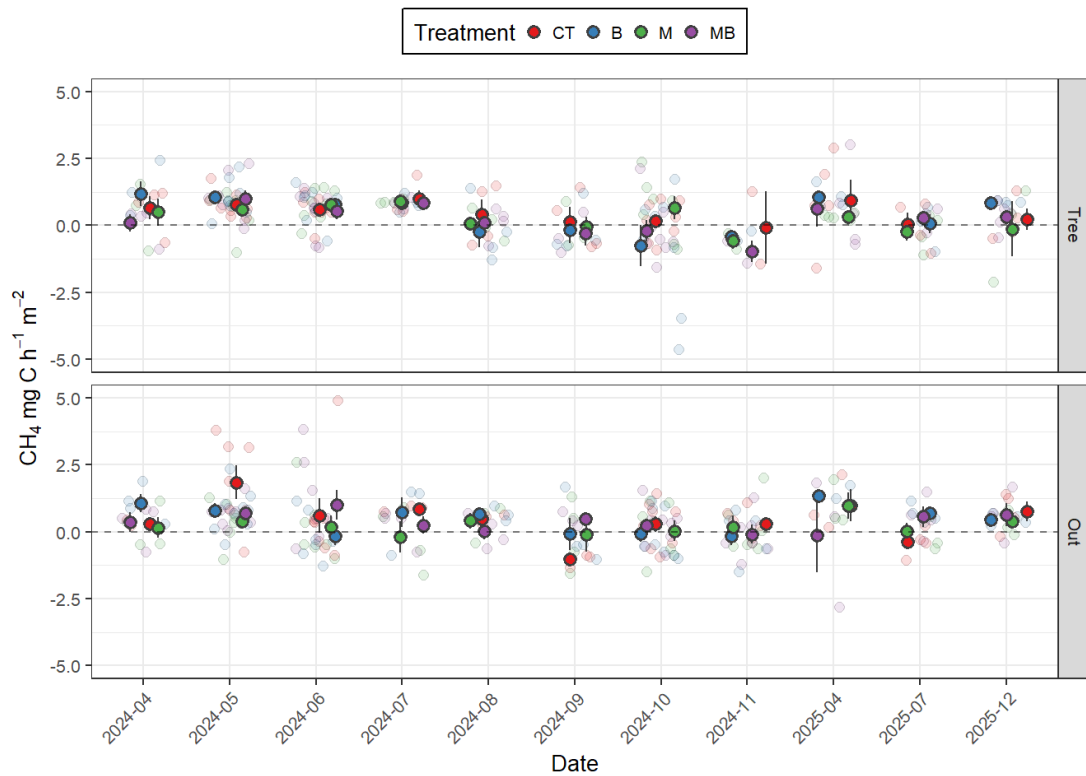


Figure 32 - Time series of soil CH₄ emission recorded in two dehesa microhabitats (open pasture (out) and beneath tree canopies (tree)) after the addition of biochar, manure or manure enriched with biochar, plus the control that did not receive any amendment.

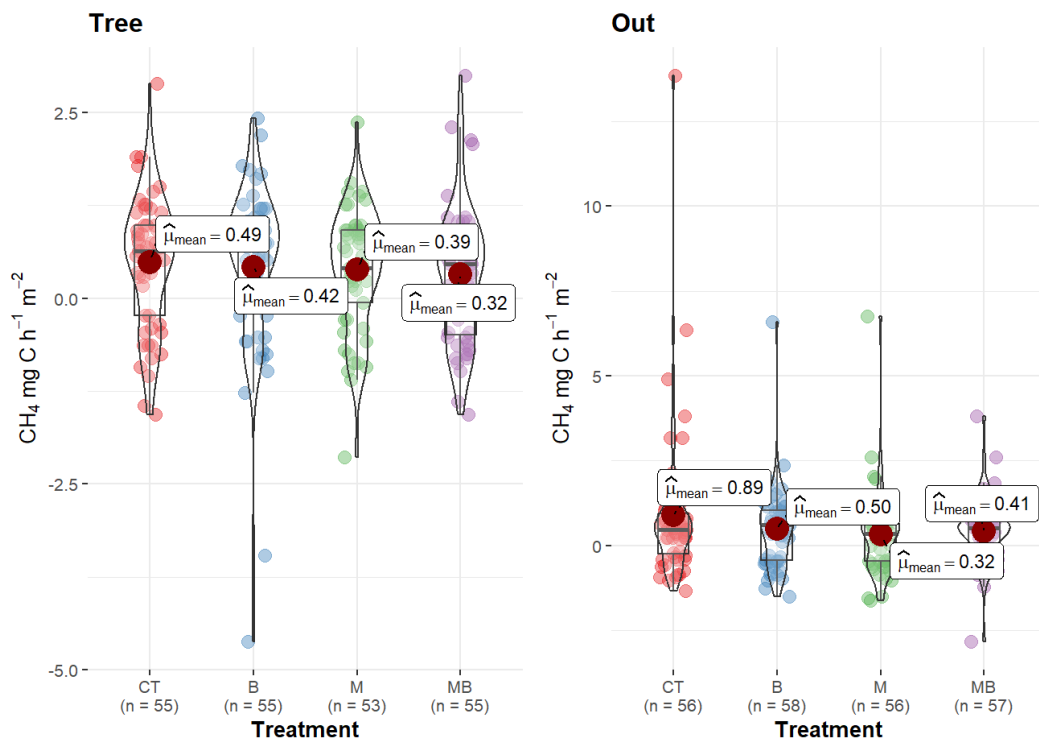


Figure 33. Violin plots with mean values of soil CH₄ emission recorded in two dehesa microhabitats (open pasture (out) and beneath tree canopies (tree)) after the addition of biochar, manure or manure enriched with biochar, plus the control that did not receive any amendment.

Emission of N₂O

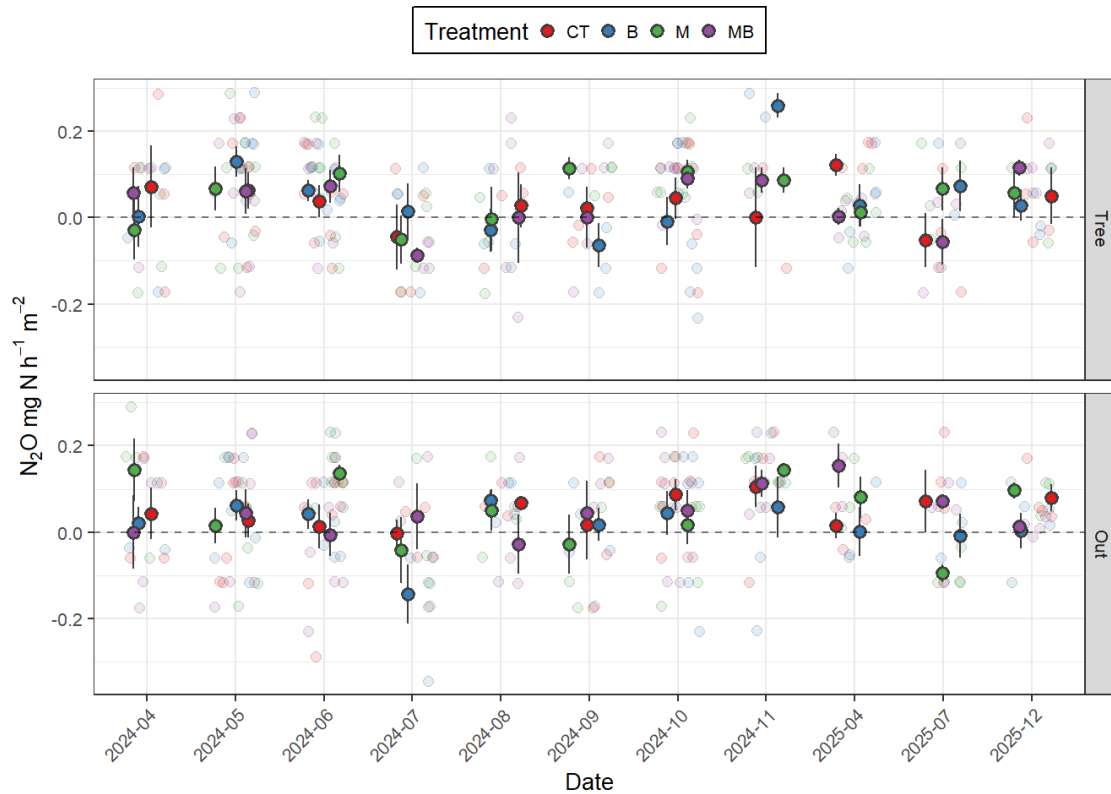


Figure 34 - Time series of soil N₂O emission recorded in two dehesa microhabitats (open pasture (out) and beneath tree canopies (tree)) after the addition of biochar, manure or manure enriched with biochar, plus the control that did not receive any amendment.

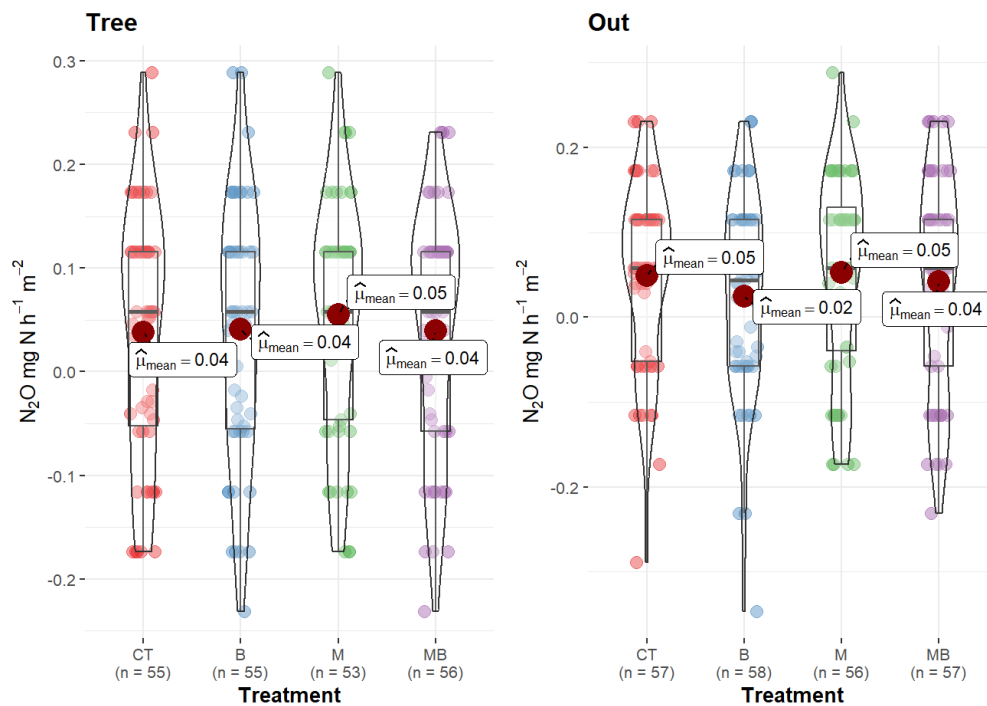


Figure 35 - Violin plots with mean values of soil N₂O emission recorded in two dehesa microhabitats (open pasture (out) and beneath tree canopies (tree)) after the addition of biochar, manure or manure enriched with biochar, plus the control that did not receive any amendment.



Summary of Results on GHG Gases Emission

Table 4 - Mean values ($\pm$ S.D.) of GHG emission rates from dehesa soils in two microhabitats after the addition of biochar, manure or manure enriched with biochar, plus the control that did not receive any amendment.

Season	Treatment	CO ₂ g h ⁻¹ m ⁻²	CH ₄ mg h ⁻¹ m ⁻²	N ₂ O mg h ⁻¹ m ⁻²
Beneath Tree Canopy	Control	203.62 ($\pm$ 13.91)	0.49 ($\pm$ 0.12)	0.038 ($\pm$ 0.016)
	Biochar	181.01 ($\pm$ 14.24)	0.42 ($\pm$ 0.16)	0.041 ($\pm$ 0.017)
	Manure	222.75 ($\pm$ 16.36)	0.39 ($\pm$ 0.11)	0.055 ($\pm$ 0.016)
	Manure+Biochar	195.87 ($\pm$ 15.29)	0.32 ($\pm$ 0.12)	0.040 ($\pm$ 0.015)
Open Pasture	Control	179.84 ($\pm$ 16.50)	0.89 ($\pm$ 0.30)	0.049 ($\pm$ 0.014)
	Biochar	117.89 ($\pm$ 11.94)	0.50 ($\pm$ 0.16)	0.025 ($\pm$ 0.015)
	Manure	141.58 ($\pm$ 15.60)	0.32 ($\pm$ 0.17)	0.053 ($\pm$ 0.016)
	Manure+Biochar	152.32 ($\pm$ 18.39)	0.41 ($\pm$ 0.13)	0.042 ($\pm$ 0.017)

Grass production

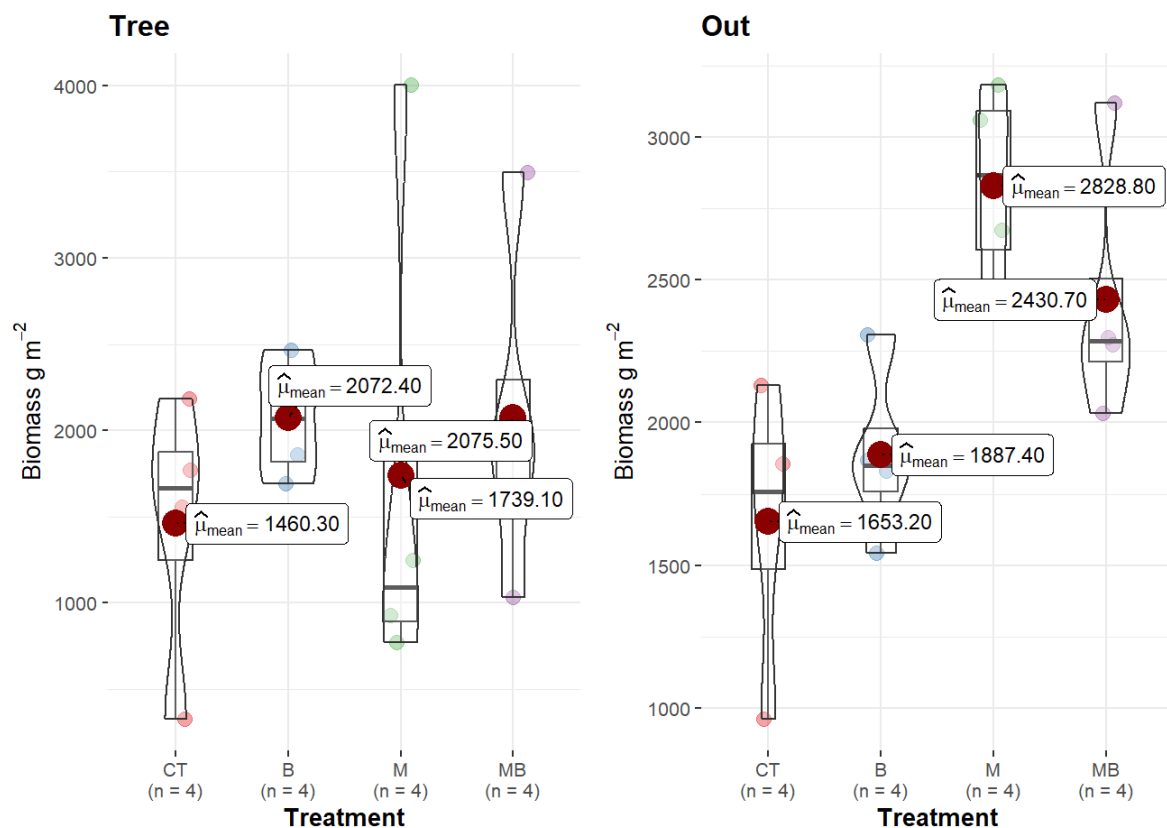


Figure 36 - Violin plots with mean values of grass production recorded in two dehesa microhabitats (open pasture (out) and beneath tree canopies (tree)) after the addition of biochar, manure or manure enriched with biochar, plus the control that did not receive any amendment.



Soil Carbon Stock and soil fertility

Table 5 - Mean values ($\pm$ S.D.) of carbon stocks in soils in two microhabitats (open pasture (out) and beneath tree canopies (tree)) after the addition of biochar, manure or manure enriched with biochar, plus the control that did not receive any amendment. The last column present values for the stand level, based on a 25% of tree cover.

Treatment	SOC, % weight		C stock, kg / m ²		C stock tn / ha
	Trees	Out	Trees	Out	
Control	6.1 ± 1.5	2.4 ± 1.1	7.9 ± 1.9	3.1 ± 1.4	43.4 ± 15.4
Biochar	5.5 ± 2.9	3.8 ± 1.1	7.2 ± 3.8	5.0 ± 1.4	55.2 ± 19.8
Manure	7.4 ± 2.4	3.0 ± 1.5	9.6 ± 3.1	3.9 ± 2.0	53.6 ± 22.4
Manure+Biochar	6.4 ± 2.7	3.1 ± 1.3	8.4 ± 3.5	4.1 ± 1.7	51.5 ± 21.3

Table 6 - Mean values ($\pm$ S.D.) of pH and electrical conductivity (as proxy of nutrient availability) of soils in two microhabitats (open pasture (out) and beneath tree canopies (tree)) after the addition of biochar, manure or manure enriched with biochar, plus the control that did not receive any amendment. The last column present values for the stand level, based on a 25% of tree cover.

Treatment	pH		Electrical Conductivity		Nitrogen, % weight	
	Trees	Out	Trees	Out	Trees	Out
Control	6.1 ± 1.5	2.4 ± 1.1	7.9 ± 1.9	3.1 ± 1.4	0.55 ± 0.13	0.25 ± 0.10
Biochar	5.5 ± 2.9	3.8 ± 1.1	7.2 ± 3.8	5.0 ± 1.4	0.50 ± 0.25	0.37 ± 0.08
Manure	7.4 ± 2.4	3.0 ± 1.5	9.6 ± 3.1	3.9 ± 2.0	0.68 ± 0.19	0.32 ± 0.15
Manure+Biochar	6.4 ± 2.7	3.1 ± 1.3	8.4 ± 3.5	4.1 ± 1.7	0.58 ± 0.23	0.33 ± 0.11

Key findings:

On GGH emissions

- CO₂ emissions from the soil were significantly reduced when biochar was added, but no differences were observed between soils that received manure and those that received manure enriched with biochar. The pattern was observed in both open pasture and under canopy, although it was more pronounced in open pasture. Overall, more CO₂ was emitted from the soil under canopy than in open grassland, which can be explained by the higher organic matter content in the soil under canopy.
- The addition of biochar also reduced CH₄ emissions from the soil, again more pronounced in open grassland. Surprisingly, CH₄ emissions were also lower in the plots where pure manure or manure enriched with biochar was added (with no difference between the latter two). Negative emission rates (CH₄ absorption) were observed in all treatments, especially in summer-autumn.
- Finally, nitrous emissions were also reduced with the addition of biochar, but this was only observed in open pasture. The addition of manure led to an increase in nitrous emissions, both under and outside the canopy. Interestingly, however, when manure is enriched with biochar, there is no such increase in nitrous emissions, which remain at levels similar to the control. Negative values (N₂O absorption) were frequent, although without a well-defined pattern.

On the soil carbon:

- The three amendments contributed to an increase of more than 20% in soil organic carbon, at least in the short term (one year). Although this finding needs to be confirmed with more soil sampling campaigns and repetitions.
- The increase in carbon was slightly greater with biochar than with manure, and it is also expected to be more persistent.
- As is well known, the concentration of carbon was higher under the canopy than in open pasture.
- Consequently, the positive effect of the amendments on soil carbon stocks was much more evident outside the canopy than under the trees.

On the soil fertility:

Beyond soil carbon, a major indicator of soil fertility, three other parameters analyzed indicate the positive effect of the three amendments on soil fertility:

- Soil pH increased slightly with the application of the amendments, especially biochar.
- Soil conductivity increased with all three amendments, especially manure (with or without biochar).
- Soil nitrogen increased with the addition of manure and biochar, although the latter only had a positive effect on open grassland.

On the pasture production:

- Grass production increased with all three types of amendments.
- Biochar alone significantly increased grass production (15% in open grassland and 40% under canopy).
- The highest production values were observed in open grassland with manure input. The effect of manure was much less significant under canopy, as expected, due to its greater fertility compared to open grassland.

The effect of biochar on manure was weak and inconclusive, as it increased productivity under canopy compared to pure manure, but reduced it in open grassland.

4.4. Compost bedded pack

In an ongoing study developed in a dairy farm in Bétera (Valencia, Spain), the UPV team has observed nitrogen concentrations slightly higher, at around 3% on dry matter and carbon concentrations from 37 to 39%. These values, despite falling in the ranges found in literature, result in a low C:N ratio, which seems to lead to an incomplete composting process. In any case, these are preliminary results that will be expanded in the near future.

Nitrogen losses in CBP systems are primarily associated with NH_3 volatilisation under warm, aerated and alkaline conditions. Nevertheless, the literature indicates that appropriate management—adequate bedding supply, controlled moisture and balanced aeration—can promote microbial immobilisation of nitrogen and improve the agronomic quality of the exported material (Bernal et al., 2009; Leso et al., 2020).

4.5. Acidification of slurry

The experimental results clearly illustrate the implications of slurry pH control, and by extension slurry acidification, on nitrogen and carbon conservation during storage. Over the monitoring period, between 69% and 85% of the initial ammoniacal nitrogen (N-NH_3) present in the slurry was emitted to the atmosphere as NH_3 , depending on sampling time and slurry characteristics, which implies that only 15–31% of the initial ammoniacal nitrogen was conserved in the stored slurry at the end of the experiment. Conditions associated with lower slurry pH consistently showed reduced NH_3 losses, indicating a higher degree of nitrogen retention. From a carbon perspective, CH_4 emissions expressed relative to the theoretical CH_4 production potential (IPCC-based MCF) ranged from approximately 30% to 59%, meaning that 41–70% of the potential CH_4 , and thus of the degradable organic carbon or volatile solids, was conserved in the slurry during storage. Higher dry matter and organic matter contents were associated with increased CH_4 and CO_2 emissions, reflecting enhanced microbial degradation of volatile solids. Overall, these results demonstrate that strategies capable of maintaining lower slurry pH, such as acidification, are critical to improving nitrogen conservation while simultaneously limiting carbon losses through methanogenesis, thereby enhancing the preservation of both reactive nitrogen and organic carbon fractions in stored slurry.

5. Conclusions and Recommendations

1. Biochar produced in dehesa farms (as could be in other agroforestry systems) is effective in reducing GHG and NH₃ emissions in stables when applied in mixture with straw bedding. Besides, the bed remained drier, young animals performed better and the farmer saved money (straw).
2. During the dry season, a single application of biochar at the beginning of the bedding cycle is sufficient. In contrast, during the wet season, it would be advisable to add biochar with each new batch of straw, as otherwise the positive effect of biochar does not persist over time. In any case, it is recommended that the final volume of biochar reach at least 10% of the volume of straw added.
3. It is also recommended to explore the possibility of adding biochar as a feed supplement, as in addition to the positive effects described in the scientific literature, this would allow for better and more gradual integration of biochar, manure, and straw, presumably increasing the effectiveness of biochar in mitigating emissions. To do this, it will be necessary to verify whether the low-cost biochar produced on the farm itself meets the requirements for feed biochar.
4. Biochar applied directly as a cover on the manure pile also contributes to reducing GHG and NH₃ emissions, but not as much as biochar that is already incorporated into the manure. Furthermore, applying it to the manure pile only once it has been removed from the barn means that its mitigation potential is not exploited during the weeks that the manure is forming in the barns. The model of applying biochar as a cover on the manure pile or slurry pond would only be recommended in cases where manure is removed daily.
5. Applying biochar as a pasture amendment has positive effects in terms of grass production, soil fertility, and soil carbon sequestration. Contrary to expectations, no negative effect was observed in low-fertility soils due to the immobilization of available nutrients. Biochar also contributed to reducing emissions of the three GHGs analyzed.
6. When biochar was incorporated into manure, the effect on soil fertility and forage production was, as expected, even more beneficial. It also helped to reduce GHG emissions after manure application, keeping emissions below the control soil without amendment.
7. Beyond the use of biochar, improving the ventilation of stables, reduce the volatilization of nitrogen from the compost bedded pack, obtaining a more rich and equilibrated manure (lower C/N ratio).
8. Similarly, the acidification of slurry contributes largely to the conservation of nitrogen and carbon conservation during storage, reducing in this way the emission of NH₃ and CH₄.

In summary, including best management practices for manure at the successive phase, from the production to the application in the field, reduce greatly the emission of GHG and NH₃ and produce a higher-quality manure. Specifically, converting biomass waste into biochar and using then the biochar in animal bedding is an investment that improves animal comfort and health, optimises waste management, reduces GHG emissions at farm level (in stables, manure pile stocks and farmed soils) and produces a valuable by-product for agriculture, closing a sustainable nutrient cycle and providing a good example of green and circular economy. In the near future, this biochar could be also marketed as carbon credit, providing an additional income to farmers.

6. References

- Ali, S., Rizwan, M., Qayyum, M. F., Ok, Y. S., Ibrahim, M., Riaz, M., ... & Shahzad, A. N. (2017). Biochar soil amendment on alleviation of drought and salt stress in plants: a critical review. *Environmental Science and Pollution Research*, 24(14), 12700-12712. <https://doi.org/10.1007/s11356-017-8904-x>
- Alkharabsheh, H. M., Seleiman, M. F., Battaglia, M. L., Shami, A., Jalal, R. S., Alhammad, B. A., ... & Al-Saif, A. M. (2021). Biochar and its broad impacts in soil quality and fertility, nutrient leaching and crop productivity: A review. *Agronomy*, 11(5), 993. <https://doi.org/10.3390/agronomy11050993>.
- Alves, C., Gonçalves, C., Fernandes, A. P., Tarelho, L., & Pio, C. (2011). Fireplace and woodstove fine particle emissions from combustion of western Mediterranean wood types. *Atmospheric Research*, 101(3), 692-700. <https://doi.org/10.1016/j.atmosres.2011.04.015>
- Amer M and Elwardany A (2020) Biomass Carbonization. *Renewable Energy - Resources, Challenges and Applications*. IntechOpen. <http://dx.doi.org/10.5772/intechopen.90480>
- Ayeneshet, B., & Temesgen, T. (2025). Role of Biochar as a Feed Additive on Animal Performance, Digestibility, Micro-Biota Dynamics, and Reduction of Enteric Methane Production. *Advances in Agriculture*, 2025(1), 9911760. <https://doi.org/10.1155/aia/9911760>
- Bai, Y., & Cotrufo, M. F. (2022). Grassland soil carbon sequestration: Current understanding, challenges, and solutions. *Science*, 377(6606), 603-608. <https://www.science.org/doi/10.1126/science.abo2380>
- Bai, Y., Ma, L., Degen, A. A., Rafiq, M. K., Kuzyakov, Y., Zhao, J., ... & Shang, Z. (2020). Long-term active restoration of extremely degraded alpine grassland accelerated turnover and increased stability of soil carbon. *Global Change Biology*, 26(12), 7217-7228. <https://doi.org/10.1111/gcb.15361>
- Barberg, A. E., Endres, M. I., Salfer, J. A., & Reneau, J. K. (2007). Performance and welfare of dairy cows in an alternative housing system in Minnesota. *Journal of Dairy Science*, 90(3), 1575–1583. [https://doi.org/10.3168/jds.S0022-0302\(07\)71643-0](https://doi.org/10.3168/jds.S0022-0302(07)71643-0)
- Bernal, M. P., Alburquerque, J. A., & Moral, R. (2009). Composting of animal manures and chemical criteria for compost maturity assessment: A review. *Bioresource Technology*, 100(22), 5444–5453. <https://doi.org/10.1016/j.biortech.2008.11.027>
- Biederman, L. A., Phelps, J., Ross, B. J., Polzin, M., & Harpole, W. S. (2017). Biochar and manure alter few aspects of prairie development: A field test. *Agriculture, Ecosystems & Environment*, 236, 78-87. <https://doi.org/10.1016/j.agee.2016.11.016>
- Black, R. A., Taraba, J. L., Day, G. B., Damasceno, F. A., Newman, M. C., Akers, K. A., Wood, C. L., McQuerry, K. J., & Bewley, J. M. (2014). The relationship between compost bedded pack performance, management, and bacterial counts. *Journal of Dairy Science*, 97(5), 2669–79. <https://doi.org/10.3168/jds.2013-6779>
- Black, R. A., Taraba, J. L., Day, G. B., Damasceno, F. A., Newman, M. C., Akers, K. A., Wood, C. L., McQuerry, K. J., & Bewley, J. M. (2014). Compost bedded pack dairy barn management: Bedding, aeration and pack characteristics. *Journal of Dairy Science*, 97(5), 2669–2679. <https://doi.org/10.3168/jds.2013-7419>
- Bo, X., Zhang, Z., Wang, J., Guo, S., Li, Z., Lin, H., ... & Zou, J. (2023). Benefits and limitations of biochar for climate-smart agriculture: A review and case study from China. *Biochar*, 5(1), 77. <https://doi.org/10.1007/s42773-023-00279-x>
- Brenzinger, K., Kujala, K., Horn, M. A., Moser, G., Guillet, C., Kammann, C., ... & Braker, G. (2017). Soil conditions rather than long-term exposure to elevated CO₂ affect soil microbial communities associated with N-cycling. *Frontiers in Microbiology*, 8, 1976. DOI: 10.1016/j.scitotenv.2021.148756
- Brown, R. W., Chadwick, D. R., Bott, T., West, H. M., Wilson, P., Hodgins, G. R., ... & Jones, D. L. (2023). Biochar application to temperate grasslands: Challenges and opportunities for delivering multiple ecosystem services. *Biochar*, 5(1), 33. <https://doi.org/10.1007/s42773-023-00232-y>
- Brtnicky, M., Datta, R., Holatko, J., Bielska, L., Gusiati, Z. M., Kucerik, J., ... & Pecina, V. (2021). A critical review of the possible adverse effects of biochar in the soil environment. *Science of the Total Environment*, 796, 148756. <https://doi.org/10.1016/j.scitotenv.2021.148756>
- Cañellas I, San Miguel A, Del Río V (1991) Evaluación de la producción silvopastoral de una dehesa extremeña: pasto, bellota y biomasa de ramas podadas. In: *Actas de la SEEP (Sociedad Española para el Estudio de los Pastos)* 31:234–240.



- Cayuela, M. L., Sánchez-Monedero, M. A., Roig, A., Hanley, K., Enders, A., & Lehmann, J. (2013). Biochar and denitrification in soils: when, how much and why does biochar reduce N₂O emissions?. *Scientific reports*, 3(1), 1732. <https://doi.org/10.1038/srep01732>
- Chadwick, D. R., Sommer, S. G., Thorman, R. E., Fangueiro, D., Cardenas, L., Amon, B., & Misselbrook, T. H. (2011). Manure management: Implications for greenhouse gas emissions. *Animal Feed Science and Technology*, 166–167, 514–531. <https://doi.org/10.1016/j.anifeedsci.2011.04.036>
- Chen, W., Liao, X., Wu, Y., Liang, J. B., Mi, J., Huang, J., ... & Wang, Y. (2017). Effects of different types of biochar on methane and ammonia mitigation during layer manure composting. *Waste Management*, 61, 506–515. <https://doi.org/10.1016/j.wasman.2017.01.014>
- Chiaromonti, D., Lehmann, J., Berruti, F., Giudicianni, P., Sanei, H., & Masek, O. (2024). Biochar is a long-lived form of carbon removal, making evidence-based CDR projects possible. *Biochar*, 6(1), 81. <https://doi.org/10.1007/s42773-024-00366-7>
- Cornelissen, G., Pandit, N. R., Taylor, P., Pandit, B. H., Sparrevik, M., & Schmidt, H. P. (2016). Emissions and char quality of flame-curtain" Kon Tiki" Kilns for Farmer-Scale charcoal/biochar production. *PloS one*, 11(5), e0154617. <https://doi.org/10.1371/journal.pone.0154617>
- Cornelissen, G., Sørmo, E., de la Rosa, R. K. A., & Ladd, B. (2023). Flame curtain kilns produce biochar from dry biomass with minimal methane emissions. *Science of the Total Environment*, 903, 166547. <https://doi.org/10.1016/j.scitotenv.2023.166547>
- Dari, B., Nair, V. D., Harris, W. G., Nair, P. K. R., Sollenberger, L., & Mylavarapu, R. (2016). Relative influence of soil-vs. biochar properties on soil phosphorus retention. *Geoderma*, 280, 82–87. <https://doi.org/10.1016/j.geoderma.2016.06.018>
- den Herder, M., Moreno, G., Mosquera-Losada, R.M., Palma, J.H.N., Sidiropoulou, A., Santiago Freijanes, J.J., Crous-Duran, J., Paulo, J.A., Tomé, M., Pantera, A., Papanastasis, V.P., Mantzanas, K., Pachana, P., Papadopoulos, A., Plieninger, T., Burgess, P.J. (2017). Current extent and trends of agroforestry in the EU27. *Agriculture, Ecosystems & Environment* 241, 121–132. <https://doi.org/10.1016/j.agee.2017.03.005>
- Dittmann, M. T., Baki, C., Terranova, M., Amelchanka, S. L., Dubois, S., Wiget, A., ... & Baumann, S. (2024). The effect of biochar supplementation on feed utilization, milk production and methane emission in lactating dairy cows. *Animal Feed Science and Technology*, 318, 116127. <https://doi.org/10.1016/j.anifeedsci.2024.116127>
- Efosa, N., Krause, H. M., Hüppi, R., Krauss, M., Vaucher, N., Zourek, F., ... & Bünemann, E. K. (2023). Emissions of nitrous oxide and methane after field application of liquid organic fertilizers and biochar. *Agriculture, Ecosystems & Environment*, 356, 108642. <https://doi.org/10.1016/j.agee.2023.108642>
- El-Naggar, A., Lee, S. S., Rinklebe, J., Farooq, M., Song, H., Sarmah, A. K., ... & Ok, Y. S. (2019). Biochar application to low fertility soils: A review of current status, and future prospects. *Geoderma*, 337, 536–554. <https://doi.org/10.1016/j.geoderma.2018.09.034>
- Fangueiro, D., Hjorth, M., & Gioelli, F. (2015). Acidification of animal slurry – A review. *Journal of Environmental Management*, 149, 46–56. <https://doi.org/10.1016/j.jenvman.2014.10.001>
- Fonseca, A. A. D., Santos, D. A., Moura-Junior, C. D., Passos, R. R., & Rangel, O. J. P. (2021). Phosphorus and potassium in aggregates of degraded soils: changes caused by biochar application. *Clean–Soil, Air, Water*, 49(12), 2000366. <https://doi.org/10.24050/reia.v20i39.1651>
- Fungo, B., Wiesmeier, M., & Cardinael, R. (2021). 39. Agroforestry 2: Sylvopastoral systems. pp 487–499. In *Recarbonizing global soils: A technical manual of recommended management practices. Volume 3: Cropland, Grassland, Integrated systems and farming approaches –Practices overview*. FAO and ITPS. Rome. <https://doi.org/10.4060/cb6386en>
- Gao, S., & DeLuca, T. H. (2020). Biochar alters nitrogen and phosphorus dynamics in a western rangeland ecosystem. *Soil Biology and Biochemistry*, 148, 107868. <https://doi.org/10.1016/j.soilbio.2020.107868>
- Gao, S., Hoffman-Krull, K., Bidwell, A. L., & DeLuca, T. H. (2016). Locally produced wood biochar increases nutrient retention and availability in agricultural soils of the San Juan Islands, USA. *Agriculture, Ecosystems & Environment*, 233, 43–54. <https://doi.org/10.1016/j.agee.2016.08.028>
- Garbuz, S., Mackay, A., Camps-Arbestain, M., DeVantier, B., & Minor, M. (2021). Biochar amendment improves soil physico-chemical properties and alters root biomass and the soil food web in grazed pastures. *Agriculture, Ecosystems & Environment*, 319, 107517. <https://doi.org/10.1016/j.agee.2021.107517>





- Ghassemi-Golezani, K., & Rahimzadeh, S. (2022). Biochar modification and application to improve soil fertility and crop productivity. *Agriculture*, 68(2), 45-61. <http://creativecommons.org/licenses/by-nc-nd/4.0/>
- Ghodsad, L., Reyhanitabar, A., Maghsoodi, M. R., Lajayer, B. A., & Chang, S. X. (2021). Biochar affects the fate of phosphorus in soil and water: A critical review. *Chemosphere*, 283, 131176. <https://doi.org/10.1016/j.chemosphere.2021.131176>
- Głąb, T., Żabiński, A., Sadowska, U., Gondek, K., Kopeć, M., Mierzwa-Hersztek, M., ... & Stanek-Tarkowska, J. (2020). Fertilization effects of compost produced from maize, sewage sludge and biochar on soil water retention and chemical properties. *Soil and Tillage Research*, 197, 104493. <https://doi.org/10.1016/j.still.2019.104493>
- Gross, A., Bromm, T., & Glaser, B. (2021). Soil organic carbon sequestration after biochar application: A global meta-analysis. *Agronomy*, 11(12), 2474. <https://doi.org/10.3390/agronomy11122474>
- Gross, A., Šolić, M., Glaser, B., Bromm, T., & Maletić, S. (2025). Relevance of biochar metabolization-evidence from a long-term biochar field experiment. *Frontiers in Sustainable Food Systems*, 9, 1578363. <https://doi.org/10.3168/jds.2024-25616>
- Guerreiro, J. F., Pires, A. J., Nunes, M., Esteves, A., Chambel, L., Pascoal, P., ... & Oliveira, M. (2025). Biochar supplementation affects the microbiome of recycled manure solids for cow bedding: A metagenomic analysis. *Journal of Dairy Science*, 108(3), 2620-2631. <https://doi.org/10.3168/jds.2024-25616>
- Gul, S., & Whalen, J. K. (2016). Biochemical cycling of nitrogen and phosphorus in biochar-amended soils. *Soil Biology and Biochemistry*, 103, 1-15. <https://doi.org/10.1016/j.soilbio.2016.08.001>
- Hallin, S., Philippot, L., Löffler, F. E., Sanford, R. A., & Jones, C. M. (2018). Genomics and ecology of novel N₂O-reducing microorganisms. *Trends in Microbiology*, 26(1), 43-55. <https://doi.org/10.1016/j.tim.2017.07.003>
- Harrison, B. P., Moo, Z., Perez-Agredano, E., Gao, S., Zhang, X., & Ryals, R. (2024). Biochar-composting substantially reduces methane and air pollutant emissions from dairy manure. *Environmental research letters*, 19(1), 014081. <https://doi.org/10.3389/fsufs.2025.1578363>
- Harrison, B. P., Moo, Z., Perez-Agredano, E., Gao, S., Zhang, X., & Ryals, R. (2024). Biochar-composting substantially reduces methane and air pollutant emissions from dairy manure. *Environmental research letters*, 19(1), 014081. <https://doi.org/10.1088/1748-9326/ad1ad2>
- Hernández-Esteban, A., Rolo, V., López-Díaz, M. L., & Moreno, G. (2019). Long-term implications of sowing legume-rich mixtures for plant diversity of Mediterranean wood pastures. *Agriculture, Ecosystems & Environment*, 286, 106686. <https://doi.org/10.1016/j.agee.2019.106686>
- Holly, M. A., & Larson, R. A. (2017). Effects of manure storage additives on manure composition and greenhouse gas and ammonia emissions. *Transactions of the ASABE*, 60(2), 449-456. DOI: 10.13031/trans.12066
- Jeffery, S., Abalos, D., Prodana, M., Bastos, A. C., Van Groenigen, J. W., Hungate, B. A., & Verheijen, F. (2017). Biochar boosts tropical but not temperate crop yields. *Environmental Research Letters*, 12(5), 053001. <https://doi.org/10.1088/1748-9326/aa67bd>
- Jose, S., Walter, D. and Kumar, B. M. 2017. Ecological considerations in sustainable silvopasture design and management. *Agroforestry Systems*. doi:10.1007/s10457-016-0065-2.
- Joseph, S., Cowie, A. L., Van Zwieten, L., Bolan, N., Budai, A., Buss, W., ... & Lehmann, J. (2021). How biochar works, and when it doesn't: A review of mechanisms controlling soil and plant responses to biochar. *Gcb Bioenergy*, 13(11), 1731-1764. <https://doi.org/10.1111/gcbb.12885>
- Kai, P., Pedersen, P., Jensen, J. E., Hansen, M. N., & Sommer, S. G. (2008). A whole-farm assessment of the efficacy of slurry acidification in reducing ammonia emissions. *European Journal of Agronomy*, 28(2), 148–154. <https://doi.org/10.1016/j.eja.2007.06.004>
- Kapoor, A., Sharma, R., Kumar, A., & Sepehya, S. (2022). Biochar as a means to improve soil fertility and crop productivity: a review. *Journal of Plant Nutrition*, 45(15), 2380-2388. <https://doi.org/10.1080/01904167.2022.2027980>
- Kazemi, M. (2025). Biochar in Animal Agriculture: Enhancing Health, Efficiency and Environmental Sustainability. *Veterinary Medicine and Science*, 11(6), e70629. <https://doi.org/10.1002/vms3.70629>
- Kolb, S. (2009). The quest for atmospheric methane oxidizers in forest soils. *Environmental microbiology reports*, 1(5), 336-346. <https://doi.org/10.1111/j.1758-2229.2009.00047.x>
- Kuypers, M. M., Marchant, H. K., & Kartal, B. (2018). The microbial nitrogen-cycling network. *Nature Reviews Microbiology*, 16(5), 263-276. <https://doi.org/10.1038/nrmicro.2018.9>





- Le Mer, J., & Roger, P. (2001). Production, oxidation, emission and consumption of methane by soils: a review. *European journal of soil biology*, 37(1), 25-50. [https://doi.org/10.1016/S1164-5563\(01\)01067-6](https://doi.org/10.1016/S1164-5563(01)01067-6)
- Lefebvre, D., Fawzy, S., Aquije, C. A., Osman, A. I., Draper, K. T., & Trabold, T. A. (2023). Biomass residue to carbon dioxide removal: quantifying the global impact of biochar. *Biochar*, 5(1), 65. <https://doi.org/10.1007/s42773-023-00258-2>
- Lehmann, J., Cowie, A., Masiello, C. A., Kammann, C., Woolf, D., Amonette, J. E., ... & Whitman, T. (2021). Biochar in climate change mitigation. *Nature Geoscience*, 14(12), 883-892. <https://doi.org/10.1038/s41561-021-00852-8>
- Lemes, Y. M. L., Garcia, P., Nyord, T., Feilberg, A., Kamp, N. (2022). Full-scale investigation of methane and ammonia mitigation by early single-dose slurry storage acidification. *ACS Agricultural Science & Technology*, 2(6), 1076–1086. <https://doi.org/10.1021/acsagscitech.2c00109>
- Leso, L., Barbari, M., Lopes, M. A., Damasceno, F. A., Galama, P., Taraba, J. L., & Kuipers, A. (2020). Invited review: Compost-bedded pack barns for dairy cows. *Journal of Dairy Science*, 103(2), 1076–1099. <https://doi.org/10.3168/jds.2019-16864>
- Li, Q., Shi, J., Li, G., Hu, J., & Ma, R. (2023). Extracellular enzyme stoichiometry and microbial resource limitation following various grassland reestablishment in abandoned cropland. *Science of The Total Environment*, 870, 161746. <https://doi.org/10.1016/j.scitotenv.2023.161746>
- Li, Y., Li, Y., Chang, S. X., Yang, Y., Fu, S., Jiang, P., ... & Zhou, J. (2018). Biochar reduces soil heterotrophic respiration in a subtropical plantation through increasing soil organic carbon recalcitrancy and decreasing carbon-degrading microbial activity. *Soil Biology and Biochemistry*, 122, 173-185. <https://doi.org/10.1016/j.soilbio.2018.04.019>
- Llonch, L., Castillejos, L., Mainau, E., Manteca, X., Ferret, A. (2020). Effect of forest biomass as bedding material on compost bedded pack performance in dry cows. *Journal of Dairy Science*, 103(11), 10676–10688. <https://doi.org/10.3168/jds.2020-18496>
- Llonch, L., Gordo, C., López, M., Castillejos, L., Ferret, A., & Balanyà, T. (2021). Agronomic characteristics of compost-bedded pack made with forest biomass or sawdust. *Processes*, 9(3), 546. <https://doi.org/10.3390/pr9030546>
- Lorenz, K., & Lal, R. (2014). Biochar application to soil for climate change mitigation by soil organic carbon sequestration. *Journal of plant nutrition and soil science*, 177(5), 651-670. <https://doi.org/10.1002/jpln.201400058>
- Lu, L., Yu, W., Wang, Y., Zhang, K., Zhu, X., Zhang, Y., ... & Chen, B. (2020). Application of biochar-based materials in environmental remediation: from multi-level structures to specific devices. *Biochar*, 2(1), 1-31. <https://doi.org/10.1007/s42773-020-00041-7>
- Lyu, X., Li, X., Wang, K., Cao, W., Gong, J., Wang, H., & Lou, A. (2022). Linking regional sustainable development goals with ecosystem services to identify ecological security patterns. *Land Degradation & Development*, 33(18), 3841-3854. <https://doi.org/10.1002/ldr.4427>
- Mahmood, R., Arooj, A., & Sarfraz, R. (2024). Potential Limitations of Biochar. In *Biochar-Solid Carbon for Sustainable Agriculture* (pp. 126-138). Bentham Science Publishers. DOI: 10.2174/9789815238068124010010
- Man, K. Y., Chow, K. L., Man, Y. B., Mo, W. Y., & Wong, M. H. (2021). Use of biochar as feed supplements for animal farming. *Critical Reviews in Environmental Science and Technology*, 51(2), 187-217. <https://doi.org/10.1080/10643389.2020.1721980>
- Manikandan, S., Vickram, S., Subbaiya, R., Karmegam, N., Chang, S. W., Ravindran, B., & Awasthi, M. K. (2023). Comprehensive review on recent production trends and applications of biochar for greener environment. *Bioresource Technology*. <https://doi.org/10.1016/j.biortech.2023.129725>
- Mehnaz, K. R., Corneo, P. E., Keitel, C., & Dijkstra, F. A. (2019). Carbon and phosphorus addition effects on microbial carbon use efficiency, soil organic matter priming, gross nitrogen mineralization and nitrous oxide emission from soil. *Soil Biology and Biochemistry*, 134, 175-186. <https://doi.org/10.1016/j.soilbio.2019.04.003>
- Meiirkhanuly, Z., Koziel, J. A., Chen, B., Białowiec, A., Lee, M., Wi, J., ... & Bakshi, S. (2020). Mitigation of gaseous emissions from swine manure with the surficial application of biochars. *Atmosphere*, 11(11), 1179. <https://doi.org/10.3390/atmos11111179>
- Misselbrook, T. H., Nicholson, F. A., & Chambers, B. J. (2005). Predicting ammonia losses following the application of livestock manure to land. *Bioresource Technology*, 96(2), 159–168. <https://doi.org/10.1016/j.biortech.2004.05.004>





- Misselbrook, T. H., Webb, J., Gilhespy, S. L., Chadwick, D. R., & Bittman, S. (2016). Ammonia emissions from outdoor concrete yards used by livestock—Quantification and mitigation. *Atmospheric Environment*, 40(35), 6752-6763. <https://doi.org/10.1016/j.atmosenv.2006.05.077>
- Montero, G., Ruiz-Peinado, R., & Muñoz, M. (2005). Biomass production and CO₂ fixation by Spanish forests. Madrid: INIA-National Institute of Agricultural and Food Research and Technology
- Moreno, G., & Pulido, F. J. (2009). The functioning, management and persistence of dehesas. In *Agroforestry in Europe: current status and future prospects* (pp. 127-160). Dordrecht: Springer Netherlands. https://doi.org/10.1007/978-1-4020-8272-6_7
- Moreno, G., & Rolo, V. (2019). Agroforestry practices: silvopastoralism. In *Agroforestry for sustainable agriculture* (pp. 119-164). Burleigh Dodds Science Publishing. DOI: 10.19103/AS.2018.0041.05
- Mosquera-Losada, M. R. (Eds) (2009) *Agroforestry in Europe: Current Status and Future Prospects*. Dordrecht, The Netherlands: Springer Science & Business Media, pp. 43–65. DOI: 10.1007/978-1-4020-8272-6
- Nepal, J., Ahmad, W., Munsif, F., Khan, A., & Zou, Z. (2023). Advances and prospects of biochar in improving soil fertility, biochemical quality, and environmental applications. *Frontiers in Environmental Science*, 11, 1114752. DOI: 10.3389/fenvs.2023.1114752
- Oliveira, C. E. A., Damasceno, F. A., Leso, L., Ferraz, P. F. P., & Barbari, M. (2023). Physicochemical bedding quality in compost-bedded pack barn systems for dairy cows: A systematic review. *Applied Sciences*, 13(17), 9832. <https://doi.org/10.3390/app13179832>
- Orefice, J., Carroll, J., Conroy, D. and Ketner, L. 2017. Silvopasture practices and perspectives in the Northeastern United States. *Agroforestry Systems* 91(1), 149–60. <https://doi.org/10.1007/s10457-016-9916-0>.
- Overmeyer, V., Perschke, Y. M. L., Chadwick, D. R., & Del Prado, A. (2021). One-time acidification of slurry: What is the most effective acid and treatment strategy? *Agronomy*, 11(7), 1319. <https://doi.org/10.3390/agronomy11071319>
- Pereira, J. L., Martins, F., Bonifácio, G., Garcia, C., Teixeira, J., & Trindade, H. (2024). Biochar as an alternative litter additive to mitigate gaseous emissions from broiler housing and subsequent storage. *Agronomy*, 14(7), 1595. <https://doi.org/10.3390/agronomy14071595>.
- Petersen, S. O., Andersen, A. J., & Eriksen, J. (2012). Effects of cattle slurry acidification on ammonia and methane evolution during storage. *Journal of Environmental Quality*, 41(1), 88–94. Perschke. <https://doi.org/10.2134/jeq2011.0184>
- Pires, A. J. D. O. N. (2025). Safebed: improving safety and sustainability of recycled manure solids as bedding material for dairy cows. PhD Thesis. Lisbon University.
- Plieninger, T., Hartel, T., Martín-López, B., Beaufoy, G., Bergmeier, E., Kirby, K., ... & Van Uytvanck, J. (2015). Wood-pastures of Europe: Geographic coverage, social–ecological values, conservation management, and policy implications. *Biological Conservation*, 190, 70-79. <https://doi.org/10.1016/j.biocon.2015.05.014>Get rights and content
- Puettmann, M., Sahoo, K., Wilson, K., & Oneil, E. (2020). Life cycle assessment of biochar produced from forest residues using portable systems. *Journal of Cleaner Production*, 250, 119564. <https://doi.org/10.1016/j.jclepro.2019.119564>
- Rigueiro-Rodríguez, A., Fernández-Núñez, E., González-Hernández, P., McAdam, J.H., Mosquera-Losada, M.R. (2009). Agroforestry Systems in Europe: Productive, Ecological and Social Perspectives. In: Rigueiro-Rodríguez, A., McAdam, J., Mosquera-Losada, M.R. (eds) *Agroforestry in Europe. Advances in Agroforestry*, vol 6. Springer, Dordrecht. https://doi.org/10.1007/978-1-4020-8272-6_3
- Ronsse, F., Nachenius, R. W., & Prins, W. (2015). Carbonization of biomass. In *Recent advances in thermo-chemical conversion of biomass* (pp. 293-324). Elsevier. DOI: 10.5772/intechopen.100060
- Saffari, N., Hajabbasi, M. A., Shirani, H., Mosaddeghi, M. R., & Mamedov, A. I. (2020). Biochar type and pyrolysis temperature effects on soil quality indicators and structural stability. *Journal of environmental management*, 261, 110190. <https://doi.org/10.1016/j.jenvman.2020.110190>
- Samad, M. S., Biswas, A., Bakken, L. R., Clough, T. J., de Klein, C. A., Richards, K. G., ... & Morales, S. E. (2016). Phylogenetic and functional potential links pH and N₂O emissions in pasture soils. *Scientific Reports*, 6(1), 35990. <https://doi.org/10.1038/srep35990>
- San Miguel A (1994) *La Dehesa Española. Origen, Tipología, Características y Gestión*. Fundación Conde del Valle de Salazar, Madrid
- Schmidt H, Hagemann N, Draper K, Kammann C. 2019. The use of biochar in animal feeding. *PeerJ* 7:e7373. <https://doi.org/10.7717/peerj.7373>





- Schmidt, H. P., Kammann, C., Hagemann, N., Leifeld, J., Bucheli, T. D., Sánchez Monedero, M. A., & Cayuela, M. L. (2021). Biochar in agriculture—A systematic review of 26 global meta-analyses. *GCB Bioenergy*, 13(11), 1708-1730. <https://doi.org/10.1111/gcbb.12889>
- Sharrow, S. H. 1999. Silvopastoralism: Competition and facilitation between trees, livestock, and improved grass-clover pastures on temperate rainfed lands. In: Buck, L. E., Lassoie, J. and Fernandez, E. C. M. (Eds), *Agroforestry in Sustainable Agricultural Systems*. Boca Raton, FL: CRC Press, pp. 111–30.
- Shin, J., Kim, D., Lee, Y., Lee, S., Wardhani, R., & Ahn, H. (2025). Evaluating the Odor Mitigation Effects of Biochar-Enhanced Bedding Materials in a Simulated Bedded Pack Dairy Barn Environment: A Laboratory-Scale Study. *Applied Sciences*, 15(11), 6361.
- Siddiqui, S. (2025). Unlocking the environmental potential of biochar: production, applications, and limitations. *Frontiers in Sustainable Food Systems*, 9, 1569941. DOI: 10.3389/fsufs.2025.1569941
- Sommer, S. G., & Hutchings, N. J. (2001). Ammonia emission from field-applied manure and its reduction—Invited paper. *European Journal of Agronomy*, 15(1), 1–15. [https://doi.org/10.1016/S1161-0301\(01\)00112-5](https://doi.org/10.1016/S1161-0301(01)00112-5)
- Sommer, S. G., Petersen, S. O., & Møller, H. B. (2004). Algorithms for calculating methane and nitrous oxide emissions from manure management. *Nutrient Cycling in Agroecosystems*, 69, 143-154. <https://doi.org/10.1023/B:FRES.0000029678.25083.fa>
- Sparrevik, M., Adam, C., Martinsen, V., & Cornelissen, G. (2015). Emissions of gases and particles from charcoal/biochar production in rural areas using medium-sized traditional and improved “retort” kilns. *Biomass and Bioenergy*, 72, 65-73. <https://doi.org/10.1016/j.biombioe.2014.11.016>
- Stavi, I. (2013). Biochar use in forestry and tree-based agro-ecosystems for increasing climate change mitigation and adaptation. *International Journal of Sustainable Development & World Ecology*, 20(2), 166-181. <https://doi.org/10.1080/13504509.2013.773466>
- Tate, K. R. (2015). Soil methane oxidation and land-use change—from process to mitigation. *Soil Biology and Biochemistry*, 80, 260-272. <https://doi.org/10.1016/j.soilbio.2014.10.010>
- Teixeira, R. F., Proenca, V., Crespo, D., Valada, T., & Domingos, T. (2015). A conceptual framework for the analysis of engineered biodiverse pastures. *Ecological Engineering*, 77, 85-97. <http://dx.doi.org/doi:10.1016/j.ecoleng.2015.01.002>
- Tucker, C. B., Jensen, M. B., de Passillé, A. M., Hänninen, L., Rushen, J. (2021). Invited review: Lying time and the welfare of dairy cows. *Journal of Dairy Science*, 104(1), 20-46. <https://doi.org/10.3168/jds.2019-18074>
- Verhoeven, E., Pereira, E., Decock, C., Suddick, E., Angst, T., & Six, J. (2017). Toward a better assessment of biochar–nitrous oxide mitigation potential at the field scale. *Journal of Environmental Quality*, 46(2), 237-246. <https://doi.org/10.2134/jeq2016.10.0396>
- Vijay V, Shreedhar S, Adlak K, Payyanad S, Sreedharan V, Gopi G, Sophia van der Voort T, Malarvizhi P, Yi S, Gebert J and Aravind P (2021) Review of Large-Scale Biochar Field-Trials for Soil Amendment and the Observed Influences on Crop Yield Variations. *Front. Energy Res.* 9:710766. doi: 10.3389/fenrg.2021.710766
- Wang, C., Lu, H., Dong, D., Deng, H., Strong, P. J., Wang, H., & Wu, W. (2013). Insight into the effects of biochar on manure composting: evidence supporting the relationship between N₂O emission and denitrifying community. *Environmental science & technology*, 47(13), 7341-7349. DOI: 10.1021/es305293h
- Wang, C., Luo, D., Zhang, X., Huang, R., Cao, Y., Liu, G., ... & Wang, H. (2022). Biochar-based slow-release of fertilizers for sustainable agriculture: A mini review. *Environmental Science and Ecotechnology*, 10, 100167. <https://doi.org/10.1016/j.es.2022.100167>
- Wang, J., Xiong, Z., and Kuzyakov, Y. (2016). Biochar Stability in Soil: Meta-analysis of Decomposition and Priming Effects. *GCB Bioenergy* 8, 512–523. <https://doi.org/10.1111/gcbb.12266>
- Webb, J., Sørensen, P., Velthof, G., Amon, B., Pinto, M., Rodhe, L., Salomon, E., Hutchings, N. J., Burczyk, P., & Reid, J. (2013). An assessment of the variation of manure nitrogen efficiency throughout Europe and an appraisal of means to increase efficiency. *Advances in Agronomy*, 119, 371–422. <https://doi.org/10.1016/B978-0-12-407247-3.00007-X>
- Yang, J., Xia, L., van Groenigen, K. J., Zhao, X., Ti, C., Wang, W., ... & Yan, X. (2025). Sustained benefits of long-term biochar application for food security and climate change mitigation. *Proceedings of the National Academy of Sciences*, 122(33), e2509237122. <https://doi.org/10.1073/pnas.25092371>





- Yuan, Y., Chen, H., Yuan, W., Williams, D., Walker, J. T., & Shi, W. (2017). Is biochar-manure co-compost a better solution for soil health improvement and N₂O emissions mitigation?. *Soil Biology and Biochemistry*, 113, 14-25. <https://doi.org/10.1016/j.soilbio.2017.05.025>
- Zhao, Q., Wang, Y., Xu, Z., & Yu, Z. (2021). How does biochar amendment affect soil methane oxidation? A review. *Journal of Soils and Sediments*, 21, 1575-1586. <https://doi.org/10.1007/s11368-021-02889-z>
- Zou, J., Hua, Y., Cheng, Y., Mo, L., Tang, S., Chen, F., ... & Shen, F. (2025). A holistic assessment of biochar amendment effects on compost maturation: a meta-analysis. *Biochar X*, 1(1). <https://doi.org/10.48130/bchax-0025-0005>
- Žurovec, O., Wall, D. P., Brennan, F. P., Krol, D. J., Forrester, P. J., & Richards, K. G. (2021). Increasing soil pH reduces fertiliser derived N₂O emissions in intensively managed temperate grassland. *Agriculture, Ecosystems & Environment*, 311, 107319. <https://doi.org/10.1016/j.agee.2021.107319>



Appendix 1. Biochar production of farms

1. What is biochar?

Biochar is a material similar to charcoal produced from the pyrolysis of biomass. With pyrolysis, biomass is carbonized in a controlled, slow, but deep combustion, which is achieved in the absence (or very low presence) of oxygen (pyrolysis), to produce a chemically stable, carbon-rich, and highly porous material (Manikandan et al., 2023). Pyrolyzing biomass avoids its rapid oxidation to CO₂, and added to the soil, biochar carbon can last for hundreds, even thousands of years (Gul and Whalen, 2016; Brown et al., 2023).

The characteristics of biochar depend on the type of raw material and the pyrolysis process, but they all share the following characteristics:

- Stable high organic C content
- High Carbon/Nutrient ratios
- High specific surface area (200-500 m² g⁻¹), which its high porosity
- High adsorption capacity, which means that a large amount of chemicals and water are retained on the surface of its pores
- High cation exchange capacity, which implies that a large number of cations are retained on their surfaces, which are essential nutrients for plants
- High water retention capacity (CRA), up to 5 times its weight in water.

2. Biochar production on farms

Biochar is a stable form of carbon that is obtained through the transformation of biomass into a closed (or semi-open) system, with the absence (or scarcity) of oxygen, in which temperatures reach between 500 and 700°C. This way of carbonizing biomass is called pyrolysis, which suppresses or reduces fire, increases efficiency (greater amount of carbon per unit of biomass burned), and reduces emissions of toxic gases into the atmosphere (Puettmann et al., 2020; Cornelissen et al., 2023).

The specific performance of pyrolysis depends on process conditions, such as temperature, and can be optimized to produce both energy and biochar. In industrial pyrolysis furnaces, the conditions can be controlled according to the preferred end product. Temperatures of 400–500 °C produce more biochar, while temperatures above 700 °C favour the performance of liquid and gas fuel components (Saffari et al., 2020).

On farms, where the infrastructure of pyrolysis furnaces rarely exists and/or the cost of extracting the biomass does not justify its transport to the pyrolysis furnaces, controlled combustion directly in the field seems an advantageous alternative, and of immediate implementation. It is sufficient to have a sufficient water reserve, which can be easily transported in a tank with a tractor. The subsequent extraction of biochar for use or transport is easier and more efficient than the extraction of biomass, especially if it is fine branches. Another advantage of traditional carbonization is that an energy source is not needed to start combustion, as is needed in closed furnaces, where the temperature of the biomass must be raised to about 300 °C for the carbonization process to begin. In traditional carbonization, this initial energy is produced by the biomass itself, which is partially consumed in flame combustion (Ronsse et al., 2015; Amer & Elwardany, 2020).

The traditional method of controlled burning of a wood pile or fine branches produces neither biofuel nor synthesized gas and releases a certain amount of CO₂ and other GHG, soot and potentially toxins into the air, but always in much lower quantities than that produced when

complete free combustion is carried out (Sparrevik et al., 2015). By using low-cost open ovens, such as the Kon-Tiki kiln, reconnects biochar manufacturing to ancient wisdom (controlling combustion by adding water on a regular basis) and the craft of making charcoal with intelligent design based on new thermodynamic knowledge to produce more and higher-quality charcoal with low emissions (Cornelissen et al., 2016).

Biochar production potential and chemical compositions are affected by the feedstock composition, reaction environment and operating parameters during the pyrolysis of biomass. The slow pyrolysis technology, such as the Kon-Tiki kiln, is currently the most used commercial technology and a sustainable route for valorization of lignocellulosic biomass from environmental perspective to synthesize biochar owing to its higher biochar yield and fewer associated technological drawbacks. Biochar yields were $22 \pm 5\%$ on a dry weight basis and $40 \pm 11\%$ on a C basis (Cornelissen et al., 2016).

3. What can biochar be used for on farm?

Because the feedstock carbon is photosynthetically fixed CO₂ from the atmosphere, producing and applying biochar is essentially a carbon dioxide removal (CDR) technology, which has a high-technology readiness level (Schmidt et al., 2021; Lehmann et al. 2021; Lefebvre et al., 2023; Chiaramonti et al., 2024).

Beyond the climate mitigation aim, biochar has also the potential to improve the soil functioning and soil productivity, making farms more resilient to climate change (climate change adaptation) (Schmidt et al., 2021; Bo et al., 2023; Yang et al., 2025). The effects of biochar on soil properties rely on four main properties: high surface area (up to 200 m² per gram), high pH, nutrient content, and very low mineralization rate (Gul and Whalen, 2016; Garbuz et al., 2021). Their characteristics depend on the type of raw material and the pyrolysis process, but they all share the following characteristics:

- Stable high organic C content
- High Carbon/Nutrient ratios
- High specific surface area (200-500 m² g⁻¹), which its high porosity
- High adsorption capacity, which means that a large amount of chemicals and water are retained on the surface of its pores
- High cation exchange capacity, which implies that a large number of cations are retained on their surfaces, which are essential nutrients for plants
- High water retention capacity (CRA), up to 5 times its weight in water.

Given the usually high C/N and other Carbon/Nutrient ratios of biochar, for its use for soil amendment, biochar must be activated by mixing it with a source rich in nutrients and microorganisms, such as manure or compost. Activated (or charged) biochar is used to increase soil fertility, both its chemical fertility (increases the availability of nutrients for plants), physical fertility (increases the structure, porosity, and infiltration and water retention capacity of the soil), and microbiological (increases the biomass and microbial activity of the soil) (Ghassemi-Golezani et al., 2022; Kapoor et al., 2022; Nepal et al., 2023).



Illustrations by Kevin D. Brown

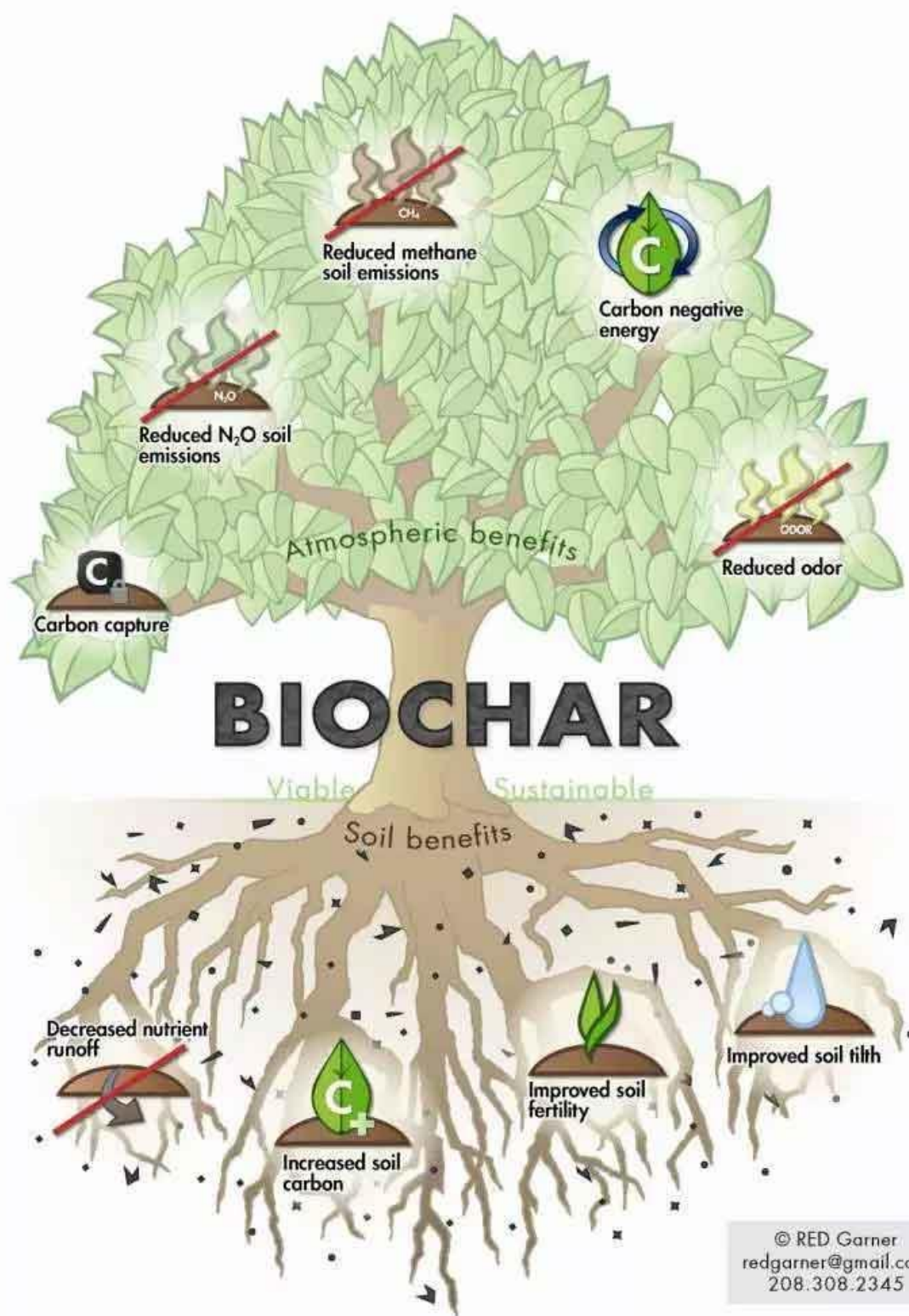


Figure 1 - Image of the main effects of biochar on the emissions of GHG on farms.

Source: <http://www.compostandociencia.com>

Appendix 2. The multiple functions of biochar on livestock farms

Biochar has different uses in livestock farming, especially to improve livestock health and to reduce GHG emissions. Here follow four uses of high interest: feed additive, manure management, bedding, and fodder crops fertilization. The main uses are divided into three areas:

1. Food Additive

Food-grade biochar is a promising dietary supplement for various species, including cattle, goats, pigs, poultry, and fish. The claimed benefits of this biochar are (Schmidt et al., 2019; Ayeneshet and Temesgen, 2025).

- **Improved Digestive Health:** It acts as a natural adsorbent in the digestive tract, similar to activated charcoal, which helps combat ingested pathogenic bacteria and toxins and stabilise the intestinal flora.
- **Increased Performance and Efficiency:** Studies suggest that adding biochar to the diet can improve feed conversion, increase daily weight gain, and produce higher quality milk in dairy cattle.
- **Reduction of Enteric CH₄ Emissions:** Studies on the effectiveness of biochar as a feed additive to reduce enteric CH₄ show variable results, but there is potential. For instance, Ayeneshet and Temesgen (2025) reported a reduction from 30% to 40% of CH₄ emission in cattle.

Nevertheless, some authors reported that biochar supplementation can be ineffective in terms of milk production and CH₄ emission in lactating dairy cows (Dittmann et al., 2024).

2. Manure Management and Composting

Biochar is a key tool in the circular economy of farms, optimising the management of livestock waste. When biochar is added to manure, it increases aeration and absorbs moisture, preventing the conditions that facilitate methane-producing bacteria. Besides, the large surface area of biochar adsorbs gases and promotes the activity of methanotrophic bacteria, which are microorganisms that oxidise CH₄ into CO₂ (a less potent GHG). Zou et al. (2025) reported a reduction in CH₄ emissions by between 27% and 51% by adding biochar to manure composting. The application not only reduces GHG emissions but also helps manage manure more effectively, minimizing odours and enhancing its potential as a soil amendment (Chen et al., 2017; Holly et al., 2017; Meir Khanuly et al., 2020; Harrison et al., 2024).

By incorporating biochar (10-12%) into composting processes or directly applying it to manure (manure pile or slurry ponds), farmers can thus accelerate the decomposition of organic waste. This not only reduces the environmental impact of manure but also converts waste into a valuable resource that can be used to enrich soil, promoting circular farming practices. Mixing biochar with manure or slurry accelerates the composting process, retains valuable nutrients (nitrogen) and minimises GHG emissions. The result is a higher quality organic fertiliser with a balanced C/N ratio and superior nutrient retention capacity, ready for application to crop fields (biochar-rich manure ~ activated biochar).

3. Additive for Livestock Bedding

Generally applied by mixing the biochar with straw or sawdust, the application is simple and easily integrated into animal bedding management routines: After the initial dose, at a typical ratio of 5% to 10% by volume, additional biochar can be sprinkled in damp or high-traffic areas as needed during the bedding cycle. When biochar is added as bedding material in stables or feedlots produces similar results to those describe for biochar added to manure or composting

piles. But in this case, some additional benefits can be achieved in terms of animal welfare, health and abatements of GHG emissions (Schmidt et al., 2019; Shin et al., 2025).

- i. **Odour and NH₃ Emission Control: Gas Absorption:** Biochar is highly porous and has a large surface area, allowing it to adsorb volatile compounds that cause unpleasant odours and, crucially, NH₃, a respiratory irritant. An environment with less NH₃ reduces respiratory health problems in animals and workers. By retaining NH₃, biochar not only improves air quality, but also prevents the loss of nitrogen, a valuable nutrient that would otherwise volatilise (Pires, 2025).
- ii. **Methane Emission Control:** The use of biochar in animal bedding contributes significantly to the reduction of CH₄ emissions, and this effect occurs from the whole period and not only during the later phase of manure management and composting (Schmidt et al, 2019; Pereira et al., 2024).
- iii. **Disease Prevention:** Biochar is hygroscopic and helps keep bedding drier for longer by absorbing excess moisture (urine and spilled water), which inhibits the growth of pathogenic bacteria and fungi. A drier environment significantly reduces the incidence of foot problems (pododermatitis) in poultry and livestock and improves the overall health of the herd (Kazemi, 2025). Guerreiro et al. (2025) also observed that biochar led to a decrease in the levels of several mastitis-causing agents (*Enterobacteriaceae*, *Streptococci*, *Enterococci* and *Staphylococci*), and in the levels of *Salmonella* spp. and gram-positive bacilli. Nevertheless, they also that some pathogenic groups such as *Brucella* could be reinforced, an aspect that requires further study to ensure the future safe and sustainable use of this environmental-friendly resource in animal production (Guerreiro et al., 2025).

4. A high quality fertilizer for fodder production

Biochar 'loads' its pores with nutrients from manure and urine. When the used bedding is removed and composted or applied directly to the field, a higher quality fertiliser is obtained. Biochar acts as a 'nutrient bank' that slowly releases minerals to plants when applied to the soil (Wang et al., 2022). This high-quality fertilizer can be used to produce fodder on farms, event to fertilize grazing pastures (Biederman et al 2017; Brown et al, 2023). Nevertheless, under certain conditions, biochar can have detrimental effects on plant productivity, deserving more specific studies (Brtnicky et al., 2021).

Appendix 3. Potential production of biochar in dehesas

1. Constraints for biochar production

Despite its advantages of biochar, its use is still a minority practice in agriculture. And not without some criticisms, mainly referring to the sustainability of its production process (Mahmood et al., 2024; Siddiqui, 2025). The reason is that conflicts can arise if the land used to produce food were to be used to produce biomass to make biochar. For this reason, the International Biochar Initiative (<https://biochar-international.org/>) proposes a series of good practices to consider when selecting the most suitable raw materials to produce biochar:

- Any type of biomass is not valid to obtain biochar.
- It is very important to keep in mind that biochar can be obtained from agricultural, forestry and even urban waste. In this way, their recycling would be encouraged. Some residues that could not be applied to crops due to their toxicity in the soil, could go through the pyrolysis process – as a sanitation treatment – and be used to obtain biochar.
- In the case of agricultural or forestry waste, not all of this biomass should be used to obtain biochar, it is essential to leave a part available for the recycling of nutrients in the soil.
- It is necessary not to promote land-use change to produce biochar. Carbon sequestration by biochar and consequently climate change mitigation would not compensate, for example, for the destruction of a forest for biochar.

In the same line with the European Biochar Certificate (<https://www.european-biochar.org/en>), a charcoal can be called Biochar only if a series of conditions are met:

- Sustainably sourced raw material.
- Energy-efficient and low-emission pyrolysis process.
- Quality of charcoal with a high content of non-labile organic carbon.
- Suitability for safe application: eco-toxicity control.

2. An opportunity for agroforestry systems

Among agricultural systems, agroforestry systems are probably the ones that best meet all these requirements, insofar as they periodically produce biomass waste from pruning and thinning trees and/or shrubs. If these practices are carried out properly, it is a sustainable form of biomass production (Stavi et al., 2013; Fungo et al., 2021). The management of this biomass waste entails a cost, and in many cases, it is resolved through on-site burning, with the corresponding emission of all the carbon into the atmosphere. Its carbonisation into biochar is therefore a mechanism for removing emissions.

Among the several categories of agroforestry systems found worldwide, silvopastoral systems are the most common and extended types (Sharrow, 1999; Rigueiro-Rodríguez et al., 2009; Orefice et al., 2016; Jose et al., 2017). Worldwide, silvopastoral systems include scattered trees in pasturelands, managed plant succession, live fences, windbreaks, fodder tree banks, cut-and-carry systems, tree plantations with livestock grazing, pastures between tree alleys and various kinds of intensive management practices (Moreno and Rolo, 2019). In Europe, these systems cover 20 million ha in Europe (Plieninger et al. 2015), of which ~15.1 million ha are regularly grazed.

In silvopastoral systems, with the presence of livestock, biochar serves the dual purpose of activating biochar with manure while reducing GHG emissions in livestock housing and/or manure piles. A third benefit that can follow is using manure rich in biochar (or activated biochar) as fertiliser on forage crops, increasing their production and thus reducing the need for external forage supplements. All in all, by transforming wastes (woody biomass and manure) into a

resource (biochar-rich manure), silvopastoral systems can be managed following a nice scheme of circular economy on the search of the carbon neutrality of the livestock farms.

3. Iberian dehesas: the most extended agroforestry system in Europe

Iberian dehesas (named *montados* in Portugal) cover around 6.5 million ha of Iberian Peninsula (den Herder et al., 2017), where they are the main land use systems (Moreno et al., 2018) and form one of the largest agroforestry systems in Europe (den Herder et al., 2017). Dehesas are open woodlands where trees, native grasses, crops and livestock interact positively under specific management practices. The scattered tree layer is dominated by Mediterranean evergreen oaks, with a density ranging from 5 to 80 trees per hectare (usually 15–45 trees per hectare) and 21–40% canopy cover (Moreno and Pulido, 2009). Mature trees are regularly pruned with the aim of maximizing acorn production and providing browse in winter, when the herbage production can be low, and of providing wood fuel for household use and sale (Moreno and Rolo, 2019).

4. Tree (and shrub) management and biomass production

Dehesa trees are periodically pruned, and lopped branches were traditionally used for firewood and charcoal production and as fodder in winter. Currently, trees are pruned every ~20 years, pruning every year a small share of the farm. After pruning, livestock consume the leaves, and later, thick branches are harvested for the firewood market and thin branches are piled up and burned in the field to clear the plot.

Alternative to burning it is the chipping of this biomass waste and left as mulch or harvested as biofuel, however, this requires specialised heavy machinery, which, in addition to the economic cost, causes adverse effects on the soil and grass when moving across the common slopes of the dehesas. The carbonization of biomass is more economic and manageable, although can be costly on term of labour time.

5. Estimating the potential production of biochar

The yield of feedstock available for biochar production as a separate fraction of coarse woody used as firewood varies significantly depending on the intensity and timing of pruning, the age of the tree, and tree cover. There is no single, universal figure, but estimates can be given of its proportion of the total woody biomass extracted. Taking as an average 50 cm of normal diameter for the trees of the pasture, based on the tables prepared by Montero et al. (2005), the biomass of medium (2-7 cm in diameter) and thin branches (2 cm in diameter), feedstock not usable as a firewood, is estimated at 214.2 and 172.7 kg of dry matter per tree. Assuming that in a typical pruning in dehesa up to 2/3 of the medium and thin branches are cut, an average tree can produce around 260 kg of feedstock per tree.

Taking 30 trees per ha on average as a reference, the brushwood produced is estimated at 7800 kg of dry matter per ha and pruning. For a rotational cycling of 20 years for tree pruning, this yields 390 kg DM ha⁻¹ y⁻¹, a figure within the range reported by Cañellas et al. (1991), who estimated a yield of 300–500 kg ha⁻¹ y⁻¹ of dry browse (fine branches + leaves). This estimation is also in the range reported by the Energy Agency of the Region of Extremadura¹: the production of pruned biomass amount to 1000 - 3000 kg DM per ha and year, with a share of 60-75% of

¹ https://www.agenex.net/documentos-ap/noticias/LA_BIOMASA_FORESTAL.pdf

biomass usable as firewood and 25-40% of fine branches usable for chipping or carbonization. Taking these values, the production of feedstock would range from 250 to 1200 kg DM of brushwood per ha and year.

For a theoretical dehesa of 500 ha that follows the rotation of 20 years for tree pruning, every year 20 ha are pruned, with a production of 195 tonnes of feedstock per year, what could be used to produce in the farm around 43 tonnes of biochar per year, provided a biochar yield of 22% of the dry feedstock (Cornelissen et al., 2016).

The estimated 43 tonnes of biochar produced per year in a 500-ha dehesa could be treated around 400 tonnes of manure, approximately the manure produced by around 100-120 fattened calves in the feedlot of the theoretical dehesa of 500 ha (the suckler cows remain in the pasture all year round, and do not produce manure). This biochar activated (or biochar-rich manure) can then be used on-farm to fertilize fodder crops.