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BOOK OF ABSTRACTS

Block B

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B1 Carbon sequestration and trade-offs

Session Description

Involved projects: INSURE, TRACE-SOILS, SOMMIT

Conveners: Felipe Bastida, Cristina Aponte, Eugenio Diaz-Pines, Kristiina Lång

The improvement of soil carbon (C) sequestration while reducing GHG emissions is a strategic target to mitigate climate change in agricultural lands. This can be pursued through a large range of management strategies, including minimizing soil disturbance, diversification of crop rotations, use of cover crops, incorporation of crop residues, addition of organic amendments, rewetting of organic soils, etc. Further, the increase of soil organic carbon stocks has a variety of co-benefits, beyond climate change mitigation, including improvement of soil health, fertility and water holding capacity. However, the environmental context, including biotic (biodiversity, microbial activity, crop type, etc.) and abiotic (soil physical and chemical properties, climate, etc.) factors can strongly shape the balance between C sequestration, CO_2, N_2O and CH_4 fluxes, and N leaching. For instance, in cultivated peat soil warming is expected to intensify organic matter degradation and further reduce C-sequestration, while contributing to GHG release. In more arid environments, the application of organic amendments can improve carbon sequestration while impacting the GHG fluxes.

In this session, we welcome contributions that give insights into how soil management influences C sequestration rates and non-CO_2 GHG fluxes in agricultural lands. We welcome experimental, modelling or synthesis approaches addressing the causes and mechanisms of the observed trade-offs and/or synergies between GHG release and soil C sequestration. The session will be convened by scientists participating in projects within the European Joint Programme Cofund on Agricultural Soil Management.

Effectiveness of soil management strategies for mitigation of N_2O emissions in European arable land: A meta-analysis

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Soil management strategies involving the application of organic matter (OM) inputs (crop residues, green and livestock manure, slurry, digestate, compost, and biochar) can increase soil carbon storage but simultaneously lead to an increase in non-CO_2 greenhouse gas (GHG) emissions such as N_2O. Although multiple meta-analyses have been conducted on the topic of OM input impacts on GHG, none has focused specifically on European arable soils. This study plugs this gap and can assist policymakers in steering European agriculture in a more sustainable direction. The objective of this meta-analysis was to quantify how OM inputs of different nature and quality, but also the application strategy, can mitigate soil N_2O emissions in different pedoclimatic conditions in Europe.

We quantitatively synthesised the results of over 50 field experiments conducted in 15 European countries. Diverse arable crops, mainly cereals, were cultivated in monoculture or in crop rotations on mineral soils. Cumulative N_2O emissions were monitored during periods of 30 to 1,070 days in treatments, which received OM inputs, alone or in combination with mineral N fertiliser; and in controls fertilised with mineral N.

The overall effect of OM inputs had a slight tendency to reduce N_2O emissions by 10% (n=53). With the increasing carbon-to-nitrogen ratio (C/N ratio) of the OM inputs, this mitigation effect became more pronounced. In particular, compost and biochar significantly reduced N_2O emissions by 25% (n=6) and 33% (n=8) respectively. However, their effect strongly depended on pedoclimatic characteristics.

Regarding the other types of OM inputs studied, a slight N_2O emission reduction can be achieved by their application alone, without mineral N fertiliser (by 16%, *n*=17). In contrast, their co-application with mineral N fertiliser elevated emissions to some extent compared to the control (by 14%, *n*=22).

We conclude that among the seven OM inputs studied, the application of compost and biochar are the most promising soil management practices, clearly demonstrating N_2O emission reduction compared to mineral N fertiliser. In contrast, other OM inputs had a small tendency to mitigate N_2O emissions only when applied without mineral N fertiliser.

Keywords: climate change mitigation; effect size; nitrous oxide; organic matter inputs; pedoclimatic characteristics

The effect of conservation agriculture interventions on greenhouse gas emissions in European temperate systems

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There is widespread interest in how conservation agriculture (CA) interventions (zero or minimum tillage (ZMT), retention of organic residues, diversification of cropping systems), adapted for local conditions, might increase the sustainability of arable systems. While evidence suggests that CA may increase the resilience of crop yields to climate variations and improve soil health, the impact on greenhouse gas (GHG) budgets remains uncertain.

A consortium of researchers is seeking to contribute substantively to the evidence base on the impact of CA on carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4) emissions in systems in Europe and sub-Saharan Africa (EJP SOIL External project: *CropGas*). We present some of our initial findings from temperate systems in Europe, focussing on the tillage aspect of CA.

Using established experiments with contrasting tillage treatments at Rothamsted Research (UK), Lyons Research Farm (Ireland) and Brody Research Station (Poland), we measured GHG emissions, contributing soil properties, crop yields and meteorological data over 12-month monitoring periods. With a particular interest in N_2O emissions, N fertiliser was withheld from small areas of experimental plots for emission factor calculation.

Patterns in GHG emissions were typically variable in space and time, being affected by seasonal weather patterns, fertilisation, and tillage. In the UK, CO_2 and N_2O emissions were increased significantly by fertilisation and non-significantly by tillage compared to ZMT. In Ireland, N_2O and CO_2 emissions were greater under tillage following a first and second fertilisation, respectively, compared with ZMT. Taken as a cumulative flux, however, CO_2 and N_2O emissions were greater under ZMT than tillage in the Ireland experiment. In Poland, greater CO_2 emissions from conventional tillage were observed in autumn, with some suggestion that N_2O emissions were lower under ZMT. In all experiments, CH_4 emissions were negligible and not affected by tillage.

Tillage effects on soil physical properties were observed. In both the UK and Ireland, soil under ZMT had a greater overall porosity, and a smaller water-filled pore space (degree of saturation) compared to conventional. This latter observation is important as it relates to the potential for denitrification and production of N_2O in wetter anaerobic soils. Water retention in unsaturated soil is important, and ZMT was associated with greater water retention in both the UK and Poland experiments. Also in Poland, there was greater C and ammonium-N, but smaller nitrate-N, in soils under ZMT.

Effects of tillage on crop yields were mixed, being little affected in the UK experiment, but greater (and with greater grain N concentration) under conventional tillage in the Ireland experiment. Improvements to the physiological condition of crops under ZMT were observed in the Poland experiment.

Data processing from the UK, Ireland and Poland experiments, and the complementary experiments in sub-Saharan Africa, is on-going and will be supported with further assessment of the effect of CA on soil chemical and physical properties. Modelling will help us to identify the key processes in the management-soil interaction which determine GHG production and will allow us to evaluate the potential role of CA in mitigation strategies with associated trade-offs.

Keywords: zero or minimum tillage; crop rotations; field experiments; nitrous oxide; soil structure

Policy measures effectively reduce soil nitrous oxide emissions with minor trade-offs in crop yield

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Nitrous oxide (N_2O) emissions are closely linked to agricultural fertilisation. European and national policy incentives have been set to reduce greenhouse gas (GHG) emissions; however, only a few evaluations have been conducted. Avoiding such emissions is an important climate change mitigation measure, but it is still uncertain which management measures over a long-term, best out-balance crop yield and GHG balances in agricultural systems. We here used the process-based LandscapeDNDC model to simulate N_2O emissions and trade-offs in yield and soil nitrogen budget for four alternative arable crop- ping systems in three Austrian agricultural production zones belonging to different climatic regions. We evaluated statistical data on crop rotations and management practices, predominant soil types, and 10-year daily weather conditions for four cropping systems: (1) conventional farming receiving the maxi- mum allowed nitrogen fertilisation rate (*Nmax*), (2) conventional farming receiving 15% less fertiliser, (3) conventional farming receiving 25% less fertiliser, and (4) organic farming. Our results showed that soil N_2O emissions could be best reduced in wet, high-yield regions. Reducing nitrogen fertilisation by 15% and 25% mitigated N_2O emissions by, on average, 22% and 39%, respectively, while the yield was reduced by 5% and 9%, respectively. In comparison, the same crops grown in the organic cropping system released 60% less N_2O, but yield declined on average by 23%. Corn, winter barley, and vegetables showed the highest N_2O reduction potential under reduced fertiliser input in conventional farming. In addition to N_2O emissions, reduced fertilisation substantially decreased other nitrogen losses into the water and atmosphere. Generally, the soils under all cropping systems maintained a positive mean nitrogen budget. Our results suggest a significant emission reduction potential in certain production zones which, however, were accompanied by yield reductions. Knowledge of the emission patterns from cropping systems under different environmental conditions is essential to set the appropriate measures. In addition, region-specific measures to reduce soil N_2O emissions have to be in line with farmers' interests in order to facilitate the successful implementation of targeted nitrogen management.

Keywords: crop rotation, cropping systems, fertilisation, LandscapeDNDC, nitrogen balance

No net carbon sequestration by willow on a cultivated peat soil

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Peatlands are a major source of greenhouse gas emissions, on a global scale and locally in Finland. More than half of agricultural emissions come from Finnish peatlands, although their share of cultivated fields is only 12%. Possibilities to decrease emissions are e.g. to raise the water table level and reduce soil disturbance by cultivating a perennial crop. Willow has been found to create a net carbon sink on mineral soils, but this is challenging in peat soils due to high loss of carbon in soil respiration.

We set up an experiment on a cultivated peatland located in southwestern Finland in the summer of 2018, where we monitored the growth of the willow and greenhouse gas emissions for four years starting from 2019. The ground water table was raised gradually from 80 to 30 cm during the experiment.

During the experiment, the willow sequestered about 87 Mg ha^{-1} of carbon in its above and below-ground parts whereas carbon loss in soil respiration was 43 Mg C ha^{-1}. In two harvests, 51 Mg C ha^{-1} of carbon was removed in total, leading to net loss of carbon and net ecosystem carbon balance of 8 Mg C ha^{-1} over the study period of four years. A 10 cm increase in water level reduced annual CO_2 emissions from soil respiration by 1.5 Mg C ha^{-1}.

Annual emissions of N_2O ranged from 2 to 17 kg N_2O-N ha^{-1} with a decreasing trend towards the end of the monitoring period. Flux of CH_4 changed from consumption (-1…-2 kg CH_4-C ha^{-1}) to moderate emissions (4-11 kg CH_4-C ha^{-1}) as the water table rose.

With the mean annual net ecosystem balance and emissions of N_2O and CH_4 from the last year when the water level had settled and willow stand well established, the total greenhouse gas emission balance can be estimated to be about 8 Mg CO_2 equivalent. This indicates that willow cultivation in wet management has potential to reduce greenhouse gas emissions from cultivated peat soils as compared to typical crops but it is difficult to reach net carbon sequestration at least during the first years of cultivation.

Keywords: organic soil, wetland, willow biomass, GHG emissions

Understanding the Role of Phosphorus Fertilisation: Long-Term Effects on Nitrogen Cycling, Carbon Sequestration and Greenhouse Gas Emissions in European Agricultural Soils

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Due to the inappropriate and excessive use of phosphorus (P) fertilisers, we are facing a global P crisis. P is a crucial element for promoting plant growth, but its scarcity can diminish both plant and microbial biomass, thereby influencing the sequestration of soil organic carbon (SOC). Alterations in soil P content have the potential to shape microbial communities, thus affecting pathways within the carbon (C) and nitrogen (N) cycles and subsequently impacting emissions of greenhouse gases. In this laboratory incubation experiment we investigate the impact of different P fertilisation levels in three European long-term experiments (LTE) on N and C transformation processes and greenhouse gas fluxes in agricultural soils using stable isotope techniques (^{15}N and ^{13}C). This study is part of the EJP SOIL project "ICONICA" (Impact of long-term P additions on C sequestration and N cycling in agricultural soils).

The soil samples derived from Johnstown Castle, JC (grassland soil, Ireland), Lanna Skara, LS (arable soil, Sweden) and Jyndevad, JY (arable soil, Denmark). Two P levels were examined from each LTE: low P (0 kg P/ha and year) and high P additions (different P application rates among LTEs). The soils were mixed with ^{13}C- and $^{13}C^{15}N$- labelled maize biomass, respectively, and received ammonium nitrate (NH_4NO_3) in the ^{13}C treatment as $^{15}NH_4NO_3$ and $NH_4{}^{15}NO_3$, respectively, and unlabelled NH_4NO_3 in the $^{13}C^{15}N$ treatment. Soil and gas samples were taken 0, 1, 3, 7 and 10 days after addition of NH_4NO_3 and were analysed for $^{(15)}NH_4^+$-N, $^{(15)}NO_3^-$-N, organic $^{(15)}N$, organic $^{(13)}C$ contents as well as for nitrous oxide ($^{(15)}N_2O$), carbon dioxide ($^{(13)}CO_2$), and methane (CH_4) fluxes.

Preliminary findings display clear differences among the three LTEs as well as the two P levels. Regarding the impact of P fertilisation history, the JC soil showed increased CO_2 emissions under high P levels compared to low P levels. Significantly, high P levels exhibited higher CH_4 uptake rates in JC

and JY soils compared to the respective low P levels. JY exhibited the highest emissions of N_2O, whereas JC displayed the lowest N_2O emissions. Additionally, JC showed higher NH_4-N values compared to LS. The highest concentrations of NO_3-N were measured in JC, and the lowest in JY. Furthermore, within JC samples, higher NO_3-N values were measured under conditions of high P compared to low P levels.

The results so far underscore the complex interactions within the carbon-nitrogen-phosphorus cycles under varying P inputs. Further analyses and interpretations are in progress.

Keywords: Phosphorus, Nitrogen, Carbon Cycle, Stable Isotopes, Agriculture

SUstainable Management of soil Organic Matter to MItigate Trade-offs between C sequestration and nitrous oxide, methane and nitrate losses: The SOMMIT Project

Eugenio Diaz-Pines, Alessandra Lagomarsino and the SOMMIT Team

The SOMMIT project evaluates trade-offs and synergies between soil C sequestration, nitrous oxide, methane and nitrate losses as affected by soil management options aimed at increasing soil C storage. The project involves an integrated and interdisciplinary approach addressing the main pedo-climatic conditions and farming systems in Europe. In this presentation, I will navigate through the main findings of the project, including the effects of organic materials application on the N2O fluxes and discussion on knowledge gaps identified. We will further present results of standardized incubations across selected European long-term experiments investigating different management strategies. Finally, we will present the application of a fuzzy-expert system to identify optimal strategies for mitigation in European agricultural soils.

C-arouNd: Refining Soil Conservation and Regenerative Practices to Enhance Carbon Sequestration and Reduce Greenhouse Gas Emissions

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While the last 60 years have seen significant progress in global food production with inorganic fertilizers, plant breeding, and pesticides, this has come at a cost to soil health. This intensive agriculture has led to a reduction in soil organic carbon (SOC) stocks, increased greenhouse gas (GHG) emissions, and ultimately contributed to global warming. Agriculture and land-use change are responsible for nearly 20% of global GHG emissions, making it a significant source of nitrous oxide (N2O) due to synthetic nitrogen fertilizers and methane (CH4) due to livestock activity and rice cultivation. This project aims to evaluate the influence of conservationist and regenerative agricultural practices on carbon (C), nitrogen (N), and phosphorus (P) cycling, soil biodiversity, and GHG emissions, with a particular focus on long-term SOC stocks and the processes governing carbon persistence. To achieve this, the project has established a consortium of long-term field experiments that assess the impact of different cropping systems and agricultural practices on soil properties. Participants from 12 countries are involved, contributing a total of 37 field sites with varying chronosequences or contrasting agricultural management practices. At 26 sites established for at least 10 years, estimates and scenario models of potential N2O, CO2, and CH4 emissions from cropping, pasture, and forest systems will be generated using the best available IPCC or local emission factors. Additionally, GHG emissions will be directly measured at a subset of these sites. The project is building a global database of C and N stocks, bulk density, soil fertility, and GHG emissions across diverse ecosystems and under different agricultural management practices. This will allow researchers to determine how climatic conditions, net primary production of the cropping systems, and soil type influence C and N stocks, nutrient dynamics, and GHG emissions. The ultimate goal of the project is to recommend best

management practices for food crop production that promote soil carbon accumulation, particularly mineral-associated organic matter (MAOM), without increasing GHG emissions. This will contribute to the long-term sustainability and resilience of agricultural systems. As promised in the project deliverables, the Long-Term Experiment (LTE) metadata has already been organized in a FAIR repository. Additionally, the protocols for soil sampling, laboratory analyses, and site characteristics are being prepared for publication. Furthermore, soil carbon sequestration is being quantified across all fields (or planned for future sampling), and in some experiments, greenhouse gas emissions are also being measured. This includes African dark earths and surrounding ecosystems, where both carbon sequestration and GHG emissions are being quantified. PhD students have also begun field trips to Norway for soil sampling.

Keywords: soil carbon persistence, agriculture intensification, sustainable development, nutrients cycling, carbon storage

Abstracts of Poster Presentations

Long-term crop residue management effects on the greenhouse gas fluxes: an Austrian case study

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Most cropland soils rely on crop residues as their sole source of carbon, especially in cereal production. In the context of climate change mitigation, incorporating these residues into the soil (instead of removing them) is one popular soil management strategy to enhance the carbon input on agricultural land.

Usually, it is observed that crop residue incorporation leads to higher soil organic carbon (SOC) stocks. However, higher carbon in the soil may also modify the N_2O and CH_4 fluxes, since these gases are produced by microbial processes mediated by carbon availability. The effect of residue management

on non-CO_2 GHG fluxes has not been comprehensively assessed, what prevent us from estimating the overall effect of management strategies on the soil greenhouse gas (GHG) balance.

Here, we monitored GHG fluxes from a long-term experiment in the Marchfeld, a productive agricultural area in east Austria. In this experiment, two crop residue management strategies have been compared since 1982: removal of residues vs incorporation.

We used static manual chambers to estimate CO_2, CH_4 and N_2O fluxes between cropland and atmosphere. In parallel, soil environmental conditions and soil nutrients were investigated. We captured flux information between 902 days with a temporal resolution of approximately 21 days between measurements. Within this period the field had a rotation of winter wheat, sorghum, and triticale.

We observed a large interannual variability in N_2O fluxes, from no effect to higher emissions following incorporation of residues. Cumulative N_2O emissions were enhanced by incorporating residues compared to the removal treatment. Nevertheless, this amount is relatively minor compared to the currently higher SOC stocks in the first 25 cm in the residue incorporation scenario. While our case study illustrates a trade-off scenario between GHG fluxes and SOC storage in temperate croplands, the trade-off is only a small fraction of the long-term climate mitigation benefit by incorporating residues.

Keywords: nitrous oxide, long-term field experiment, static chambers, climate change mitigation, soil C and N pools.

Effects of long-term soil organic matter decline on soil nutrient status and organic matter composition in organically managed grass-clover ley and permanent pasture in Norway

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Grasslands are often seen as a beneficial measure to increase soil organic matter (SOM) content in (former) croplands and reduce GHG emissions. In permanent grassland the continuous ground cover and the high root density protect the soil against erosion, leading to an accumulation of organic matter. In cultivated grasslands, such as grass-clover leys, the nutrient cycle encompasses an accumulation phase during the ley period, followed by a rapid decomposition after ley termination. Upon ploughing the grass-clover ley, there is an increased mineralization of nutrients, contributing to the buildup soil fertility. As part of the global C-arouNd project consortium, which aims to investigate how short and long-term agricultural management practices affect SOM persistence in the soil profile, we want to investigate how SOM decline affect the soil nutrient status and organic matter composition in the long term, in a permanent and cultivated grassland in West Norway.

At Tingvoll gård experimental farm, organic milk production was established in 1986, replacing the previous conventional sheep farming. Records of bought additional feed and sold products have been kept, allowing to calculate a farm nutrient budget. Since 1990, soil samples (0-20 cm depth) have been taken every 5–7 year for determination of SOM and soil fertility status. In addition grass-clover yields have been annually measured since 1991. Preliminary analyses of the historical data show a decline on the SOM concentration (ignition loss) in the 0-20 cm top layer over 30-y period. On average in the cultivated grassland, SOM concentration declined from 14.0 % and 7.9 % in 1990 to 7.4 % and 6.4 % in 2021. In the permanent pasture, where the soil is not ploughed every 4 years, the losses of SOM content were smaller, on average SOM decreased from 10.2 % to 8.0 %.

We hypothesize that soil from fields with the largest decline in SOM over the past decades will contain relative more stable carbon components while also being richer for most macronutrients. Analysing the farm nutrient budget, i.e. the in- and output of nutrients from the farm system, will give further

insight in potentially deficient nutrients in soil and help establish a more durable soil management. Soil nutrient imbalances can lead to higher SOM turnover and a further decrease in SOM content can be expected. To test these hypotheses, soil samples will be taken in autumn 2024 to study the macronutrients and SOM composition in more detail. C, N and S will be measured by dry combustion, available P by the Bray-1 Method and exchangeable Ca, K and Mg using ammonium acetate extraction. SOM composition will be examined using a thermal fractionation method on the different size fractions (fPOM, oPOM & MAOM) of the soil.

Keywords: Grasslands, SOM decline, Nutrient mining

The impact of long term compost application on soil N_2O emissions

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Application of compost in cropland generally results in enhanced carbon sequestration. However, compost application may stimulate the emission of soil borne nitrous oxide (N_2O), a potent greenhouse gas. This trade-off may offset the climate change mitigation obtained via carbon sequestration. Our study investigates the impact of long-term compost application on soil-borne N_2O emissions.

In the long term BOPACT field trial installed by ILVO, compost has been applied yearly since 2010. The soil organic carbon (SOC) content has been measured every 4 years. Since May 2023, N_2O emissions have been monitored weekly in both the compost and the control treatments. After application of cattle slurry and mineral fertilizer, potatoes were planted. Compost was applied in September after harvesting the potatoes. White mustard was sown as cover crop. Since potatoes are cultivated on rigdes, N_2O was monitored both on the ridges and in the furrows.

After planting the potatoes, higher emissions were observed from the furrows compared to the ridges. This effect was only observed for a limited period, while by the end of the growing season higher emissions from the ridges were measured. The cumulative N_2O emissions measured in the compost treatment were similar to the emissions observed in the control treatment. Combined with the enhanced SOC content observed in the compost treatment, these results suggest the positive impact of compost application on climate change mitigation. Further, our results stress the need to monitor N_2O emissions in winter periods, since significant emissions were measured during this season.

Keywords: N_2O emission; compost, carbon sequestration, climate change mitigation, field experiment

The impact of over a century of different organic fertilization on the properties of soil organic matter and water holding capacity

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The long-term experiment was established in 1921 at the Experimental Station of the Warsaw University of Life Sciences in Skierniewice (central Poland) on sandy loam Luvisol, which received mineral fertilization (Ca, N, P, K). The treatment included: (1) control with arbitrary crop rotation; (2) manure applied every five years at a rate of 30 t ha^{-1}; (3) legumes (*Trifolium pratense* L.); and (4) manure with legumes. Soil samples from A horizon (0-20 cm) were collected during the 2022 mid-growing season and analyzed for total organic carbon (TOC), fractional composition of soil organic matter (SOM) for humic acids (HA), fulvic acids (FA) and humin (HUM), as well as spectroscopic properties of bulk soil (TC-GC/MS) and isolated HUM (UV-Vis and fluorescence). In addition, plant available water, soil moisture, soil temperature, and CO_2 emission were measured in the field during the 2022 and 2023 growing seasons from treatments 1 and 2 only.

The greatest impact on SOM content was observed in plots where manure was applied, which resulted in an increase in TOC by 48% and 68% in variants (2) and (4), respectively. The application of legumes alone caused an increase in TOC by 32%. The analysis of the fractional composition of HS revealed that the transformation of organic matter under fertilization with manure led to a significant increase in HUM amount and decrease in the HA/FA ratio concerning control. Different management caused also changes in the spectroscopic properties of HUM, which indicated an increase in UV-Vis absorbance and fluorescence emission in legume applied soil.

Thermochemolysis and gas chromatography/mass spectrometry showed that HUM was enriched in carbohydrates in almost all pairs of soil and HUM. Manure fertilization and application of legumes resulted in enrichments in carbohydrates in bulk soil and HUM samples as well as in decrease in lipids.

Changes in the amount and properties of SOM were accompanied by changes in the water-holding capacity. Manure fertilization increased plant available water by 20% and 10% in variants 2 and 4, respectively, while legumes alone decreased plant available water by 11%. Based on the two years of monitoring, CO_2 emissions were affected by soil temperature only.

The results confirmed that appropriate cultivation can significantly increase C resources in the soil, contributing to the mitigation of climate change. This is particularly effective when using legumes supported by fertilization with manure. Furthermore, the long-term different soil management not only altered the SOM contents and properties but surprisingly also the chemical composition of HUM which is considered as particularly stable and a long-term sink of atmospheric carbon.

The research was financed by EJP SOIL program (NCBR project EJPSOIL/I/78/SOMPACS/2022 and European Social Fund ESF), and the Ministry of Education, Science and Culture of Mecklenburg-Western Pomerania within the scope of project WETSCAPES (ESF/14-BM-A55-4790029/16-64160025).

Keywords: long-term field experiment; carbon sequestration; SOM spectroscopic properties; humin; plant available water.

Can pore water nutrients and high frequency water table data improve estimation of CO_2 emission from rewetting peatlands?

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Peatlands store approximately 30% of the global soil C pool. Peat drainage causes mineralization and CO_2 emissions. Although water table is a main controlling factor of greenhouse gas emissions from drained peatlands, nutrient status may also affect emissions. Biomass production in paludiculture provides an alternative management of peatlands under wet conditions. This study aimed to (1) quantify the effect of reed canary grass (RCG) management on a rewetted fen peatland in central Denmark, (2) calculate annual CO_2 emissions using high frequency water table data, and (3) relate water chemistry parameters (WCP) to CO_2 emission trends. Four plots established with RCG in 2018 were selected for the study and subdivided into subplots corresponding to three management treatments (0, 2, and 5-cuts per year). The 2-cut and 5-cut treatments received 200 kg N ha^{-1} y^{-1} in equal split doses. CO_2 measurements were conducted biweekly between May 2021 and May 2022 using a transparent manual chamber connected to a GLA131-GGA Los Gatos gas analyser and manipulating light intensities with four shrouding levels. WCP (NO_3, NH_4, total N, total dissolved N, total P, total dissolved P, total organic C, dissolved organic C, and Fe) were measured biweekly in water samples collected from piezometers. Auxiliary measurements (water table depth (WTD), ratio vegetation index (RVI), soil temperature, and photosynthetically active radiation) were taken on each campaign or continually to assist model-based interpolation of measured ecosystem respiration (Reco) and gross primary productivity, the latter calculated as the difference between the NEE and Reco. Reco models using hourly WTD were compared to models using the mean annual or seasonal WTDs. Additional effects of WCP were tested in linear mixed models predicting Reco, GPP, and NEE based on changes in WTD, RVI, PAR and soil temperature. The Reco interpolation model gave the best fit to measured data when both WTD and RVI were included in addition to soil temperature (Nash-Sutcliffe efficiencies between 0.74 and 0.98). The use of an annual mean instead of hourly WTD resulted in a 7% underestimation of Reco. The calculated net ecosystem C balances (NECB) were between 6.0 and 6.9 t C ha^{-1} yr^{-1} for all harvest treatments. Considerable differences in NEE were found between the plot replicates with some plots having as much as 8 times higher NEE than others. Significant differences in WCPs were found between plot replicates, with the plot farthest from the stream having the lowest C, N, P, and Fe concentrations and the plot closest to the stream having the highest nutrient

concentrations. Including WCPs in the linear mixed models improved the explanation of Reco as indicated by R^2 and RMSE. The study showed that paludiculture increased photosynthesis (GPP) without increasing Reco leading to no significant difference in NECB despite a biomass resource being obtained from the field. The advantage of paludiculture compared to no harvest relied on the most nutrient rich plot replicates.

Keywords: paludiculture, fen peatland, pore water nutrients, rewetting.

Trade-off analysis of conventional and organic crop rotations under current and future climate scenarios in Finland

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Keywords: crop rotation sustainability; trade-offs analysis; crop modelling; climate change scenarios; organic farming practices.

Balancing agricultural productivity with environmental impacts like soil organic carbon (SOC) loss, greenhouse gas emissions, and groundwater contamination poses a significant challenge for European agriculture. While organic farming practices are expected to enhance soil health and have increased their share of Europe's cultivated lands, the results regarding their effects on soil biogeochemical properties, biodiversity, and nitrogen emissions have been mixed. This study employs the process-based ARMOSA crop model to assess the impacts of conventional and organic farming practices on yield, SOC dynamics, nitrate (NO_3) leaching, and nitrous oxide (N_2O) emissions in both crop and livestock farms.

The research was conducted using simulations under current and projected future climate conditions in the South Savo region of Finland, characterized by a subarctic climate (Köppen-Geiger classification). The soil type used in the simulations was loamy sand (sand 76%, clay 4%, silt 20%), classified as an Aquic Haplocryod according to Finland's Soil Taxonomy, with an SOC content of 3.5%, a carbon-to-nitrogen ratio of 17, and a pH of 6.2 in the top 30 cm of soil.

Five-year crop rotations reflective of prevalent practices in the area were designed for both crop and livestock production systems. Crop production rotations included cereals (with fodder pea in organic management), oilseed rape, and grass. Livestock farm rotations featured two years of

cereals followed by a three-year fescue and timothy meadow (including clover in organic management). Nine scenarios were simulated to explore various residue management and fertilization strategies: conventional systems employed mineral fertilizers alone or combined with slurry, while organic systems used slurry, green manure, and a commercial organic fertilizer.

To assess the environmental impact and production efficiency of these crop rotations, a fuzzy logic based trade-off analysis was employed for each climate scenario. This analysis quantifies the trade offs between crop yield, N_2O emissions, NO_3 leaching, and SOC stock changes, resulting in a composite index known as the ∑ommit index. This index rates these trade-offs on a scale from 0 (poor) to 1 (excellent). To accommodate diverse evaluation criteria, alternative versions of this trade-off analysis were implemented, each varying the weightings of the input components to reflect the perspectives and priorities of different representative stakeholder categories.

Using the ∑ommit index to evaluate a five-year rotation rather than analyzing individual cropping cycles offers significant benefits. This approach accounts for the interconnected effects of each cycle and its interactions with preceding and subsequent cycles. By considering these cumulative impacts,

the index provides a more comprehensive view of the dynamics involved in trade-offs during crop transitions. This holistic perspective is crucial for making well-informed decisions about sustainable agricultural practices and long-term rotation strategies.

Thermal and physical soil organic carbon fractions in French topsoil and subsoil monitoring network

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Evaluating soil organic carbon (SOC) biogeochemical stability is key to better predict the impact of SOC on both climate mitigation and soil health. This evaluation can be conducted using SOC partition schemes that allow us to quantify SOC fractions with different biogeochemical stability. However, most of these schemes are costly or time consuming and cannot be implemented on large sample sets. Two exceptions are the widely used physical fractionation protocol allowing to separate particulate organic carbon (POC) and mineral-associated organic carbon (MAOC) and the emerging $PARTY_{SOC}$ thermal fractionation protocol distinguishing active SOC (C_a; MRT ≈30 years) from stable SOC (C_s; stable at a centennial timescale).

Here, we use analyses conducted on samples from the French soil monitoring network (RMQS) to compare the results of $PARTY_{SOC}$ thermal fractionations (C_a/C_s) performed on ca. 2000 topsoil samples, and physical fractionations (POC/MAOC) performed on ca. 1000 topsoil samples. Furthermore, we compare the results of the $PARTY_{SOC}$ thermal fractionations on topsoil and subsoil samples.

Our results show that MAOC and C_s from one side and POC and C_a from the other side have different sizes. The most biogeochemically stable fractions (C_s and MAOC) are mostly influenced by soil characteristics whereas land cover and climate influence more substantially POC and C_a. However, the

more stable fractions provided by both fractionation schemes (respectively the more labile fractions) do not have the exact same environmental drivers. Our results therefore suggest that both fractionation scheme gives complementary results. Regarding the topsoil vs subsoil fractions, the proportion of C_s increases with depth, as the C_a is the compartment that decreases the most with depth. In the deep horizon, the effect of the land cover on the amounts of C_a is also far less visible than in the topsoil.

The relative contribution of these two fractionation schemes to the evaluation of soil functions and SOC stock evolution remains to be evaluated on soil monitoring networks and constitutes a promising research avenue.

Keywords: Soil organic carbon, Biogeochemical stability, Rock-Eval® thermal analysis, Physical fractionation, Mineral-associated organic matter

B2 External organic matters for circular economy

Session Description

Involved projects: EOM4SOIL, BIOCASH

Conveners: Sabine Houot (INRAE), Walter Rossi Cervi (WR)

The use of external organic matters (EOM) in agriculture has been realized since many years through the application of animal manures and slurries. Now it becomes mandatory to recycle biowastes from urban activities (from homes, restaurants, stores) and their application on soils after treatment contribute to nutrient cycling and bioeconomy in territories, together with organic carbon contribution to soils and climate mitigation. Before application, different treatments may be applied that increase the diversity of characteristics of the EOM applied on soils, increase or decrease the efficiency of nutrient recycling. Such EOMs may also carry contaminants (organic contaminants, impurities, trace elements) that needs to be known and controlled to prevent environmental impacts associated with EOM recycling. To consolidate the uses of these EOMs in fertilizing practices with maximum nutrient use efficiency, positive carbon budget and economically viable without environmental impacts, it is important to improve the knowledge of the available EOM (quantity and quality), on the relationship between treatments and EOM characteristics and efficiencies and on the multi and simultaneous impacts of their use. Long-term experiments with repeated EOM application are useful tools for such assessments. Recommendation for good management of organic wastes treatment and use as fertilizers need to be produced for end users at the farm or territory scale together with policy recommendation at the territory or national level. Moreover, understand the economic potential of these EOMs and their impact on the current fertilizer market as well as on farmers cash flow.

The session will address these questions of best management practices in recycling EOMs to close nutrient and carbon cycles for sustainable territorial bioeconomy.

Soil Organic Carbon in farm level economic models: data needs for considering local specific contextual factors

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FarmDyn is a bio-economic farm model that simulates farmers` production and investment decisions under different macro-economic policy scenarios and international prices. Although *FarmDyn* is a farm-level model, an aggregation of farms is often made at European NUTS2 in order to reduce computational costs and to better integrate with its data sources as well as to provide comprehensible outputs for policy makers at regional level. The majority of the parameters and indicators in *FarmDyn* are composed by agro-economic indicators, such as production volume and costs, taxes, subsidies, among others. Moreover, additional agronomic-biophysical variables also considered in the model`s parameters (e.g. soil type, tillage levels, nutrient needs), which are relevant for capturing environmental externalities and add value to better agricultural practices (e.g. carbon price and valuing ecosystem services). The downside is that *FarmDyn* does not capture the high spatial granularity of these parameters; instead, it considers simplistic assumptions. This limits the model in providing more coherent information on environmental economic indicators. Given that, the objective of our study is to create a coherent integration of *FarmDyn* with an agronomic-biophysical model in order to incorporate more detailed information on Soil Organic Carbon (SOC).

We opted to improve the SOC representation because FarmDyn presents a pre-defined structure to calculate the SOC dynamics (so-called in the model as "*FarmDyn-HumusBalance*), which accounts for the humus input and output from arable farms. However, the structure is very specific for the German context and provide no linkage between Organic Carbon (OC) and soil texture (i.e. clay, sand). In the current version, *FarmDyn-HumusBalance* is composed by four main variables: *i*) initial OC removal (i.e. accounts for the deficit in OC due to harvest removal of above-ground biomass), *ii*) OC incorporation from crop-residues (i.e. accounts for the OC that can be incorporated in the soils if crop-residues are kept on the field), *iii*) OC deduction from crop-residues (i.e. accounts for the deficit in OC if crop-residues are removed from the field), *iv*) additional OC from external organic fertilizers (i.e. accounts for the OC that can be incorporated in the soils if organics fertilizers such as animal manure is used as fertilizer).

To improve the SOC balance quantification in *FarmDyn*, we make use of *Miterra-EU* model, which is a dynamic agronomic-biophysical model that estimates soil health indicators. The advantage of using *Miterra* is that all the outputs are available at NUTS2 level, which integrates well in FarmDyn parameter resolution at NUTS2 level. Hence, we have initially requested: a) baseline SOC stocks of arable and grassland areas at NUTS2 level, b) SOC lost rate in arable and grasslands areas and c) a relational table between C emissions and C stocked under different soil textures levels at NUTS2 level. The implementation of these new components is currently ongoing, and we expect as a result that *FarmDyn* could indicate regions where a given economic policy could lead to major SOC depletion/increase, and therefore steer appropriate measures at regional levels. Further results about the model integration will be presented in EJP-ASD 2024 in Vilnius.

Keywords: Farm-Economics; Soil Organic Carbon, Model integration

Economic, soil health and environmental impacts of use of renewable fertilisers at farm level in the EU

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With valuable nutrients often ending up in the form of waste such as sewage sludge, food waste, and green waste, this provides the opportunity for composting and then reuse these now often lost and unused nutrients. Further innovation in manure processing techniques can also create opportunities for use of manure based products that are better aligned with the crops nutrient demand. The use and implementation of these recycled and waste based renewable fertilisers can help reduce the dependency on artificial fertilisers and help close the nutrient cycle for agricultural production. For both farmers and policy makers it is important to know what renewable fertilisation products, as different types compost and animal manure products, would suit within arable production systems and how use of these products will impact farm income, use of artificial fertilisers, soil health and nutrient balances. Here we present the results of an extensive literature review regarding carbon content, nutrient content and user prices of a list of more than 25 renewable fertiliser products. The list contains two compost products, one from green waste and one from food waste. The remaining fertilisation products can be categorised as untreated animal manure and thick fraction, thin fraction and mineral concentrates from processed pig and cattle manure. Next we will use bio-economic farm models to assess impacts of different fertilisation strategies on farm income, nutrient balances and average organic matter balance, depending on availability of renewable fertiliser products and policies. The bio-economic farm models optimise farm income and it is expected that policies and the availability of more renewable fertiliser products against competitive prices, will lead to different production management choices regarding production and fertilisation. The first bio-economic farm model that is used focusses on some typical arable farms in the Netherlands. For upscaling to the EU, a second bio-economic farm model is applied to EU average NUTS2 arable farms, as derived from individual farm data from FADN.

Keywords: Renewable fertilisers, Arable farms, farm-Economics; Soil Organic Carbon, nutrient balances

Assessing agronomic and environmental impacts of external organic matter amendments in diverse agricultural practices: a comprehensive study

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Agricultural practices that utilize external organic matter (EOM) amendments have a notable impact on agroecosystems. Evaluating these impacts relies on long-term field experiments, encompassing soil organic carbon (SOC) assessment, greenhouse gas (GHG) emissions, and soil contamination post-EOM application. However, effective waste management and fertilization practices, specifically for the farmers, play a crucial role in optimizing nutrient utilization efficiency, achieving a positive carbon balance, and ensuring economic viability without adverse environmental consequences. The specificity and territorial nature of the experiments, influenced by factors such as climate, soil type, cropping systems, and EOM application methods, necessitate a nuanced approach. This study aims to evaluate the agronomic and environmental performance of various EOM utilization scenarios across diverse agricultural contexts in different regions. Emphasizing both short-term and long-term effects, we use the PROLEG tool, which integrates the AMG model, the STICS model, pedotransfer functions, and fundamental calculations of GHG balance, to comprehensively assess the impacts of EOM application in farmers' fields. Representative case studies in European regions, defined with local experts, include diverse soil types, cropping systems, and the main EOM used by farmers. Our investigation focuses on SOC assessments, soil fertility dynamics, nutrient balance and fertilizer savings, as well as quantifying nitrogen losses through leaching and volatilization, balancing GHG emissions, assessing soil trace element contamination, and conducting economic evaluations. These simulations are conducted across diverse cropping systems and consider both the short and long-term

effects of EOM application across varied pedoclimatic conditions. Data collection and case study definition across several European regions enable us to simulate these effects, acknowledging significant differences in EOM usage between regions based on availability and farmers' cropping systems. Additionally, this study explores prospective scenarios involving various EOM treatments, including methane production, to anticipate future agricultural practices in selected regions. In conclusion, our study provides valuable insights into the diverse practices of EOM use and their effects on agriculture. It offers guidance for implementing sustainable practices tailored to specific agricultural contexts and environmental conditions.

Keywords: Cropping systems, EOM application, GHG emissions, PROLEG tool, SOC assessment.

Renewable horticultural substrates as source of external organic matter: the link between circular horticulture and soil friendly practices

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Future use of C-rich external organic matter for a variety of applications including C storage in soil is expected to increase, potentially resulting in a shortage of these sources of exogenous organic matter. Using C-rich materials in a cascade is one strategy to avoid competition for these types of bio-circular waste streams. Biomass use in cascade, i.e., first using biomass in an application in the bio-economy will affect the characteristics of the biomass and its agronomic value for the second use, and the final use as external organic matter for soils. In some case, the transformation of the biomass may improve its value for soil application afterwards. One case study of the BioCASH project explored the opportunities in horticulture to use biomass in cascade in order to avoid competition for renewable biomass. The case study is an example of the use of renewable biomass in horticultural substrates, with the spent growing media having a higher stability and a more optimal nutrient profile after use in controlled environment agriculture. In the current transition from linear to circular horticulture, horticultural substrates (growing media) play an important role. Circularity for growing media means that renewable materials are used, reused and then finally applied as soil improver and for C storage.

The study starts from a comparison of chemical characteristics (organic and inorganic C, total N, P, K, Ca, Mg, C/N and C/P, CEC, pH, EC), biochemical composition (Lignin/cellulose/hemicellulose), microbial biomass and biological stability (C and N mineralization) of green composts and woody biochars versus spent horticultural substrates as such or further processed into compost or biochar. This comparison allows to assess the changes in the quality of external organic matter when used directly in the soil or only after use in a horticultural cascade. The green composts and wood-based biochars are examples of materials that are produced and then in most cases directly applied in the soil but that also can be used as bulk replacement for peat in growing media. The spent horticultural

substrates applied directly or after further processing into compost or biochar are examples of materials used in a cascade.

It is concluded that exogenous organic matter from circular use of renewable growing media may result in materials with a higher added value as soil improver and source of stable C than green compost when nutrient retention during the horticultural cascade is managed. Biochars produced from spent growing media have clearly different chemical characteristics than wood-based biochars and may have a lower biological stability when produced at 400-450°C. Although spent growing media have a high biological stability and low N mineralization rates, they still carry a high microbial biomass. The case study indicated potential for biomass use in cascade, i.e., first using and reusing biomass in horticulture combined with the final use as external organic matter for soils.

Keywords: green compost, wood-based biochar, peat replacement, controlled environment agriculture, biochar-based fertilizers

The effects of cattle manure and straw co-digestion on the digestate carbon stability

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Maintaining or even increasing soil organic carbon (SOC) content is crucial for soil fertility. The use of bio-based fertilizer products not only increases the amount of organic matter in the soil but also promotes nutrient recycling. The stability of organic matter and carbon in soils is dependent on the characteristics of the material and applied treatment. For example, anaerobic digestion alters the composition of the treated organic matter and influences the stability of carbon by transforming easily degradable organic matter into biogas, concentrating more stable forms of carbon into digestate.

In the EJP SOIL program funded EOM4SOIL project, the goal was to investigate whether the digestate's carbon content and stability could be increased through the co-digestion of cattle manure and straw. The hypothesis was that the lignin-rich straw, added along more easily degradable manure, introduces less degradable carbon into the digestion process. The objective was to examine the effects of co-digestion on the whole process, considering both gas production and digestate properties, especially from the perspective of carbon stability and retention in soils.

The co-treatment of cattle manure and straw was studied in two 1 m3 pilot-scale leach-bed batch reactors. The experiment was conducted under mesophilic (37°C) conditions by circulating leachate through the bed of manure and straw. Manure and straw were added to the reactors in a carbon ratio of 60/40, where straw comprised 16% of the total mass of the raw materials. The biogas production was monitored throughout the 139-day experiment. The produced digestate was characterised and the digestate carbon was fractionated into acid-soluble (A), water-soluble (W), ethanol-soluble (E), and non-soluble (N) fractions, i.e., AWEN fractions. Additionally, the results of the AWEN fractionation were utilized in Yasso07 modelling to examine the stability of digestate carbon in the soil.

As a result, the co-digestion of manure and straw converted 23–27% of the feedstocks' carbon into biogas, while 53–63% concentrated into digestate (Fig. 1). According to the AWEN extraction, 37–40% of the carbon in the digestate consisted of more stable carbon (E and N fractions). Thus, about 22% of

the carbon input into the biogas process was considered as more stable carbon (Fig. 1). The same value would be 26% in a mixture of untreated cattle manure and straw. Despite slightly lower carbon retention, the co-digestion converts part of the carbon into valuable methane and contributes to the production of renewable energy.

The Yasso07 modelling indicated that approximately 26% of the digestate carbon remained in the soils 20 years after the application. This is higher than with untreated manure (21%) and straw (17%), which supports the use of anaerobic digestion as the processing step for manure and straw, to aid the build-up of SOC. This type of organic amendments are often repeatedly applied regularly each year, and thus, their application has potential to gradually increase SOC also over long-term.

Keywords: co-digestion; digestate; carbon stability; cattle manure; straw

Bottom-up dialogue with local actors of biochar and digestate value chains in Italy

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In order to support the development of useful guidelines for end-users and fair policies promoting the sustainable use of Exogenous Organic Matters (EOMs), a bottom-up dialogue among actors of biochar and digestate value chains has been established, in Italy, in spring 2024. More specifically, two focus groups on biochar and digestate production and use have been conducted to gather more realistic knowledge of the EOMs value chains in specific local contexts.

For example, the Italian Northern Regions can be described as a case study, where common strengths and problems connected with the production and use of digestate are present. In fact, in these Regions biogas plants are highly concentrated (83,4% of the 2.201 biogas plants in Italy in 2021), with a consequent high production (the majority of the 3 million tonnes per year produced in Italy) and application of digestate. However, application rates are limited by the European Directive 91/676/CEE for Nitrate Vulnerable Zones (NVZs) vs. non-Nitrate Vulnerable Zones (nNVZs).

On the other hand, biochar value chain is still very poorly developed in Italy. Out of 29 authorized biochar producers in Italy, only 6 are currently producing biochar (around 1000 t/year) because of strict regulations on physicochemical characteristics of the biochar, economic unsustainability of the production plants and no demand by farmers.

These examples highlight the diversity of EOMs value chains and the importance of the local context on EOMs availability and use.

In this context, in the framework of the EOM4SOIL project, CREA researchers organized the two focus groups with the aim of collecting information about:

gaps in legislation for EOMs producers and farmers;

environmental sustainability of EOMs use in different contexts (e.g. where relevant, NVZs vs. nNVZs);

economic sustainability for EOMs producers and farmers.

The focus groups were opened to a maximum of 30 invited participants, to facilitate interaction, representing each phase of the value chain. The actors that participated to the focus groups were highly relevant: Ministry of Agriculture, Regional authorities, Environmental quality inspectors,

research institutes, EOMs producers and producers' associations, farmers, farmers' association, multinational enterprises, carbon credits certifiers, EOMs dealers and distributors.

Focus groups were conducted with the following structure:

introductory session about the EoM4SOIL project goals and findings;

introduction of participants (affiliation and role in the EOM value chain);

division of participants into 4 working groups for discussion around tables. Each group was guided by a mentor to define the Strengths, Weaknesses, Opportunities and Threats of EOM production and use. A rapporteur was chosen among the participants of each group;

the rapporteur presented to the whole audience a summary of the discussion ran in each of the table and the debate was opened.

Based on this fruitful discussion, common views on Strengths, Weaknesses, Opportunities and Threats of EOMs value chains were observed and will be valued to formulate policy recommendations as well as guidelines for end-users. These results will be presented during the Annual Science Days of EJP Soil 2024.

Keywords: Exogenous Organic Matter; focus groups; farmers; policy recommendations; barriers

Fertilizer quality of anaerobic digestate produced from marine residual resources (CIRCULIZER)

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The access to marine residual resources is large in Norway, yet its use in agriculture remains limited. **Circulizer project** aims to improve the circularity between the blue and green sector, by increasing the knowledge of the use of marine residues (i.e. fish sludge and fish silage) for biogas production and its effects on the fertilizer quality (digestate) and environment. While the quality of digestate from food waste and animal manure has been extensively studied, the impact of incorporating increasing proportions of new marine residual resources remains to be investigated. To be able to substitute mineral fertilizer with digestate derived from marine residues, farmers require knowledge of its nutrient composition and availability. In contrast, biogas plant operators need assurance of a market for both biogas and digestate before investing in new facilities. Circulizer will run lab and field scale experiments where the biogas process performance and digestate quality will be assessed. Expected outcomes are: (i) Enhancing the green transition and circularity of Norwegian food production by recycling valuable nutrients from fish production for agricultural use; (ii) Ensuring environmental safety by addressing concerns related to heavy metals and organic pollutants; (iii) Increasing the utilization of marine residual resources for biogas production; (iv) Supporting the growth of the fish farming industry in Norway by improving waste treatment and recycling options for unavoidable residual resources, thereby facilitating increased fish production and nutrient recycling.

Long-term impact of anaerobic digestion of dairy cattle slurry on grass clover yields and soil properties

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Anaerobic digestion (AD) of animal manure generates renewable energy in the form of biogas. However, there is a gap in our understanding of the long-term impacts of AD-treated manure on soil attributes and crop productivity in comparison to untreated manure. To address this, a long-term field experiment was initiated in 2011 within a perennial grass-clover ley. The objective was to investigate the effects on key soil and crop parameters when slurry from organically managed dairy cows underwent AD.

The results (2011-2021) indicated that while the application rate of manures influenced soil nutrient levels and pH, these parameters were unaffected by AD treatment. Higher slurry application rate (220 kg of total N $ha^{-1}year^{-1}$) led to a surplus of N, while deficits were observed in the untreated (non digested) control and the treatments with low application rates (110 kg of total N $ha^{-1}year^{-1}$). Treatments were not limited by P. For K, there were deficitsin all treatments. Soil organic matter (SOM) concentrations decreased across all plots, especially in those with inherently high SOM levels. This decline in SOM was similar with both untreated (non-digested) slurry and anaerobically digested slurry, and there was no significant effect of application rate. The decline may be attributed to the initial high SOM content, prolonged drainage, and increasing temperatures due to climate change.

Notably, both US and ADS demonstrated similar yields of grass-clover ley (2 cuts $year^{-1}$) and green fodder, averaging 7.9 and 4.0 kg DM ha^{-1}, respectively. Additionally, within the same production year the mean clover yields of the fertilized treatments did not differ from the control. In terms of crop yields and chemical soil characteristics, the long-term effects (over 10 years) of AD within an organic dairy cattle farming system were generally minor. The advantages of harvesting energy from slurry did not compromise the long-term productivity of grasslands or the soil chemical characteristics.

Keywords: Grass-clover ley; botanical composition; digestate; soil organic matter; organic farming

References

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The DeliSoil Project - Delivering safe, sustainable, tailored & socially accepted soil improvers from circular food production processes for boosting soil health

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The poster presents the EU-funded 'DeliSoil' project (years 2023-27), which supports the EU Mission 'A Soil Deal for Europe'. DeliSoil focuses on improving the sustainability of food systems and enhancing soil health by developing improved recycling and processing solutions for food industry residues. It focuses on delivering safe, sustainable, customized and societally acceptable soil improvers from circular food production processes to promote soil health. The project will establish 5 regional Living Labs (in Finland, Denmark, Germany, Italy and Spain), including 5 Lighthouses.

Different processing methods and best practices for food industry residues are discussed and co-created with partners, members of DeliSoil Living Labs, and other stakeholders, taking environmental aspects into account. Information is distributed to the actors of the entire food value chain and to the general public. The project ensures the acceptability and safety of soil improvers and organic fertilizer products made from food industry side streams, as well as their effectiveness in promoting soil health.

Natural Resources Institute of Finland (Luke) is coordinating the DeliSoil project and 13 other partners from 10 different European countries are involved. Acknowledgement: DeliSoil project is funded by the European Union under the Horizon Europe Program, Grant Agreement No. 101112855.

Keywords: EU Mission Soil, soil improvers, food value chain, soil health, circular bioeconomy

Effects of Anaerobic Digestates and Biochar Amendments on Soil Health, Greenhouse Gas Emissions, and Microbial Communities: A Mesocosm Study

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This study addresses the need for a comprehensive understanding of digestate and biochar in mitigating climate change and improving soil health, crucial for sustainable agriculture within the circular bioeconomy framework. Through a mesocosm experiment, soil was amended with digestates from pilot-scale reactors and two concentrations of biochar produced by pyrolysis of digested sewage sludge and waste wood. The Germination Index (GI) assay assessed phytotoxicity on *Lactuca sativa* and *Triticum aestivum* seeds. Greenhouse gas emissions (CO_2, CH_4, N_2O) measurements, soil characteristics analyses, and the study of microbial community structure enriched the study's depth. The GI assay revealed diverse responses among by-products, dilution rates, and plant types, highlighting the potential phyto-stimulatory effects of digestate and biochar water-extracts.

While digestate proved to be effective as fertilizer, concerns arose regarding microbial contamination. Biochar application reduced Clostridiaceae presence in soil but unexpectedly increased N_2O emissions at higher concentrations, emphasizing the need for further research on biochar's role in mitigating microbial impacts. CO_2 emissions increased with digestate application but decreased with a 10% biochar concentration, aligning with control levels. CH_4 uptake decreased with digestate and high biochar concentrations. The study underscores the critical role of biochar composition and dosage in influencing soil GHG fluxes, emphasizing the need for tailored approaches to optimize its impact on microbial communities and nutrient availability. The unexpected stimulation of N_2O emissions by high biochar concentrations challenges previous hypothesis, highlighting the complexity of biochar-soil interactions. Understanding the specific soil and biochar characteristics and origin is crucial for sustainable agricultural practices. The results offer new insights into the short-term effects of anaerobic digestates and biochar on soil microorganisms, emphasizing the complexity of microbial responses. Persistence and contrasting effects on microbial functional groups highlight the need for

continued research, especially exploring biochar as a tool to mitigate the impact of Clostridiaceae in soil ecosystems influenced by digestate application.

Keywords: digestate; biochar; soil nutrient; greenhouse gas emission; microorganisms; Clostridiaceae

Biological activation and N enrichment as tool to optimize biochar-based fertilizers

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Biochar-based fertilizers are a new type of engineered fertilizers, where biochar is formulated with mineral fertilizers and/or beneficial microorganisms for precise plant nutrition and the enhancement of soil properties. For soil application, biochar as a source of stable C can have an added value when it is enriched in N. Activation of the biochar is used to maximize their N retention capacity but some chemical activation methods may result in strong mass and C losses during the treatment. In one case of the BioCASH project we focused on the optimization of biochars by biological activation and increasing their N concentration, to develop a new type of engineered fertilizer. We compared: 1) biological activation of biochar by simultaneosly adding elemental S and chitin, and 2) addition of chitin to already chemical activated biochars by either hydrogen peroxide or nitric acid. Chitin and elemental S were applied for optimizing these biochars. Chitin was tested as N source to enrich the biochars. Elemental S was tested to optimize the pH of alkaline biochars in order to allow for N mineralization from the biochar. The pH of the biochar determined the effect of the treatment: only in the optimal pH range for microbiological activity, effects of elemental S and chitin in terms of S and N mineralization were observed. When chitin (2g/L biochar) was added to the intact biochar with pH 9.1, the pH increased to 9.7 and no net N mineralization occurred. The chitin addition to the biochar activated by hydrogen peroxide resulted in biological N enrichment, while chitin addition to the intact and HNO_3-treated biochars did not produce significant microbial changes. The biological acidification of the biochar with elemental S was a slow process due to the high acid-buffering capacity of the biochar, but resulted in a pH decrease from pH 9.1 to pH 6.5. Then additional chitin was added to the S-treated biochar, which resulted in a further pH decrease to pH 4.2 and clear mineral N release. When higher doses of chitin were tested to assess the potential of N enrichment, it was observed that only the combination of the intact biochar with elemental S resulted in a strong increase of the mineral N content. In this biochar, mineral N was only present as NH_4-N, not as NO_3-N or NO_2-N. After N mineralization, there were indications of immobilization of mineral N on the biochar. The addition of

higher doses of chitin did not result in mineral N release for the biochar after oxidation with hydrogen peroxide. However, lower doses resulted in significant NO_3-N release in biochar activated with hydrogen peroxide. Biochar oxidated with nitric acid showed a decrease in mineral N contents with higher chitin doses. Biological activation and N enrichment of biochar with higher chitin doses was only successful for the intact biochar after S amendment, indicating a positive interaction between chitin and elemental S. This study illustrates that specific combinations of chemical or biological activation of biochar result in higher N release after chitin addition.

Keywords: wood-based biochar, biochar-based fertilizers, biological acidification, chitosan

Impacts of biochar on nitrous oxide emissions and ammonia volatilisation in wheat and maize cropping systems

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Agriculture and other land use practices are major contributors to greenhouse gas emissions, especially for N_2O and NH_3. Nitrous oxide (N_2O) is a highly potent greenhouse gas and ammonia (NH_3) can re-react with soil and forms N_2O or can cause other environmental issues in the surrounding. Biochar is known for its carbon sequestration potential due to its high proportion of recalcitrant organic compounds, however, biochar can also positively influence soil properties like water holding capacity, nutrient leaching and mitigation of nitrous oxide emissions and ammonia volatilisation. However, these effects depend on pedoclimatic conditions, the properties of the applied biochar, and other agricultural practises. Therefore, it is necessary to expand the knowledge of these effects, especially under field conditions, to generate valid estimates on biochar's mitigation potential for N_2O and NH_3 emissions. A good and extensive data basis is essential for recommendations and a large-scale application in agriculture. In a two-year field experiment in Grabenegg (Lower Austria) we cultivated silage maize (Zea mays) in 2022 and spring wheat (Triticum aestivum) in 2023 with different organic (external organic matter, EOM) and inorganic (NPK) fertilisers. For the biochar treatments we applied 7 t/ha hardwood biochar additionally. The original soil was loamy, low in organic carbon and slightly acidic. We found substantial reductions with 36% (NPK) and 53% (compost) for N_2O and 56% (NPK) and 40% (compost) for NH_3 emissions. There are several factors discussed in literature how biochar mitigates N_2O and NH_3 emissions. We suggest that the immobilisation effect of biochar on NH_4^+ and NO_3^- (which was observed in the soil) and possibly an increased dinitrogen monoxide reductase activity are responsible for this reduction. Our data support that biochar can be a suitable amendment for highly productive agroecosystems where high amounts of fertiliser are needed and often applied at one timepoint. Still, further investigations on the long-term effect on emission mitigation of biochar and the mechanisms behind are necessary.

Keywords: nitrous oxide, N_2O, ammonia volatilisation, biochar, external organic matter

Shrimp shells valorization for chitosan and chitosan nanomaterial synthesis and their applications as antimicrobial agents in agriculture.

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The valorization of the large portion of shrimp biowaste as a sustainable source for chitosan extraction and chitosan nanomaterial synthesis is a novel approach that presents a promising avenue for addressing environmental challenges and promoting circular economy principles. Shrimp shells, a byproduct of the seafood industry, are rich in chitin, a polysaccharide that can be converted into chitosan through deacetylation. Chitosan, a biopolymer with unique properties, has garnered attention for its potential applications as a sustainable in various fields, including agriculture. additionally, the antimicrobial properties of chitosan nanomaterials make them effective against a wide range of plant pathogens, including bacteria and fungi. This research aims to evaluate the optimization feasibility of the inorganic and organic acidic demineralization phase on chitosan extraction and characterization of morphological and physicochemical properties. Furthermore, we will shed light on the applications of chitosan nanomaterials as antimicrobial agents in agriculture, particularly in the context of plant disease management and soil remediation. Shrimp shells were collected from the Lithuanian market. The optimization experiment was carried out using various concentrations of 1, 2, 3, 4, 5, and 10% of hydrochloric, acetic, and lactic acids for acidic demineralization at room temperature at stabilized deproteinization and deacetylation conditions to study the effect of acidic demineralization of inorganic and organic acids on the physicochemical and structural characteristics of yielded chitosan. Chitosan production with a high deacetylation degree > 80% for all samples was confirmed by FT-IR spectroscopy compared to commercial chitosan. The ash content, moisture content, and chitosan yield were in the ranges of (0.24-4.2%), (0.19-5.1%), and (15.1-51.3%), respectively. Furthermore, XRD and SEM combined with EDS showed that commercial chitosan had a complete amorphous structure. In contrast, the isolated chitosan samples showed a bit higher crystallinity index than commercial chitosan due to the formation of natrite (Na_2CO3) and thermonatrite ($Na_2CO_3.H_2O$) in the samples recovered using HCl. Whereas the samples extracted using acetic and lactic acids showed the existence of calcite and halite crystals. Finally, this study found that chitosan production can be optimized from shrimp biowaste with a high resemblance to commercial

chitosan using the concentration manipulation approach of inorganic and organic acids in the demineralization stage. Our future research will discuss the green synthesis of Chitosan nanomaterial from chitosan samples obtained in this study. Moreover, we will test their antimicrobial activity against soil pathogenic microorganisms (In vitro assay). Moreover, testing the efficiency of chitosan-nanomaterial among Fusarium graminiarum fungi will be determined in the greenhouse experiment, The fungicidal effect on spring wheat growth, development, and the prevalence of the disease will be assessed.

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Keywords: Shrimp Biowaste, Chitosan, Nanomaterial

A stocktaking of long-term field experiments in Europe dealing with the application of exogenous organic matter: current knowledge, gaps and perspectives

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Extending and optimizing recycling of organic wastes in agriculture is a key element in shifting conventional agriculture towards systems adapted to both energy depletion and climate change. Long-term field experiments (LTEs) play a crucial role in assessing and modelling the effects of repeated exogenous organic matter (EOM) application to soil, which allows to formulate locally adapted recommendations of use. Nevertheless, a meta-database gathering exclusively LTEs dealing with organic fertilization in Europe and specifying fertilisation conditions is currently missing. To close this gap, we listed LTEs dealing with repeated application of EOM from existing online databases and scientific literature, and collected and harmonized all available metadata. The aim of this work was threefold: (1) to facilitate connections between comparable LTEs to foster data harmonization and compilation, (2) to map the diversity of pedoclimatic contexts and experimental designs in the LTE list and, (3) to highlight current knowledge gaps and research needs. Data were collected from five online databases, allowing us to describe 201 LTEs. Key characteristics such as trial name, responsible institution, location, pedoclimatic context, duration, crop type and availability of online resources are well-described in contrast to LTE goal and owner contact, experimental design, soil type, studied EOM and monitored parameters (EOM characteristics, soil and crop properties), which are more difficult to gather and harmonize. The analysis of LTE metadata highlighted first that substantial harmonization efforts are required, particularly regarding the reporting of soil, crop and EOM properties over time. Second, the survey outlined that some European regions are poorly represented in the database, which may result either from an absence of LTE or from a lack of reporting. In the future, improvement of predictive models could contribute to provide recommendations of EOM use to uncovered situations, whether in terms of soil, climate or type of EOM. Third, long-term effects on soil properties such as changes in soil biology composition or accumulation of organic contaminants (PFAS, microplastics, antibiotics, ...) appear to be poorly documented. LTEs have a key role to play in

answering these emerging questions, having the potential to provide the rationale to fix acceptable thresholds in soils and EOMs for emerging pollutants and accordingly provide the best possible guidelines for the use of EOM in agriculture.

Keywords: Long term experiments; Organic fertilization; Metadata; Network; Harmonization

Effects of sheep wool pellets and black soldier fly (*Hermetia illucens*) frass on soil biota

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Black soldier fly cultivation has been conducted in the pilot laboratory of the Estonian University of Life Sciences since September 2018. The sheep wool pellets mixed into the soil release nutrients to plants gradually throughout the entire growing season. Nitrogen, potassium, phosphorus, and other essential nutrients are slowly released as they degrade.

The experiment was carried out at the Eerika Experimental Station in Tartu, Estonia. The experiment with sheep wool pellets had three different treatments (80, 60, 40 kg N ha^{-1}), followed by a control, and then two areas treated with black soldier fly manure (1.65 kg and 2.2 kg). In first year the summer wheat 'Mistral' was sown and on second year the oat 'Symphony' was cultivated. The following sown crop is rye 'Elvi'. In total, there were 6 different treatments, each replicated three times. Soil biota (earthworms, microbes) samples were taken on September 23, 2022, and August 26, 2023. Earthworms were collected using the vermifuge method, where a 50x50 cm sample square was made in the centre of each test plot and soaked with a 15% mustard powder solution. Earthworms were collected, and their abundance was calculated per square meter of land. A composite soil sample was collected with a soil auger, with a diameter of 5 cm and a depth of 10 cm, and from the composite soil sample, soil chemistry and microbiological biomass and respiration activity were determined. The crop yield and yield structure was analysed following harvest (29.08.2022; 24.08.2023, respectively). Upon analysis of the results, it was observed that 2022 was more favourable for earthworm abundance compared to 2023. In 2022, the treatment with sheep wool pellets had a higher abundance at the higher rate (880) (80.0±18.9). There were three earthworm species in 2022 and four in 2023 (with a total of 13 species in Estonia). In areas treated with black soldier fly manure, it appeared that the greater impact on earthworm abundance was at the higher rate (2.2 kg) (2.2 kg: 96.0±14.1 vs 1.65 kg: 85.3±23.4 in 2022). Microbial respiration was the highest in 2022 in the control area and the lowest in the area treated with the higher rate of sheep wool pellets. A greater impact on respiration was observed with the lower rate treatment of black soldier fly manure (1.65 kg). The subsequent effects

in 2023 on microbial community respiration activity and biomass due to sheep wool pellets and black soldier fly frass seemed to be relatively similar. The lower abundance of earthworms in 2023 could be attributed to the extreme drought conditions during the same year. The yields from experiment were 6.4 -7.9 t ha^{-1}.

Keywords: organic fertilizers, earthworms, field experiment

The impact of Black Soldier Fly (*Hermetia illucens*) larvae frass on the abundance and diversity of springtails (Collembola) and on cereal crop yield

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Insect farming is a novel but potential industry in Estonia. Black soldier fly cultivation has been conducted in the pilot laboratory of the Estonian University of Life Sciences since September 2018. *Hermetia illucens* larvae are highly efficient decomposers of various types of organic waste, food waste, and agricultural by-products. Throughout their growth cycle, they decrease the amount of organic matter and transform it into valuable organic fertilizer, which can be successfully used as an alternative to mineral fertilizers. Like most organic fertilizers, larvae frass can improve the physical, chemical, and microbiological properties of soil and add essential nutrients for plants. In addition to nutrient supply, larvae frass acts as a biostimulant for plants by adding biomolecules and microorganisms that enhance germination, increase plant growth, improve nutrition, enhance abiotic stress tolerance, and increase resistance to pests and pathogens. The aim of this research is to assess how soldier fly larvae frass affects the abundance and diversity of springtails (Collembola) and how it influences cereal crop yield. The experiment was carried out at the Eerika Experimental Station in Tartu, Estonia. In the field trial, there were six different treatments: control (unfertilized), mycorrhiza (unfertilized), mycorrhiza + frass (74 kg N/ha), small dosage of frass (74 kg N/ha), large dosage of frass (150 kg N/ha), and full agrotechnology (fertilized with NPK mineral fertilizer, 150 kg N/ha). Each treatment was replicated three times. In 2021, the crop culture was spring wheat (*Triticum aestivum L*), variety ´Quarna´. In 2022, it was winter barley (*Hordeum vulgare L)*, variety ´Tenor´. Soil biota (collembola) samples were taken on September 2021 and 2022. Soil samples of springtails were collected using a soil corer (Ø 5 cm) at a depth of 0-10 cm, four soil samples were taken from each sample plot, a total of 12 soil samples were collected per treatment in September 2021. In September 2022, two soil samples were taken from each plot, a total of 6 samples per treatment. A composite soil sample was collected with a soil auger, with a diameter of 5 cm and a depth of 10 cm, and from the composite soil sample, soil chemistry and microbiological biomass and respiration were determined. Although the average abundance of springtails differed between 2021 and 2022, it was

observed that in both years, the highest average abundance was in the treatment where mycorrhiza + frass was applied (respectively 2021: 134.0±38.0 and 2022: 83.7±30.9). A total of 42 species of springtails were identified. The most abundant species were *Xenylla grisea*, *Parisotoma notabilis* and *Folsomia quadrioculata*. Due to the very hot and dry conditions in the experiment conducted in 2021, the yield of spring wheat remained very low, averaging 1.3-1.6 t/ha. This was higher in the variant with mycorrhiza + frass. The yield of winter barley in 2022 averaged 3.5-6.1 t/ha. This was higher in the variant with a large dosage of frass.

Keywords: frass; springtails; yield

The impact of various organic materials in pot experiments on the survival of forest trees

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Estonia, like many other countries, has a rich history of mining activities, with its landscape punctuated by the remnants of quarries. Mining is essential to provide the resources for industries but can result in a destruction of pre-mining and post-mining ecosystem. The aim of this research project is to find techniques and materials that retain moisture for forest trees to assist in better rooting in mining areas. The goal is to promote plant growth and thus accelerate forest ecosystem establishment. In the pot experiment, we used two different mixtures. One was an imitation of oil shale quarry tehnosol (50% gravel and 50% soil), with the tree species being used pine (*Pinus sylvestris*). The other was sand from sandy quarry and the tree species used were pine (*Pinus sylvestris*) and spruce (*Picea abies*). In the pot experiments, the control variant varied according to the mixtures - either the imitation of oil shale quarry technosol (50% gravel and 50% soil) or sand. The following materials were tested: soil (100%), 2.3% sheep wool pellets (N-9.03%; K_2O-5.61%; S-1.15%; MgO-0.14%; P_2O_5-0.16%; OM-89.79%), sheep wool discs, 2% humate, 0.63% biochar (pHKCl – 8.75, Ntot – 0.08%, Ptot – 0.05%, Ktot – 0.13%, 60% ash content), 3.3% sewage sludge, 3.3% surface-applied sewage sludge substrate, 0.27% silica fume (by-product from the production of elemental silicon or alloys containing silicon, the particles are very fine, having a mean size of 0.1–0.3 µm), a mixture of materials (sheep wool pellets, biochar, sewage sludge on top). A total of 10 different variants, all in three replicates. The trees were planted in June 2023, and the monitoring of their survival is still ongoing. Based on the preliminary results, it can be stated that biochar and sheep wool discs had a positive impact on survival of forest trees. The sheep wool pellets and mixture of materials (sheep wool pellets, biochar, sewage sludge on top) had a negative impact on the survival of the forest trees. This research is supported by the Circular Economy program of the Environmental Investment Centre through a project with the number RE.4.09.22-0034 and by developmental project of Estonian University of Life Sciences “Valorization of sheep wool for agricultural utilization”.

Keywords: organic matter; pine, spruce; quarry reclamation

Short-term study on the fate of organic contaminants in soil after the application of biowaste compost or biogas digestate

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There is a significant interest in recycling waste to promote a circular economy. Using organic waste as soil amendments can improve soil fertility and structure. However, these amendments may contain organic contaminants or affect the behaviour of contaminants in the soil by adding organic matter.

In this study, we assessed the effect of applying biowaste compost or biogas digestate to a silty loam soil on 34 organic contaminants, including 18 polyaromatic hydrocarbons (PAHs), 7 polychlorinated biphenyls (PCBs), 2 bisphenols (BPA and BPF), 2 alkylphenols (octylphenol (OP) and nonylphenol (4-n-NP)), 2 parabens (methylparaben (MeP) and propylparaben (PrP)) and 3 organophosphates (TBP, TCEP, and TCPP) in a 12-month field experiment. The biowaste compost or biogas digestate used in this study derived from regional providers. The effect of these amendments on the fate of the mentioned above compounds was assessed by analysing the content of the contaminants in the soil before and after applying the treated wastes as amendments.

The application of organic amendments in soil may enhance the retention of compounds, resulting in lower availability. To determine the maximum extractable amount of organic contaminants in the soil samples, a mixture of ethyl acetate and methanol was used as extraction solvent, while their bioavailability was determined by analysing the soluble fraction (aqueous extract).

The extraction of soil using organic solvents revealed that five out of the 34 compounds evaluated were not present in the soil before or after its amendment. Additionally, the concentration of others, such as PCBs, was either very low or could not be quantified. In addition, the analysis of the soluble fraction of the soil suggests that the contaminants are more readily adsorbed in compost-treated soil, resulting in lower availability of contaminants in the aqueous fraction.

Although an increase in the concentration of some target contaminants was observed immediately after soil amendment, the overall concentration remained constant for the 12 months following

application. The analysis of the soluble fraction shows that the availability of the compounds remains throughout the 12-month period.

Keywords: organic contaminants; soil, compost, digestate, amendment

Assessment of the presence of microplastics in compost samples

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Compost application is a widely recommended practice in order to maintain and improve soil fertility. However, such practice could be a main entry path for plastic into soil. Accordingly, in the present work, different compost samples and corresponding feedstocks (substrate and biochar) were analysed in order to evaluate the presence of microplastics.

Samples were processed by oxidation, flotation and filtration. Microplastics on the filters were first visualised and counted by using a stereomicroscope. Those microplastics large enough to be separated from the filter with micro tweezers were stored for further observation using an inverted microscope equipped with a digital camera for size calibration. Those microplastics larger than 1 mm were further characterised by Attenuated Total Reflectance Fourier Transformed Infrared Spectroscopy (ATR-FTIR).

In all samples measured, there was a concentration of microplastics in the 1-3 fragments/g of dry sample range. Fragments presented different shape, size and colour. Microplastics were identified by comparing FTIR spectra with open access databases and with our own database. Three polymers represented the totality of identified plastic items: polyethylene (including both low and high density), polyethylene terephthalate and polypropylene in order of abundance. These results confirm the continued presence of plastics in this food waste compost and highlight one of the major challenges related to the potential for microplastics pollution when applying these wastes as organic fertilizer in agriculture.

Keywords: microplastics, compost, environmental pollution, agricultural soils

B3 Indicators for soil ecosystem services

Session Description

Involved projects: SERENA, MINOTAUR, WP6

Conveners: Stefano Mocali, Antoniio Bispo, Maria Fantappie, Isabelle Cousin

European soil policy is developing towards a regular assessment of soil health on the basis of monitoring by the Member States of the chemical, physical and biological condition of soils and their actual capability to contribute to the provision of ecosystem services (ES). This call invites contributions on indicators for soil health, including specific references and target values associated to healthy soils, and approaches for monitoring, defining sampling scheme, modelling and mapping of indicators and their linkage to ES. Methodological approaches aimed to the characterization of bundles of soil ES and soil threats are particularly welcome.

What is the consequence of the definition of soil ecosystem services, soil threats, and indicators used to map them, on bundles mapping at EU scale?

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Keywords: Soil ecosystem services, soil threats, bundles, European scale

Soils are diverse ecosystems consisting in living and non-living components that interact in various ways, and from such interactions is that we derive the supply of a wide range of ecosystem services. Despite their significant role, soil ecosystem services (SESs), soil health and soil security are increasingly endangered by soil threats (STs). While there is an increasing amount of information accessible regarding individual STs and SESs, further studies are needed to understand the interactions of multiple SESs and STs at the same time, also known as bundles. One potential approach to define these bundles would be through the critical analysis of STs and SESs indicators used in existing exercises assessing individual STs and SESs. Through a systematic literature search we reviewed the indicators used for the different STs and SESs mapping at the EU level. We found 32 and 17 mapping studies for ST and SES, respectively. The considered STs are soil organic carbon loss, erosion, and

compaction, while SESs includes climate regulation and carbon sequestration, hydrological control, biomass production, and erosion control. For the considered STs/SESs, various indicators exist in the literature, with an average of seven indicators per ST/SES. For many SESs/STs a consensus on the indicator used seems not to exist, as each study defines its own indicator. Five distinct reasons explained this lack of consensus: i) the indicators targeted specific but different sub-services or sub-threats, ii)different parts of the ecosystem are considered when assessing SESs or STs, iii) the STs and SESs are assessed at different steps iv)the ST is expressed as a process or as the state of the soil resulting from this process (or not), v)the potential or the current ST/SES is assessed. Due to the differences in SES/ST conceptions and indicators used to estimate them, we expect very different maps for a given SES/ST at the EU scale. Consequently, it is important to consider the varying significance and spatial patterns of the existing maps for each individual ST/SES when reusing and combining them to create bundles or other products. It is crucial to carefully assess the relevance of the resulting products, as certain combinations are particularly meaningless. Combining various sub-threats, such as different types of erosion, to assess total soil loss or multiple sub-services like nutrient and water provision for plants to evaluate biomass provisioning, is a highly efficient method for assessing complex ST and SES.

Recommended indicators to assess soil health: proposal from EJP SOIL

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More than ever, the important role that soil plays in sustaining life is recognized. This is, amongst others, expressed in high level objectives at EU scale and in the UN Sustainable Development Goals (SDGs). Achieving these targets and goals is in large part reliant on sustainable land and soil management. As discussed by EEA (2023), soil quality is often described using soil indicators. These are observed and evaluated soil properties, which can indicate the degree to which soils fulfil expected functions as needed for the wellbeing of crops, livestock, and consequently, human society. To be able to use indicators for evaluation purposes, reference values, thresholds and target values are also needed. It is, however, not straightforward to set reference values, thresholds and target values, nor

to select appropriate indicators, because such values, and even indicators, likely should vary depending on e.g. land use, soil type, climate, degradation type, soil management status.

Several past (e.g. EU soil research projects) and recent initiatives have proposed and published soil indicators and reference, thresholds or target values, including EEA (2023), the Soil Monitoring Law proposal (SML, EC 2023) and the EU soil dashboard (JRC 2023). Considering those documents and also existing literature, a large group of soil scientists from EJP SOIL reviewed information on indicators and threshold setting, dealing with a range of indicators that can, on the one hand inform on soil degradation, and on the other about soil fertility also. Adding their expertise and knowledge they provided recommendations for the selection of soil indicators to be used for accounting soil fertility and degradation changes. Topics like selection of indicators, determining the costs of soil monitoring by using field/laboratory methods as well as Remote Sensing (RS)/Proximal Sensing (PS) methods, scale effects, and modelling were also included. Depending on the indicators to be measured best periods and methods to sample as well as sampling frequency were also discussed.

A reasonable agreement was found between the main recommendations and the indicators proposed by the Soil Monitoring Law, the EUSO soil dashboard and EEA (2023), except for certain indicators (e.g. biodiversity, soil sealing, Available Water Content) and for threshold values that should be discussed and adapted to local conditions.

Keywords: soil indicators; soil sampling; soil threats; soil fertility

Comparing soil fauna parameters and ecological indices to evaluate agronomic tillage and fertiliser management in European long-term experiments

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Soil fauna actively contribute to the maintenance of various soil functions and ecosystem services, and agricultural management practices have a varying degree of influence on soil fauna biodiversity. Therefore, several groups of organisms should be considered simultaneously for a comprehensive assessment. The evaluation of the effect of farming practices on soil fauna is commonly carried out using several types of indices: (i) abundance indices, indicating the quantity of animals; (ii) taxonomical indices, evaluating taxa diversity; and (iii) functional indices, measuring the roles of taxa in ecosystems. Still, the complexity of factors involved in the agricultural management and sustainable use of soil resources, as well as the composition and diversity of the soil organisms in the different soils, do not allow to have clear evidence on the priority indices suitable for the precise and accurate monitoring detection of changes in the soil status.

This work will compare the three categories of indices mentioned, within the EJP-MINOTAUR project. The aim is to determine which type of indices are most sensitive in detecting differences in soil fauna

communities when organic or mineral fertilisation practices and standard, reduced or no tillage management are applied.

The impacts of farming practices on soil fauna abundance and diversity were evaluated in nine European Long Term Agricultural Experiments (LTEs) across a gradient of pedoclimatic conditions, employing different tillage systems and fertilisation practices. In autumn 2022, these LTEs were sampled to assess soil health, also on the basis of fauna diversity indices. Specifically, nematodes, microarthropods, and earthworms were selected as representative of micro-, meso-, and macrofauna biodiversity, respectively.

Overall data variability resulted very high, notably that of abundances (coefficient of variation >83% in all cases) probably due to different pedoclimatic conditions. However, it is noteworthy that the abundance data for all micro-, meso-, and macrofauna showed greater overall variation than that showed by both diversity indices and ecological indices, probably due to the aggregate distribution of edaphon. Generalized linear mixed models was applied setting (i) tillage and fertilisation and (ii) LTE sites as fixed and random effect, respectively. Comparison of treatments was complicated by crossing effects, that necessarily reduce the number of direct relations. Both no tillage and reduced tillage showed a greater micro- and mesofauna abundance than in standard tillage. Likewise, the QBS-ar ecological index concerning mesofauna was significantly higher in no tillage than in standard tillage.

Our results suggest that the development and application of appropriate ecological indices not only will facilitate a more accurate and comprehensive evaluation of soil fauna biodiversity, but it will even contribute to the formulation of targeted conservation and to foster sustainable management strategies aimed at promoting long-term soil health.

Keywords: nematode; microarthropod; earthworm; soil health; alpha biodiversity

Comparing soil properties between LUCAS Soil and National Soil Information Monitoring System (N-SIMS): major differences and implications for future policies to evaluate soil quality

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Soil is crucial for life as it provides us food and fibre, regulates water and climate, and hosts thousands of organisms. A recent assessment states that 60-70% of soils in Europe can be considered as unhealthy due to different soil degradation processes. To protect this non-renewable resource at human scale, we first need to acquire knowledge about it and implement soil monitoring to determine the current soil properties, assess the soil status and detect soil changes over time.

In Europe, two types of monitoring networks currently exist in parallel. Many EU Member states (MS) developed their own soil information monitoring system (N-SIMS), some of them in place for decades. Since 2009, a European topsoil monitoring programs has been established by the European Commission based on the Land Use/Land Cover Area Frame Survey (LUCAS) led by EUROSTAT. This survey was repeated several times since 2009 and offers a consistent spatial database. Nevertheless, N-SIMS and LUCAS Soil were established for different purposes with diverging monitoring strategies.

To evaluate soil quality and support European policies, there is a clear need to establish reference values to assess soil health, based on reliable soil data. Consequently, a question remains whether the soil properties obtained by both monitoring programs (N-SIMS and LUCAS Soil) are comparable, and what could be the limitations of using either one dataset or the other.

In the context of workpackage 6 of EJP Soil, a comparison of statistical distribution of three soil properties (organic carbon, pH and clay content) has been conducted among 12 different EU countries including BE, DE, DK, EE, ES, FR, DE, HU, IT, NL, PL, SE and SK. In addition, a comparison of the results of two indicators including soil loss indicator OC/Clay and pH classes using N-SIMS and LUCAS Soil datasets has been conducted. The results underlined substantial differences in soil properties statistical distributions between N-SIMS and LUCAS Soil in many countries, particularly for woodland and grassland soils, affecting the evaluation of soil quality using indicators. Such differences that might be explained by both the monitoring strategy (spatial distribution of sites) and sampling protocols exposes the significance of selecting reliable data to support European and national policies. Those results advocate for a further effort of dialogue between national institutions conducting soil monitoring and LUCAS Soil to strengthen future soil monitoring and provide reliable data to reach the objectives of healthy soils.

High-resolution thematic soil mapping at EU level based on the combined use of LUCAS and national soil monitoring data in the framework of the EJP SOIL project

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The EJP SOIL project aims to provide the research and policy-making community with detailed and harmonised EU-wide thematic maps of agricultural soils, based on a common methodology, to improve the effectiveness of European agricultural and environmental policies, to contribute to European international reporting. Currently the national and the EU reporting are performed independently, which results in contrasting figures on soil status. Since national soil data sharing constraints are in place, a bottom-up approach is preferred to include as much relevant data as possible. However, this can in return, generate transboundary issues.

The specific objective of the EJP SOIL mapping exercise is to set-up a digital soil mapping procedure to: i) support participants in a bottom-up approach allowing countries to produce high-resolution thematic soil maps, ii) develop soil property maps based on the national databases (SIMS) and the LUCAS Topsoil database, iii) solve the problems of transboundary issues, iv) provide spatially explicit uncertainty estimates.

To achieve this, both top-down and bottom-up mapping approaches have been applied, using the same mapping algorithm (quantile random forest) but with different input data: i) EU-level mapping, using the most predictive EU-level auxiliary variables and LUCAS point data ii) country-driven mapping, using a) EU-level auxiliary variables, using national point data (SIMS), b) EU-level auxiliary variables, using both LUCAS and national point data (SIMS), c) the best covariates among EU-level and national covariates, using LUCAS point data, d) the best covariates among EU-level and national covariates, using national point data (SIMS), e) the best covariates among EU-level and national covariates, using both LUCAS and national point data (SIMS).

The spatial resolution chosen for the mapping exercise was a 100 m grid, which implied the production of an EU-wide covariate set at 100 m in INSPIRE-compatible projection by ISRIC. Soil properties commonly observed in both LUCAS and SIMS were selected for the maps, of which the methodologically most consistent pH was mapped first. In parallel, other activities aimed at comparing and developing transfer functions among LUCAS and SIMS are carried out in the EJP SOIL WP6.

Keywords: Digital Soil Mapping, EU-wide covariates, combined monitoring datasets

Harmonized soil biodiversity database to describe ecological status and soil health (MINOTAUR database)

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Existing differences in soil biodiversity data quality and geographic distribution seriously hamper effective use of available knowledge. The MINOTAUR project aims to optimize the data coupling, harmonization and analysis of soil biodiversity from various national and European data sources to support long-term harmonized European soil information and soil health monitoring. A standardized template for each data type was developed to collect soil biodiversity data. Soil biodiversity (macro fauna to microbes) data were collected 59 data sources (dataset, database, data warehouse) and 62 European projects. Collected biodiversity data along with meta-data were assessed and harmonized using standardized templates. The OpenADOM (Open source Application for Data Organization & Management), platform enables the creation of Information Systems (IS) quite rapidly and supports data sharing using FAIR principles. OpenADOM enables to describe the data model using a specific syntax with indentation to represent data structure and nesting. Data from different soil biological

groups (macro, meso and micro fauna, bacteria and fungi) are linked to metadata (e.g. country, soil type, agricultural practices…). So far, macrofauna data were collected from over 9000 samples across 35 European countries. The use of OpenADOM platform allowed the rapid development of an IS for the MINOTAUR database, which otherwise would have been more time consuming considering the diverse set of data and meta-data types to be described and harmonized. The Minotaur database provides valuable information on harmonized soil biodiversity, supporting policy analysis and promoting soil biodiversity in global sustainability efforts.

Keywords: soil biodiversity, harmonization soil information systems, soil health, soil health monitoring, harmonized metadata.

An approach for mapping Net Ecosystem Productivity (NEP) as a pragmatic indicator of soil ecosystem service greenhouse gas (GHG) regulation including carbon sequestration in EU Member States

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Modelling the spatio-temporal distribution of Soil Ecosystem Services (SESs) can provide insights to identify their drivers (e.g., land use, agricultural management), improving our understanding of SESs and their relationships, and the implementation of environmental policies. The SES regulation of greenhouse gas (GHG) fluxes from agricultural soils in EU, would especially benefit from such spatio temporal modelling.

Within SERENA project funded by EJP SOIL EU programme, to fill this gap, we are developing an approach to be included in a cookbook for the estimation of the net ecosystem productivity (NEP Gross primary production, GPP and Ecosystem respiration, R_{eco}) as pragmatic indicator of the GHG

regulation selected in the first stage of the project. The selection was based on the ranking of different types of GHG indicators from a literature review. Based on different criteria (scientific soundness, data availability, and ability to convey information), we were not able to select an "ideal" indicator which provided complete information (such as the sum of all GHG fluxes) for this SES, but instead selected NEP as a "pragmatic" GHG indicator. At the next stage, we realized that methods to estimate NEP based on the analysis of light-use efficiency models were impractical to be implemented by project partners. It was also suggested not to use mechanistic models for assessing NEP since methods should be easily applicable, even without scripting knowledge. Thus, we focused on a newly developed

empirical model that could relate NEP to spatially exhaustive environmental covariates and be applicable with open GIS software. This was done by relating the well-known Fluxnet database of eddy covariance measures to spatially exhaustive covariates for agricultural areas (3600 8-day estimates of CO_2 fluxes). The approach for mapping NEP in EU member states includes three main stages:

1) GPP estimation from Fluxnet stations that grow/have grown wheat in the EU (and one US station) were related to the MODIS 8-days GPP values, monthly average temperature (WorldClim), and a recent high temporal resolution database of daily soil volumetric moisture.

2) R_{eco} estimates from the selected Fluxnet stations were fitted with a thermal performance model to monthly average temperature (WorldClim).

3) The NEP estimate is calculated as GPP-R_{eco}, and after the calculation, there is an additional last step where its finer spatial distribution is made explicit with the EU-2018 crop layer at 10-m resolution, published by JRC, for locations recorded as wheat.

Whereas the fitting quality for each independent component of NEP was relatively good, the overall fitting of the NEP indicator was not. Improvement could be obtained by applying other model fitting techniques (e.g. Gaussian Process Regression), using high-resolution environmental variables (with a weekly step), and trying to incorporate soil properties that have a much lower temporal variability (scales of several years) than the temporal scale of the main CO_2 flux data (weekly, seasonal and yearly). However, such improvements most certainly would come with a cost in terms of cookbook applicability.

Keywords: Soil ecosystem services, greenhouse gas and climate regulation, digital soil mapping, net ecosystem productivity, cookbook

Assessment of temporal dynamics of soil microbial biodiversity on chronosequences: preliminary results

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Soil ecosystems provide habitats for diverse groups of organisms. Monitoring soil biodiversity over the long-term is necessary to identify proper soil management practices and to preserve soil ecosystem services. Archived soil series offer promising opportunities to characterize microbial temporal dynamics. However, soil microbes are usually studied using cryopreserved fresh soils, while almost all archived soils are dried and stored at room temperature.

The aims of the present project are to assess the feasibility of using dried soil samples for the study of microbial biodiversity, to estimate the potential biases compared to frozen samples, and then to use such soils to study the temporal trends of microbial communities in response to environmental changes.

Soil samples were obtained from two long term experiments located in Italy (CREA) and in Slovenia (ULBF). These soils were subjected to different management practices, and were collected in 2011 (or 2012), stored both as frozen and dried (oven-dried or air-dried). Thereafter, the same soils were collected in 2022 and again stored frozen and dried, though for a shorter period of time (7-8 months). DNA was extracted from all these samples and used to quantify the abundance of bacterial functional genes, for sequencing of bacterial V3-V4 16S rDNA to assess the bacterial composition and will also be used for enzymatic analyses.

For CREA samples, we observed no effect of storage conditions on bacterial communities, while the effects of tillage and sampling year were prominent. Conversely, for ULBF, different storage methods influenced the composition of the bacterial communities, while the effect of the different tillage practices resulted masked. It is possible that different physicochemical soil properties or the different soil drying procedure might determine a different preservation of bacterial DNA in dried soils.

Future perspectives include evaluating the effects of different drying procedures and studying the enzymatic activity of these soils, to better understand the potential use of archived dried soil samples for soil biodiversity monitoring.

Keywords: soil archive; soil microbiota; microbial DNA; biodiversity monitoring

The EJP SOIL ARTEMIS framework for on-farm monitoring of the impact of agroecological systems on soil quality and soil ecosystem services

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Agroecology represents an agricultural approach that focuses on sustaining productivity while optimizing local resources and mitigating negative environmental and socio-economic impacts. Understanding the efficacy of agroecological systems and promoting their adoption necessitates comprehensive monitoring, encompassing socio-economic and environmental factors, soil quality, and associated ecosystem services. Through approaches such as soil health assessment, ecosystem services assessment, and farmer participatory monitoring, we can evaluate the outcomes of agroecology and make informed decisions to support sustainable agricultural practices. Integrating these methodologies into on-farm assessments further enriches our comprehension and application of agroecology since it allows for the inclusion of a more diverse, and thus more realistic, set of employed agricultural practices.

Within ARTEMIS WP5, our objective is to devise a monitoring framework comprising direct and indirect indicators and tools tailored for on-farm monitoring of soil health and soil-related ecosystem services. This framework aims to ascertain whether implemented agroecological practices can sustain or enhance soil health and soil-related ecosystem services. Recognizing the vast array of ecosystem services offered by soil and the multitude of management options, we conducted an inventory of soil

and management-related ecosystem services, categorized according to Paul et al. (2021), and solicited input from WP partners to rank their relevance to the scope of ARTEMIS. To refine and select indicators, we disseminated an inventory of potential soil and plant indicators, along with relevant properties for monitoring the impact of agroecological practices. These indicators were evaluated and ranked by WP partners to facilitate on-farm assessments.

The final goal of the monitoring framework task is to provide a catalogue of direct and indirect (e.g. remote sensing products, models, and tools) indicators for monitoring soil health, while also establishing correlations between these indicators and specific soil-related ecosystem services. Drawing from inventory rankings and consultations with farmers and agroecology experts, we have identified a list of direct indicators and significant ESS for inclusion in ARTEMIS. These indicators serve as a foundation for ongoing monitoring efforts in selected farms, fostering a basis for a long-term assessment and monitoring farm network.

Keywords: Ecosystem services; soil health, agroecology, indicators

Scientific indicators and stakeholders' perceptions on soil threats in France: how do they compare?

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Soils are under multiple threats on a global scale, with varying levels of intensity and nature in different regions. Therefore, it is crucial to assess soil threats at a local level using specific indicators. Scientific indicators have been developed to accurately assess soil health, yet they can be challenging to implement at a local scale. As some stakeholders have a good knowledge of soil condition, the objective of this paper is to determine whether stakeholders' perception of soil threats can be used as a complementary indicator. The study focuses on five soil threats: erosion, artificialisation, compaction, soil organic carbon (SOC) loss, and contamination. It is based on 1,951 responses from a participatory stakeholder consultation conducted in France in 2021. We explored stakeholders' prioritization of soil threats and elaborated perception maps at the departmental scale. We then compared stakeholders' perception maps with scientific indicator maps per soil threats at the departmental scale. Our findings indicate that stakeholders consider artificialisation to be the most important threat in France. The spatial distribution of soil threats based on stakeholders' perceptions and scientific indicators matches in 43% of the departments for SOC loss, and in over half of the departments for erosion (50%), artificialisation (63%), compaction (57%), and contamination (74%). However, disparities remain in certain departments and depending on the threat. These disparities can be explained by biases in the used indicators (scientific or stakeholders' perception) or in the comparison. It can be concluded that, when these biases are taking into consideration, stakeholders' perception can be used as an indicator for soil threats and can supplement existing scientific indicators.

Keywords: Multi-actor consultation; Soil challenge; Soil degradation; Soil health; Stakeholder perspective

SoilManageR – An R package to derive soil management indicators

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Sustainable agricultural soil management is essential for restoring, maintaining, and enhancing soil health. Many studies investigating soil management focus on comparison of single management factors (e.g., no-till vs conventional tillage, with and without cover crops), thereby overlooking other management differences that could also be crucial. Moreover, on-farm studies have revealed that classifying fields into broad categories such as organic, no-till, and conventional systems can obscure significant management variations within each category (Büchi et al., 2019). Transforming nominal management data into continuous soil management indicators offers an approach to analyse gradients in soil management intensities. While an increasing number of studies are adopting soil management indicators, the comparability of results across studies is hindered by the lack of standardized management data and readily available tools for calculating management indicators.

To tackle these limitations, we developed the SoilManageR package for R. This package includes routines for deriving numerical management indicators and a comprehensive template for collecting management information in different contexts (field experiments, monitoring programs, farm networks). The current version of SoilManageR incorporates indicators for estimated soil carbon input, tillage intensity, soil cover, nitrogen fertilization intensity, and livestock integration, with the potential for further indicators to be added in the future. The routines allow to work with different levels of data availability and the package contains tables with default values that were extracted from the literature to represent the conditions of temperate agro-ecosystems.

We illustrate the utility of the SoilManageR by comparing soil management between Swiss agricultural long-term field experiments and management data collected in different on-farm networks. Additionally, we demonstrate that the soil management indicators are closely correlated with differences in earthworm populations and soil organic carbon contents.

Keywords: soil organic carbon input, tillage intensity, soil cover, long-term experiments, monitoring, on-farm studies

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New soil quality monitoring tools in the Soil Web Portal of Sardinia (Italy): automatic calculation of SEs at regional scale

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Keywords: ecosystem services; quality indicators; soil quality monitoring

According to the definition of the MEA - Millennium Ecosystem Assessment (2005), Ecosystem Services (ES) are "the benefits that people obtain from ecosystems" and can be divided into four broad categories: life support, provisioning, regulation and cultural values, the latter category not addressed in this paper.

This study addressed how to calculate the SEs of Sardinian soils through the determination of suitable pedofunctions applicable at the regional level, in line with other European soil protection projects, including the SOIL4LIFE - Save Our Soil For Life project, which focuses in particular on the quantification of soil Ecosystem Services (SEs).

Good knowledge of the soil characteristics of the territory, supported by adequate data availability, was the starting point for this study, which made it possible to standardise SEs assessments on a regional scale and introduce new tools for monitoring soil quality.

The main source of information for the analysis carried out was provided by the more than 5,000 pedological data in the Sardinian Soils Database (DBSS), the actual engine of the Sardinian Soils Web Portal, which made it possible to normalise the SEs on a regional scale and standardise the pedofunctions developed.

Eight ecosystem services provided by soil were considered in the study: BIO - biodiversity of soil organisms, BUF - purification capacity, CLI - effect on microclimate, CSP - potential carbon stock, PRO - agricultural productivity, SUP - infrastructure support, WAS - water storage and WAR - deep water infiltration.

Each service was described by means of indicators based on measured (or quantitatively estimated) properties, which were then standardised from 0 to 1 for the entire regional territory so that they

could be used in different spatial contexts. Subsequently, a Soil Quality Index IQ, obtained as the sum of the indicators, was determined in order to have a summary picture of the provision of the SEs.

The automatic SEs evaluation method thus obtained represents an important step forward in the management and conservation of natural resources.

Furthermore, the integration of these new algorithms for the automatic calculation of SEs into the Sardinian Soil Web Portal provides easy and transparent access to soil information for researchers, farmers, planners and other interested stakeholders.

In summary, the DBSS and the Sardinian Soils Web Portal play a key role in providing reliable data and assessment tools to support spatial planning and natural resource management, thus contributing to the environmental sustainability and socio-economic development of the region.

Adaptability of tillage practices for waterlogging risk reduction on two soil types with different texture

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The occurrence and severity of extreme meteorological events is predicted to increase even under moderate climatic conditions. This situation is the reason to revise management practices adaptability in different soils. A high amount of water during crop vegetation and post-vegetation period may involve the risk of short- and long-term waterlogging on glacial till.

Four field trials were carried out on loamy *Dystric-Epihypogleyic Retisol ((Retisol* (L)*), Endocalcari-Epihypogleyic Cambisol ((Cambisol* (L)) and *Cambisol* (SL) of morainic genesis and on clayey *Endocalcary-Endohypogleyic Cambisol* ((*Cambisol* (CL/C)) of limnoglacial genesis in Lithuania. Three contrasting tillage practices were investigated in each of the experiment: 1) CT - Conventional tillage (stubble cultivation + deep (20-22 cm) mouldboard ploughing + presowing shallow cultivation), 2) RT - Reduced tillage (shallow stubble cultivation + presowing shallow cultivation), and 3) NT – no soil disturbance in *Cambisol* (i.e. direct sowing) or shallow (12-14 cm) mouldboard ploughing (ShPL) in *Retisol*.

Data revealed that the values of soil structure (water stable aggregate (WSA) and the ratio between large pores which enable water movement and storage (i.e. macropores and mesopores) and micropores) were lower in limnoglacial than in morainic soils. The increase in clay content significantly affected the increase in soil aggregate stability from topsoil to a deeper layer in the *Cambisol* (L, SL and CL/C) only. Hydraulic conductivity (Ks) significantly correlated with water saturation in morainic but not in limnoglacial soil. The increase in WSA contributed to increase in Ks by sequence from deeper to upper layer in morainic *Retisol* (L) only. The increase in clay content decreased water saturation in all soils and decreased Ks in morainic soils by sequence from upper to a deeper soil layer. The action of soil organic carbon (SOC) as driving factor for Ks was clearly pronounced in fine-textured soils rich in silt and clay (*Retisol* (L) and in *Cambisol* (CL/C)). The decrease in SOC content contributed to decrease in Ks by sequence from upper to deeper layer. SOC in morainic *Cambisol* (L and SL) acted as indirect factor. Ks and water flow character determined adaptability of different tillage systems. Thus,

considering to possible climate change threats, the controlling of soil management intensity allows maintaining soil physical quality and environment sustainability. Reduction of management intensity is advisable by increasing the sequence of benefits: *Cambisol* (CL/C) → *Retisol* (L) → *Cambisol* (L) → *Cambisol* (SL). On *Cambisol* (CL/C) the long-term CT, on *Retisol* (L) the ShPL, on *Cambisol* (L) the RT and on *Cambisol* (SL) the long-term NT management could be considered as the tillage practices being suitable to prevent waterlogging condition.

Keywords: soil aggregation, water permeability, organic carbon, clay

An innovative approach based on machine learning and satellite data to assess the impacts of land-use change in Europe on soil carbon sequestration

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Keywords: LUCAS 1; Corine Land Cover (CLC) 2, SOC stock, land-use change 3, Soil Carbon Sequestration 4.

Understanding and evaluating the impact of land use changes on soil carbon stocks is essential for developing effective strategies to devise strategies that balance the demands of food security, biodiversity conservation, and greenhouse gas emissions. Countries need robust data to set realistic targets, track progress, and implement policies that contribute to global carbon reduction goals. One of the main challenges in estimating the impact of land use change on soil carbon sequestration is the large measurement uncertainty, mainly caused by limited availability and quality of soil carbon data (Somarathna, Minasny, and Malone 2017; Chen, Smith, and Yang 2015; Stanley et al. 2023). To resolve this issue, we estimate the impact of land use change on soil carbon across Europe, by leveraging field data from LUCAS survey and satellite data from Corine Land Cover (CLC). The LUCAS program, by conducting ground observations at approximately 22,000 diverse land cover points across the EU, stands as the most extensive and uniform topsoil data collection initiative in the European Union. To overcome the short duration of land use history of LUCAS, we train a machine learning model to predict land use since 1990, based on CLC data. We use this novel dataset to produce upscaled estimates of SOC response over time to LUCS with high precision across EU. We then use the estimates to publish country specific emission factors, compliant with the IPCC guidelines and the LULUCF Regulation, and ready for use in national GHG inventories. In assessing Soil Organic Carbon (SOC), we leverage topsoil samples from the years 2009, 2015, and 2018, a 10% subset of the LUCAS survey more generally aimed at monitoring land use change. For changes in land use, our methodology encompasses data from five sequential waves of the LUCAS survey in 2006, 2009, 2012, 2015, and 2018. However, it may take decades for carbon sequestration to achieve equilibrium (Poeplau et al., 2011). To augment the temporal and spatial

scope of our carbon response analysis, we adopt a machine learning model to fit Corine Land Cover (CLC) on LUCAS data. The trained model was then used to predict missing values on land use based on CLC data since 1990, and detect probable land-use changes having occurred between 1990 and 2006. We then derive the carbon response function following land use change and provide country-specific guidelines for assessing the impacts of land use change on carbon response.

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SOIL-ES: a methodological proposal for evaluating soil ecosystem services at multiple scales for South American countries.

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Soils can offer multiple benefits to humans, through all their ecosystem functions and flows, relating to water, climate, biodiversity, and food production, known as Soil Ecosystem Services (SES). Comprehensive tools on how soil management practices and land use and land cover (LULC) changes affect SES and the consecutive benefits for society are essential to subsidize consistent decision-making. Due to their importance, we proposed and approved the project titled: *"Soil ecosystem services under sustainable intensification of agriculture: looking for innovative mapping and monitoring at multiple scales (SOIL-ES)"*. It aims to develop and adapt protocols for assessing SES at multiple scales, in intensive agricultural production areas in South American countries (Brazil, Colombia, Argentina and Uruguay). The SES and indicators being evaluated are: food provision (agricultural productivity), climate regulation (carbon stock), water regulation (water infiltration), erosion control (soil structure) and biodiversity maintenance (enzymes). The main land uses are: conventional soybean, integrated production systems (soybean-corn-pasture), conventional pasture, well-managed pasture, coffee and agroforestry. At the local scale, soil samples are being collected and analyzed; at the watershed scale, remote sensing and modeling tools are being used (for example, the InVESTt software); and at the regional scale, an SES zoning is being developed, based on soil types and natural or anthropic characteristics of the landscape. The project began a year ago and therefore does not yet have conclusive results.

National soil data in EU countries, where do we stand?

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At the European scale, soil characteristics are needed to evaluate soil quality, soil health and soil-based ecosystem services in the context of the European Green Deal. While some soil databases exist at the European scale, a much larger wealth of data is present in individual European countries, allowing a more detailed soil assessment. There is thus an urgent and crucial need to combine these data at the European scale. In the frame of a large European Joint Programme on agricultural soils launched by the European Commission, a survey was conducted in the spring of 2020, in the 24 European participating countries to assess the existing soil data sources, focusing on agricultural soils. The survey will become a contribution to the European Soil Observatory, launched in December 2020, which aims to collect metadata of soil databases related to all kind of land uses, including forest and urban soils. Based upon a comprehensive questionnaire, 170 soil databases were identified at local, regional and national scales. Soil parameters were divided into five groups: (1) main soil parameters according to the Global Soil Map specifications; (2) other soil chemical parameters; (3) other physical parameters; (4) other pedological parameters; and (5) soil biological features. A classification based on the environmental zones of Europe was used to distinguish the climatic zones. This survey shows that while most of the main pedological and chemical parameters are included in more than 70% of the country soil databases, water content, contamination with organic pollutants, and biological parameters are the least frequently reported parameters. Such differences will have consequences when developing an EU policy on soil health as proposed under the EU soil strategy for 2023 and using the data to derive soil health indicators. Many differences in the methods used in collecting, preparing, and analysing the soils were found, thus requiring harmonization procedures and more cooperation among countries and with the EU to use the data at the European scale. In addition, choosing harmonized and useful interpretation and threshold values for EU soil indicators may be challenging due to the different methods used and the wide variety of soil land-use and climate combinations influencing possible thresholds. The temporal scale of the soil databases reported is also extremely wide, starting from the '20s of the 20th century.

Keywords: survey; soil, data, indicator

Comparison of national and LUCAS soil datasets for soil health mapping and assessment

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Soil is a vital and dynamic component of our planet's ecosystem, and its health plays a fundamental role in sustaining life. Assessing soil health requires data and ways of interpreting the results. In this study, we focused on national and LUCAS datasets comparison for assessing and mapping soil health using pH as an indicator and a scoring function. Using mainland France as a pilot, we used the national RMQS dataset (2145 points) and the LUCAS dataset (2930 points) for the digital mapping of pH in combination with environmental covariates and a machine learning approach. A concept of soil districts (pedo-climatic zones) was implemented through stratification using soil, land use and climate types. We developed scoring functions based on mean, standard deviation, and Z scores using predicted pH values within each unique soil district. The “optimum is best” type of soil scoring function was used for health assessment. Our findings demonstrated that although spatial patterns of soil health levels were similar using both datasets, some regions still showed opposite results. These first set of results will be completed with other parameters such as SOC and developed within other countries. It also demonstrates the importance of appropriate choice of datasets in national soil health assessments.

Keywords: soil health, LUCAS, soil quality, digital soil mapping

The advantage of a dense grid: Comparing LUCAS Soil and the German Agricultural Soil Inventory regarding the distribution of soil organic carbon

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As part of the EJP SOIL project, work package (WP) 6.3 aims to develop a harmonized, reliable soil database for Europe. Data of national soil inventories were compared with the Land Use and Coverage Area frame Survey (LUCAS) Soil. The first nationwide Agricultural Soil Inventory in Germany (BZE-LW) had the goal to analyse soil parameters, such as soil organic carbon (SOC), texture, pH and determine the influence of site factors and management, e.g., tillage, fertilizer and crop rotations. Between 2011 and 2018, soil samples for chemical and physical analyses were collected at 3104 agricultural sites (2233 croplands, 819 grasslands, 50 permanent crops) in Germany using a systematic random approach (8 km x 8 km grid). Sampling was carried out in a profile pit with sampling depths of 0-10, 10- 30, 30-50, 50-70 and 70-100 cm. A multi-stage, stratified random sampling approach was chosen for LUCAS Soil. In the second LUCAS inventory (2015), 1274 German agricultural soils (816 croplands, 411 grasslands, 20 permanent crops) were sampled to a depth of 20 cm.

To align with the sampling depth of LUCAS Soil, the mean SOC content for the 0-20 cm layer of the BZE LW dataset had to be estimated, which was done by a mass-weighted averaging of the 0-10 cm and half of the 10-30 cm layer. In general, the SOC content and the density distribution of SOC of both inventories was similar. The average SOC content in croplands was in BZE-LW (17.4 g kg^{-1}, +/- 15.2 g kg^{-1}) and LUCAS Soil (17.4 g kg^{-1}, +/- 14.5 g kg^{-1}). For grassland the values differed insignificantly with 57.8 g $kg^{-1}$for BZE-LW, and 52.3 g $kg^{-1}$for LUCAS Soil.

A digital soil mapping exercise was performed to evaluate the difference in spatial prediction based on BZE-LW and LUCAS Soil samples. Certain regions, such as the grassland dominated Pre-Alps in southeast Germany, differed systematically. Across the entire region, SOC contents were displayed significantly lower in the LUCAS Soil map than in the BZE-LW map. As the sampling grid of the BZE-LW is more balanced and denser, a more detailed prediction of SOC was possible. The multi-stage, stratified random sampling of LUCAS Soil might thus have a critical disadvantage for regionalization approaches with high spatial resolution. A higher quality of creating SOC maps is shown in the BZE-LW map with a systematic random sampling approach.

Keywords: digital soil mapping, soil monitoring systems, soil organic carbon

Towards soil health assessment establishing a unified framework for monitoring soil microbial diversity across Europe

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Healthy soils play a crucial role in providing essential ecosystem services, such as food supply and climate regulation. With the ultimate aim of having all soils in healthy condition by 2050, the European Commission (EC) has recently proposed a Soil Monitoring Law. One of the key indicators of soil health is the diversity and resilience of its microbial communities. To facilitate the monitoring of soil health across Europe, in 2009, the EC's Joint Research Centre (JRC) initiated a large-scale soil survey named LUCAS Soil (European Land Use and Coverage Area Frame Soil). Since 2018, LUCAS Soil has expanded its scope to include the biological component.

In this context, a lack of evaluation in the comparability of biodiversity data obtained from LUCAS Soil and individual EU Member States is still present. Discrepancies may arise due to various factors, including sampling procedures and computational analysis methods.

As part of the European Joint Programme on Soil (EJP SOIL), efforts are underway to compare the JRC's approach with national strategies for biodiversity assessment. The main objectives are to harmonize the analytical procedures and define standard methodologies for soil health monitoring. In particular, our work aims to assess the impact of different sampling procedures on soil microbial analysis by comparing LUCAS method with a national approach (Italy).

In 2022 LUCAS campaign, the JRC collected 98 fresh soils samples in Italy. Among these, 17 sites were also sampled following the Italian strategies. Soil DNA was extracted from all samples and bacterial 16S (V3-V4 rDNA) and fungal ITS2 regions were sequenced and analysed following the Italian pipeline.

Preliminary findings suggest that environmental variables (e.g., land cover) exert a significant influence on the structure of soil microbial communities, while the sampling strategy itself has minimal or negligible effects. Further comparisons will be made between Italian and JRC soils once they will be sequenced and analyzed following LUCAS' pipeline. That will allow to evaluate the impact of different analytical methods, like DNA sequencing targets and bioinformatics strategy.

Our work aims to contribute to the establishment of standard procedures in both national and European soil monitoring schemes. Additionally, it provides valuable insights for data comparison and harmonization, overall promoting the advancement of soil health monitoring.

Keywords: soil sampling; soil microbiota; data harmonization; Europe

The influence of covariates and sample density on digital soil mapping performance at a national scale

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In the context of Global Soil Nutrient and Nutrient Budget maps, the FAO Global Soil Partnership (GSP) initiated a country-driven digital soil mapping (DSM) approach. This involved predicting ten soil properties using national point data and a set of widely available covariates (GSP_Cov). In this study we demonstrated the impact of including additional national-based covariates and soil observations on prediction model performance, using mainland France as a pilot area. A Random Forest approach combined with the Boruta selection method was employed to map ten soil properties, including soil organic carbon, pH (water), total nitrogen, available phosphorus, available potassium, cation exchange capacity, bulk density, and texture (clay, silt, and sand). The GSP_Cov included common covariates representing terrain, climate, and organisms, whereas the second set included these covariates extended to additional national-level data such as existing soil and geological maps, remote sensing products, etc. Results showed notable enhancements in prediction performance for more than half of the properties, particularly for pH, CEC, and texture, whereas geological variables and previous pH maps significantly improved accuracy. Adding around 25,000 points to the learning dataset improved the performance of soil particle-size fraction predictions. This research emphasizes the importance of incorporating a diverse range of covariates at a national scale and densifying soil information to expand the feature and geographical spaces of multidimensional soil/covariates combinations.

Keywords: digital soil mapping, spatial covariates, sampling size, random forest