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Block A

A1 Carbon sequestration at national and European scale and effects of policy and socio-economic factors

Session Description

Involved projects: CarboSeq, SIMPLE

Conveners: Muhammad Mehran Anjum (Agroscope), Felix Seidel (Thuenen)

Soil carbon sequestration is the net removal of carbon dioxide from the atmosphere and could make an important contribution to climate change mitigation. The key for carbon sequestration in soils is to reach a positive balance between carbon inputs and outputs. This can be achieved through improved land management towards increased soil carbon accrual through enhanced inputs of organic matter or through reducing decomposition rates of C in the soil (i.e. by adding C in more stable forms). Such measures are affected by bio-physical (e.g. soil type, climate) and technical constraints (e.g. irrigation). Thus, a differentiated analysis at national and European scale is necessary to assess the true potential of optimized land management to achieve carbon sequestration in soils when implemented on large scale.

In addition to these factors also policies like the Farm to Fork strategy of the EU could potentially have effects on soil carbon sequestration. To reduce nutrient losses from agricultural soils, a reduction in fertilization is foreseen. Likewise socio-economic effects like increasing fertilizer prices or changes in diets could affect soil carbon stocks and/or accrual. To assess potential co-benefits or trade-offs, system boundaries need to be expanded. This allows to include indirect effects on soil carbon stocks and/or accrual through e.g. changes in yields or crop types.

In this session, we welcome contributions that give insights into the topic of carbon sequestration in soils on European and national scales as well as studies that discuss carbon sequestration in soils in a broader context.

A first glance at carbon sequestration potentials of agricultral measures at European scale from the CarboSeq Project

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In order to estimate a feasible carbon (C) sequestration potential in European agricultural soils, we need to know the area where additional measures that increase soil organic carbon (SOC) can be implemented and the corresponding SOC accrual rates. This will allow us to understand how effective which measure is on European scale.

The practices considered include a higher share of agroforestry, cover crops replacing bare winter fallows, crop residue management, reduced and no-tillage instead of ploughing, the integration of perennial legumes and leys into crop rotations, biochar application and irrigation. Open-access data of European Farm Structure Surveys as provided by EUROSTAT at NUTS2 level serve as a reference for the intensities at which the measures are already implemented in Europe. Only areas where these measures could be additionally implemented were considered.

For the first time, we will bring these measures, their area of implementation and the linked C accrual rates together and show for some measures a feasible C sequestration potential across Europe which is one of the key outputs of the CarboSeq project.

Increasing the share of forage leguminous crops in the crop rotation positively affects the soil organic carbon stocks – Analysis of European LTEs

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The storage of soil organic carbon (SOC) is subject to human influence through various management options. By adopting appropriate land management practices, agricultural systems can contribute to mitigate climate change by reducing carbon (C) loss from soils or even sequester C in soils. This can be achieved by promoting practices that enhance C inputs to the soil and improve the quality of these inputs, thereby facilitating the removal of atmospheric carbon dioxide, or by reducing C turnover. In this study, we investigate crop rotation options utilizing legumes, identifying their potential for SOC accrual. We propose regression equations, serving as emission factors, to quantify this potential, based on data from mid- and long-term field experiments conducted across Europe. Furthermore, we analyse soil inherent properties, environmental factors, and management practices to evaluate their impact on these emission factors. Our findings indicate that incorporating and/or increasing forage

leguminous crops in the rotations leads to SOC accrual, in contrast to the inclusion of grain legumes. Additionally, our observations suggest that the crop growth duration (annual or multi-annual) does not exert a significant impact on SOC accrual. From the evaluated management and pedoclimatic factors, the climatic zone in which the system is located significantly influences the SOC stocks. Overall, integrating forage legumes in a cropping system can enhance its sustainability and presents a viable option for climate change mitigation.

Keywords: EJPSoil CarboSeq, emission factor, leys, alfalfa, soil organic carbon

Effect of anthropogenic soil management for increasing soil organic carbon status in Lithuanian acid soil

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Soil organic carbon (SOC) represents the largest carbon supply in terrestrial environments making carbon sequestration in them crucial to global climate regulation, food production, nutrient supply, and the control of erosion. For this reason, it is the primary objective of current research and a key subject in soil science. As soils are the largest carbon sink in the world, even little changes there can have a significant impact on the global carbon cycle. Over the last few decades, particularly the last ten, there has been an increase in scientific interest in soil conservation techniques like minimal/no-till agricultural activities, fertilization with both organic and inorganic amendments, and residue retention that aim to improve soil organic carbon and natural soil fertility. Reasonable management practices, especially sustainable fertilization, are urgently needed to enhance the carbon sequestration capacity of acid soils, which could improve soil quality and mitigate climate change. This study aimed to achieve following objectives: (1) analyse the alterations in SOC caused by the various management techniques in Lithuania's acid soil; (2) estimate and compare the effect size of different agro-techniques on SOC sequestration and other chemical parameters in acid soil; (3) determine an appropriate management practice benefiting for SOC sequestration and improving soil quality.

Comparison of data from three long-term studies, carried out in the western region of Lithuania, on physicochemical indicators served as the basis for the study. Over the past 24 years (1999-2023), changes in the properties of the soil have been identified. The most widely used practices in Lithuania, including tillage, residue maintenance, manuring, and soil liming, have been chosen for analysis. The analysis of soil organic carbon sequestration indices of studied agricultural practices ranked as: manuring > residue management > reduced tillage > liming (in the direction of carbon transformation and sequestration). The results of this study showed that long-term fertilization approaches could raise the SOC content in acid soils in Lithuania, and that organic fertilization in combination with liming accumulate more SOC compared to other techniques. Assessment of the relative annual change of SOC content indicated that long-term soil fertilization had considerable SOC sequestration potential. The mean effect size of SOC and other investigated soil parameters was largest under manure fertilized limed soil treatment. This finding indicated that the combination of liming and organic fertilizers was a relatively effective measure to improve soil quality. In general, conducted analysis provide an in-depth quantitative assessment of the effects of management practices on SOC

content and other parameters, which could assist in further understanding the feedback of SOC to agricultural management practices and offer evidence in support of the preservation of the acid soil.

Keywords: soil organic carbon transformation 1; agricultural management practices 2; soil quality 3; response ratio 4; acid soil 5

Some indicators of organic carbon status in Norwegian agricultural soils

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Diverse pedoclimatic zones lead to large variations in soil organic carbon (SOC). Key questions involve how much carbon the soil contains, what is its potential for more storage and whether levels are sufficient to maintain soil structure stability (SSS). We evaluate current SOC levels using ratios of clay/silt fractions to SOC, to identify potential SOC storage areas and to gauge likely SSS status.

SOC retention is affected by clay and silt, which protect it from microbial activity. Hassink (1997) used the ratio of clay plus silt <20 µm (fines20) to SOC to indicate this relationship, whilst Dexter et al. (2008) used the ratio of clay to SOC. Jensen et al. (2019) found critical ratios for SSS to be ~10 for clay/SOC and ~20 for fines20/SOC, above which SSS is impaired and below which SOC is less likely to be retained. These ratios appear valid under Norwegian conditions, where greatest declines in SOC have been found in soils with high initial SOC levels and lowest declines in clay soils (Riley & Bakkegard 2008).

After 28 years of a cropping system trial in eastern Norway (Riley et al. 2022), equilibrium between SOC gains and losses was at a fines20/SOC ratio of ~18, whilst in the same trial SSS declined sharply in an arable cropping system with a clay/SOC ratio >10, compared to systems with ratios of 6-8. In western Norway, on grassland soils with generally low fines20/SOC ratios, SOC appears to be declining despite manure inputs, especially in cases with high initial SOC levels (Rittl et al. 2023). To obtain insight into the potential for SOC across Norway, data was used from a study in which SOC and soil texture was analysed on 600 fields in agricultural districts throughout the country. Results are grouped into 13 regions with relatively uniform climate and cropping within each.

Greatest proportions of fields with high ratio levels were found in regions around Oslo and east of Oslofjord, with predominantly clay and silty clay loams, where 65% of fields had clay/SOC >10 and 80% had fines20/SOC >20. Proportions of fields with fines20/SOC >20 were somewhat lower west of Oslofjord (65%) and in central Norway (44%), where many soil textures are found, and in an inland region with predominantly silty soils (55%). Proportions of fields with high ratio levels were low in inland regions with loam soil, where 15-20% had clay/SOC >10 and 24% had fines20/SOC >20. All these regions are mainly arable, with some livestock, and mean SOC levels are <3,0%.

In the predominantly grassland/livestock regions of southern, western and northern Norway, and in upland areas, the soils are mostly sandy and silty loams, and mean SOC levels are mostly >3,5%. In these regions, the proportion of fields with clay/SOC >10 was below 5% whilst that of fines20/SOC >20 was below 10%. Mean clay/SOC ratios were 1-3 and mean fines20/SOC ratios were 4-10. Arable land has thus greater potential for carbon storage than grassland, whilst at the same time increasing SSS and reducing erosion risk.

Keywords: texture; arable; grassland; storage; stability

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Assessing soil carbon sequestration in the Netherlands by enhancing a dynamic soil organic carbon turnover model using Earth Observation data

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As part of the climate mitigation plan, the Netherlands aims for an additional CO_2 sequestration of 0.5 Mt in mineral agricultural soils by 2030. Besides climate mitigation, soil organic carbon (SOC) can also enhance the resilience and fertility of the soil. However, monitoring SOC stock changes is difficult on the short term, because the changes are relatively small compared to the stock. Dynamic organic carbon turnover models can solve this problem by assessing SOC stock changes over longer time periods. The RothC model is a scientific, widely adopted SOC turnover model that requires relatively little input data that is often available at field level. Assumptions in the input data were made running the model at national level in the Netherlands, but these assumptions seems to be quite rough when running the model at field level. Making use of Earth Observations (EO), which can provide additional information on vegetation cover, the growth period of cover crops, grassland renewing, and crop production, can help improving the input data. This study shows the effect of replacing some input data of the RothC model by EO. The model runs for time period 2018-2023 (i.e. 6 years) for the whole of the Netherlands at varying spatial resolution (i.e. at postal code level for ~3400 units and parcel level for ~500.000 parcels). When weather data were fixed, the effect of land management became more clear. Being able to assess the carbon balance at field level for the entire country brings opportunities, but also challenges for national and regional policy makers as well as for farmers. In a later stage, the adapted RothC simulations will be validated against soil C-measurements taken in approximately 100 fields as part of the national soil sampling campaign of 2018 and 2024.

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The effect of a business-as-usual scenario on the evolution of the soil organic carbon stocks in Flanders' arable fields

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Soils play an important role in the carbon cycle and carbon farming practices could significantly contribute to mitigating climate change by ensuring soils become C sinks. In Flanders, there is uncertainty regarding the impact of current soil management practices on the evolution of soil organic carbon (SOC) stocks in arable fields. The objective of this study was to simulate the evolution of the SOC stocks under current management practices across all arable fields in Flanders using a Roth-C based model. This model was tailored for Flanders by adjusting the method for calculating the C-inputs coming from crops and organic amendments and by implementing a simple initialization method to increase its efficiency. The simulation required data on the climate, crop rotation, fertilization and soil characteristics. In Flanders, detailed information on crop rotation, including cover crops, from the Land Parcel Identification System (LPIS) is made publicly available by the government of Flanders. This data layer also contains historical agricultural field information. Additionally, a map for the SOC stock and soil texture is publicly available in the Flemish soil database (DOV). Data on organic fertilization was obtained from the fertilization allocation model (BAM) used by the Flemish Land Agency to allocate the amount and type of fertilization to a field based on certain calculation rules in function of the crop type, type of farm and soil type. All necessary data layers were collected and processed to allow parcel level implementation of the Roth-C based model across Flanders. The output of this simulation will be used as a baseline for scenarios involving the implementation of management practices beneficial for carbon sequestration, as well as scenarios simulating crop rotation changes in arable fields.

Keywords: carbon sequestration; Roth-C model, carbon farming

APPLYING A TRADE-OFF ANALYSIS AT THE EUROPEAN SCALE TO QUANTIFY EFFECTS OF REDUCED FERTILIZATION ON ECOSYSTEM SERVICES OF SOILS

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Agricultural soils provide a wide array of ecosystem services that need to be maintained and enhanced to improve the sustainability of agricultural production. Building on soil carbon sequestration rates provided by the EJP SOIL project CarboSeq project, we expand the potential for climate-smart soil management through reductions in nitrogen fertilization rates to comply with the EU's Farm to Fork Strategy. To assess potential trade-offs on soil carbon storage we are setting up a modelling framework that allows to quantify effects of 20 % lower mineral nitrogen fertilization rates on crop yields, soil organic carbon (SOC) stocks, nitrous oxide (N2O) emissions and nitrate (NO3) losses. We will apply the SOMMIT Index that was developed within the EJP SOIL project SOMMIT for trade-off analysis with four trade-off components: yield, SOC, N2O and NO3 (Calone et al. 2024). Our results will offer a quantitative assessment of the trade-offs among these components, presenting a comprehensive evaluation of reduced fertilization. We will obtain SOMMIT Index values for main crops grown in Europe and for different pedoclimatic conditions that will indicate the overall desirability/effectiveness of reduced fertilization. Additionally, three narratives will be used to evaluate the results considering varying perspectives. For this purpose, different weighting schemes for young farmers, an agro-chemical corporation and an environmental agency will be applied. Based on the results policy recommendations will be formulated.

Keywords: trade-off components, Nitrogen fertilization, soil organic carbon, greenhouse gas emissions, modelling

Roadmap for improvement of carbon sequestration in the Netherlands

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In the Netherlands, the government has set goals for climate mitigation and soil health regarding agricultural mineral oils. Measures for carbon sequestration in these soils are important for reaching these goals and were studied in the past five years in the research program Smart Land Use. The results show that it is possible to reach the climate goals for Dutch agricultural mineral soils, but proper implementation of the measures is important. To determine which actions are necessary to reach sufficient implementation, a roadmap has been composed to set the focus of the research in the follow up of Smart Land Use in the period 2024 – 2026. The roadmap takes into account the policy goals, the role of research, the role of farmers and other stakeholders. The roadmap covers the period until 2030, where the policy goals should be reached.

Several outcomes have been identified that contribute to the goals. The main focus of these outcomes is towards placing measures in a complete farm set up, which provides farmers with perspectives on how to implement carbon sequestration at farm level on the long term.

In this poster, we will present the roadmap.

Keywords: roadmap**,** carbon sequestration, mineral soils, climate mitigation, soil health

Sensitivity analysis of a Roth-C based model

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The Belgian Soil Organic Carbon Calculator (BeSOCC) is a Roth-C based model specifically developed for Flandersto simulate the evolution of soil organic carbon (SOC) for arable fields. The BeSOCC model differs from the models in many other European countries in the methodology for calculating the C inputs and in the initialisation method. The BeSOCC model will be used to simulate the effect of current management practices and several alternative management scenarios on the C-stock across Flanders. This will require simplification and assumptions regarding the inputs.

The objective of this study is to perform a sensitivity analysis to evaluate which input parameters impact the model output the most, and thus require the highest accuracy. The sensitivity analysis is performed on the following inputs: C-supply and the ratio decomposable plant material to resistant plant material (DPM/RPM) of crops; C-content, DPM/RPM ratios and dose of organic fertilizers; the percentage of incoming C supplied by the fertilizer going to Roth-C's HUM pool; initial SOC percentage and the initial distribution of the SOC stock over the DPM, RPM, BIO and HUM pool. A global sensitivity analysis is performed by using the Monte Carlo approach to account for all interactions between the parameters.

The preliminary results indicate that the initial SOC percentage has the highest impact, while the DPM/RPM ratios exhibit the lowest impact.

Keywords: Roth-C model; sensitivity analysis

Exploring Soil Organic Carbon Persistence for Sustainable Land Management Practices: A Thermal Analysis Approach

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Understanding the persistence of soil organic carbon (SOC) is pivotal for developing effective strategies in climate change mitigation and sustainable land management. Relatively cheap and easy to use methods are needed to study the underlying processes on a larger scale. However, the intricate nature of soil organic matter (SOM) and environmental factors poses significant challenges to accurately assess SOC persistence. This study proposes an integrated approach combining standardized thermal analysis methods with density fractionation to quantify SOC persistence. By comparing techniques such as Thermogravimetric Analysis coupled with Differential Scanning Calorimetry and a multiphase carbon and moisture determinator with a ramped heating analysis, we aim to elucidate distinct patterns in SOC stability across diverse soil compositions and environmental conditions. To do so, we will establish a standardized thermal method for determining SOC persistence in the different density fractions (fPOM, oPOM & MAOM). We will expect that the integration of standardized thermal analysis methods with density fractionation for assessing SOC persistence will reveal distinct patterns in SOC stability across different soil compositions and environmental conditions.

Our research seeks to contribute to the advancement of understanding SOM dynamics in the large scale, essential for devising sustainable land management practices and addressing pressing global challenges related to soil carbon storage and climate change mitigation.

Keywords: soil organic carbon, soil carbon stability, climate change mitigation

Relevance of the organic carbon to clay ratio as a national soil health indicator

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The soil organic carbon (SOC) to clay-sized particles ratio (SOC/clay) has recently been selected as an indicator of the soil organic matter status in managed mineral soils within the framework of the European Soil Monitoring Law proposal. This indicator was initially developed to predict soil structural quality, in a local study in Switzerland and subsequently tested at national scales in England and Wales, and in Germany. In this study, we evaluated if the SOC/clay ratio was relevant to assess the structural quality of soils at the national scale in mainland France. We additionally evaluated its variant, SOC/(silt < 20 µm + clay). We confronted SOC/clay and SOC/(silt < 20 µm + clay) to two indicators of soil structure, the soil bulk density and aggregate stability, and we tested the effect of land use and soil type using information from the French Soil Quality Monitoring Network (RMQS). We showed that the SOC/clay and SOC/(silt < 20 µm + clay) were poor indicators of the soil bulk density and aggregate stability. In our analysis, the SOC content was the best indicator of soil structure. Both land use and soil type had an effect on the SOC/clay value. SOC/clay was found to be strongly affected by soil pH with acidic soils consistently being classified as healthy according to the threshold of 1/13 and alkaline soils often being classified as unhealthy. The domain of applicability of SOC/clay excludes soils involving other SOC stabilization mechanisms than associations with the clay fraction and climate is not taken into account. We hence question the relevance of the SOC/clay ratio and its proposed threshold of 1/13 as a soil structure indicator, and more broadly as an indicator of the SOC status of healthy soils for all European pedoclimatic contexts. Based on the RMQS dataset, 63% of cropland, 81% of permanent crop and 23% of grassland soils were below the SOC/clay threshold of 1/13, which would classify them as unhealthy according to the European Soil Monitoring Law. An adaptation of the threshold to soil types and climates seems to be required for France, and probably for other countries, because some pedoclimatic contexts will never allow a satisfactory value to be reached.

Keywords: Soil organic carbon; Clay content; Soil structure

Effects of different crop management options on SOC stocks and deriving emission factors – the CarboSeq approach based on European LTEs

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Crop management options, such as, choice of crops in the rotation, residue management, fertilisation, tillage and irrigation, are known to affect soil organic carbon (SOC) stocks and can be considered as effective mitigation strategies to remove atmospheric CO_2.

This research, as part of the EJP SOIL CarboSeq project, aimed at estimating the effect of seven crop management practices on SOC stocks, considering available data and metadata from European long-term experiments (LTEs). The following crop management options were evaluated: 1) cultivation of cover crops in comparison with not growing cover crops; 2) increased share of leguminous crops in comparison with less or no legumes in the crop rotation; 3) incorporation of crop residues compared

with their removal; 4) non-inversion tillage compared with inversion tillage; 5) zero tillage compared with inversion tillage; 6) irrigated in comparison with non-irrigated systems and 7) the comparison of two agroforestry systems (alley-cropping and hedgerows) with croplands or grasslands without these elements.

The available information from published literature, existing databases, meta-analyses, and personal communication with the LTE owners was collected through a structured homogeneous template, checked for data quality both manually and through an automatic error detection tool, and subsequently deposited in the CarboSeq crop and soil management database. The database is coupled with an export module which allows to explore, filter, query and eventually export the data required for the analysis.

For each management option, emission factors (EFs) were calculated as ratio of SOC stocks of the management option to the SOC stock of the respective control option. Different bio-physical variables (e.g., climatic zone, soil type) as well as variables relevant for each management option (e.g., crop type, tillage depth, amendments type) were used to identify significant predictors of the EFs using a mixed effect model approach. The analysis resulted in different EFs or regression equations for each crop management option based on the specific variables that significantly affect these in each case. All the management options have the potential for SOC accrual, with agroforestry to present the highest EF. Considering the identified data gaps and limitations, the derived EFs can be used as a basis for the estimation of the SOC accrual in the European croplands.

Keywords: SOC sequestration, conservation agriculture practices, climate-smart agriculture, EJP Soil

Dynamics of Soil Organic Carbon Stocks on Arable Land under Varied Soil Management and Climate Scenarios: Insights from Long-term Experiments in Eastern Slovak Lowland

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The soil organic carbon (SOC) is one of the most important indicators of soil quality, and it impacts all soil ecosystem services, especially climate regulation. On arable land, the amount of SOC is low; however, its stock can be positively influenced by good soil management (the optimal doses of mature farmyard manure (FM), ploughing of post-harvested residues, diversification of the cropping procedure, application of intercropping etc.).

Long-term soil experiments provide important data on changes in SOC stocks and can be used to test the accuracy of the SOC inventory changes model. The National Agriculture and Food Center has long-term soil experiments on the experimental station Milhostov, located on the Eastern Slovak Lowland. Milhostov belongs to a warm and very arid lowland continental climate region. The soil type is gleyic Fluvisol, with high gley particles. In this locality, since 2006, the impact of three tillage methods on track changes of soil properties and achieved harvests has been followed. Crop rotation contains corn for gain, spring barley, soybeans, and wheat; all post-harvested residues remain in the soil. The RothC model was used to track changes in SOC stock under conventional tillage. In 2006-2021, validation of the model and the subsequent prediction of SOC stock using the MPI climate model's latest climate scenarios (CS) and several management scenarios (MS) at soil depth 30 cm was carried out. Climate parameters for 2006-2021 were used from the meteorological station Milhostov, and soil data was collected from an experimental field where the SOC concentration is measured annually. The inputs of organic carbon from the plant residues of individual cultivated crops were calculated from the harvests in individual years, and the coefficient Kc represents the amount of carbon in the residues of the evaluated crop according to the mentioned sowing procedure.

From 2006-2021, modelling and measured SOC values fluctuated around 60 t/ha. According to the Kruskal-Wallis test, t-test, sign test, signed rank test and chi-square test, no statistically significant

differences were found between modelled and measured SOC stock values. For the estimation of SOC stock in the future (2022-2100), two CS of the MPI model and four MS were used. CS rcp 2.6 assumed a lower growth, and rcp 8.5 had a higher growth temperature. The MS I (BAU) presents actual climate and management conditions; the MS II has actual crop rotation with FM application; the MS III clover grass was incorporated into crop rotation, and the MS IV has the same crop rotation without ploughing plant residues. Modelling results show that BAU SOC stock is maintained at the present level, and MS IV SOC stock has decreased. An increase of SOC stock can be achieved at the MS II and mainly the MS III at both CS, but a higher increase at CS rcp2.6 was observed. It can be concluded that at the expected temperature increase in the future, an increase of SOC can be achieved only by increasing the input of carbon into soil (FM or including clover grass into crop rotation).

Keywords: soil organic carbon; arable land; RothC model; soil management; climate scenarios

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Synthesis of knowledge availability and knowledge needs in carbon research across European agricultural soils.

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The interest in agricultural soils as a tool for climate mitigation strategies is increasing all over the world and triggered a rapid growth in European research on soil carbon issues in recent years. For researchers working in this discipline, it is important to keep track of knowledge developed. Gray literature can offer valuable information often prior to peer reviewed publications. Taking advantage of the wealth of knowledge contained in gray literature, this study built an inventory of different types (annual reports, technical reports etc.,) available gray literature relevant to soil carbon and aims to analyze the evolution of knowledge availability, especially the one pertaining to European agroecosystems. This study focuses on reviewing different types of gray literature published (~1000) by 38 European initiatives. This work employs the machine learning technique of topic modeling, an approach to extract the main topics that emerge from gray literature and *analyze their trends over time to conduct a quantitative synthesis*. Performing this activity is important to identify if and how the main soil carbon research trends are adopted in gray literature, *how they have shifted over time (2000 – 2021), to highlight co-occurrences and identify knowledge gaps*. The generated literature pool was analyzed using a set of research concepts and keywords and machine learning tools. Prior to applying the topic modelling technique, a manual screening of titles and abstracts reveals a first ranking of the designated research concepts and keywords in the documents identified. As such, this study can help to clarify the key aspect regarding soil carbon issues in the gray literature of European initiatives and can identify especially the shortcomings which exist in this “big data” pool.

Overall, this study will contribute to the EJP SOIL expected impact areas such as climate change adoption and mitigation, effects of sustainable management practices and harmonization of soil indicators. Furthermore, the study assists to improve the awareness on climate smart soil management practices (EI1), and soil carbon relevant indicators (EI4). In addition, this study results on soil carbon research evolution and knowledge development hold the potential to contribute to the individual roadmaps of European initiatives focusing on soil carbon such as Carbon removal certification, Soil health monitoring directive, nature restoration law etc.

Keywords: soil carbon, European initiatives, gray literature, automated content analysis, topic modelling

Carbon footprints result from livestock production in Poland based on NPC tools from CCCFarming project - limitations and perspectives

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The use of accounting tools for estimating greenhouse gas (GHG) and ammonia (NH3) emissions from dairy farms is of increasing importance for monitoring environmental performance and identifying effective mitigation strategies. In the EU project, Climate Care Cattle Farming Systems ('CCCfarming') three GHG accounting tools were used: ANCA, Agrecalc, CAP'2ER. In Poland – one of the project participants - eight selected farms representing a country-wide variety of housing systems, management practices, breeds, feeding, and land were used. One large farm with 1437 cows and the smaller one's with 10 to 100 cows were monitored. Average milk production per cow was 9241 kg (from 5600 in small 10 cows-farm and in ecological to 15 000 in intensive production farms) in all analyzed farms. Compared with the other farms from the other CCCfarming project countries, based on NPC tools, GHG emission intensity in Poland was one of the highest (1620 g CO_2eq/kg FPCM). The average GHG emission intensity in Polish farms was 1.44 kg CO_2eq/kg FPCM whereas in the other project countries from 0.94 to 1.08 kg CO_2eq/kg FPCM. However, it should be emphasized that the implemented NPC tools were adapted to Polish conditions and were not always easy to use, therefore, the results obtained for other countries such as Latvia, or Lithuania may systematically differ. We can however conclude that the emission reduction strategies proposed in the project, e.g. covering slurry tanks or nutritional strategies, can significantly reduce emissions from Polish dairy farms.

Project CCCfarming National Centre for Research and Development (SUSAN/II/CCCFARMING/03/2021)

Keywords: Climate effects on livestock, Greenhouse gas emissions and environmental impact, Livestock effects on environment

A meta-analysis and modelling exercise on the GHG trade-offs of soil carbon sequestration measures

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Promoting soil organic carbon (SOC) storage via agricultural management could theoretically store up to 62 t ha^{-1} over the next 50 to 75 years (0.8 to 1.2 t $ha^{-1}y^{-1}$). However, some management practices that increase SOC stocks may also have an impact on other GHG emissions, such as CH_4 and N_2O emissions, and on nitrate leaching. This risk is especially relevant on the longer term, if N_2O emissions remain, while the effect of the carbon sequestration is becoming less due to reaching a new steady state in the soil. Previous studies have shown that this might reduce or even completely off-set the mitigation potential of SOC-sequestration. Therefore, the potential trade-offs of soil carbon sequestration need to be assessed to evaluate the implementation of SOC storage management.

A meta-analysis was carried out as part of the EJP SOIL CarboSeq project. In this meta-analysis the effect of twelve carbon sequestration mitigation practices on N_2O emissions were evaluated. Besides, the causes of these N_2O emissions were explored including the effect of environmental, soil and management practices. The results showed quite some variation in the effect of carbon sequestration measures on N_2O emissions, yet overall, we can conclude that biochar, agroforestry and land use change from cropland to grassland or energy crop reduced N_2O emissions, whereas residues of green plant biomass (mainly vegetables) and the use of digestate increased N_2O emissions significantly, while for irrigation, tillage, and other organic amendments, no significant increase or decrease in N_2O emissions were found.

In addition, trade-offs related to indirect emissions when applying soil carbon sequestration measures were assessed in a modelling exercise. The indirect emissions caused by machinery use, production of fertilisers or pesticides, and fertiliser application were considered. First, literature was searched to find which farm operations change when a carbon measure is applied. The results showed that miscanthus had the highest reduction in emissions compared to the baseline, followed by willow and the inclusion of a legume crop to the rotation. None of the other measures (agroforestry, cover crop, and no -and reduced tillage) had off-set the carbon sequestration by indirect emissions, except when silage maize is replaced by perennial ryegrass, and when straw is incorporated in the soil. These

indirect emissions are respectively caused by an increased use of fertilizer for ryegrass compared to silage maize, and by the loss of straw as bioenergy source.

Keywords: climate change mitigation, N_2O emission, sustainable agriculture, greenhouse gases,

Analyzing efficient incentive mechanisms of carbon farming: A mixed-method approach

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The study aims to evaluate incentive mechanisms of carbon farming contracts, with a focus on result-based, action-based, and hybrid models through expert interviews to assess the preference of these mechanisms. Important contract design attributes are measured against key performance indicators specific to carbon farming, identified through literature review. Findings from interviews with ten experts have been analyzed using the multi-criteria decision analysis tool known as Technique for Order Preference by Similarity to Ideal Solution. The alternatives, the contract design attributes, were ranked in order of preference of the experts using TOPSIS using a conceptual framework designed to illustrate an efficient carbon farming contract. The final ranking indicates that "hybrid payments," funded through market-based mechanisms, was scored highest by the experts. In contrast, "low transaction costs" scored the lowest, suggesting that experts believe a mixed mode of incentives from private funds will most significantly contribute to the maximum performance of a carbon farming project, and transaction costs borne by farmers will contribute the least. The underlying reasons for these results are qualitatively analyzed.

Roadmap for improvement of carbon sequestration in the Netherlands

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In the Netherlands, the government has set goals for climate mitigation and soil health regarding agricultural mineral oils. Measures for carbon sequestration in these soils are important for reaching these goals and were studied in the past five years in the research program Smart Land Use. The results show that it is possible to reach the climate goals for Dutch agricultural mineral soils, but proper implementation of the measures is important. To determine which actions are necessary to reach sufficient implementation, a roadmap has been composed to set the focus of the research in the follow up of Smart Land Use in the period 2024 – 2026. The roadmap takes into account the policy goals, the role of research, the role of farmers and other stakeholders. The roadmap covers the period until 2030, where the policy goals should be reached.

Several outcomes have been identified that contribute to the goals. The main focus of these outcomes is towards placing measures in a complete farm set up, which provides farmers with perspectives on how to implement carbon sequestration at farm level on the long term.

In this poster, we will present the roadmap.

Keywords: roadmap**,** carbon sequestration, mineral soils, climate mitigation, soil health

A2 Leveraging different approaches in the development of farmer friendsly tools for sustainable soil practices and schemes

Session Description

Involved projects: ROAD4SCHEMES, IntoDIALOGUE, PRAC2LIV

Conveners: Morten Graversgaard, Meriem Jouini, Francesco Galioto and Monika Vilkiene

EJP SOIL is committed to advocate for the utilization of regionally tailored methodologies for furnishing multispectral insights into agricultural soil-based ecosystem services, particularly in the context of climate change. The prevailing trajectory underscores the need to investigate how to further encourage sustainable soil practices and schemes. The degree of practice implementation and adherence to guidelines for sustainable soil management in Europe exhibits considerable heterogeneity among farmers and across regions. Numerous studies have identified a wide range of barriers to the adoption of these sustainable practices, with special reference to soil management, encompassing disparities in advisory frameworks, country-specific data, knowledge creation and dissemination, type of incentive instruments and governance mechanisms.

We invite abstract submissions to elucidate experiences from projects concerning end-users' engagement, development and adoption of new tools and methods or implementation of new agroecological strategies.

More than a Dialogue between actors, seeking the integration of soil-based principles in agroecological systems

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Into-DIALOGUE focus on investigating contingent soil-related issues and to explore potential solutions. Particular attention is paid to those soil functions that can contribute dealing with environmental issues, including climate change, exploring both adaptation and mitigation actions from the field level to the landscape. Building on the results of previous EU and Turkish projects, Into-DIALOGUE aims to determine:

farmers' knowledge, behaviour and risk perception associated with the progressive loss of functions of their agricultural soils. Assessment of this knowledge according to the different characteristics of the farms (size, crop specialization, soil type, etc.).

drivers and barriers for farmers' acceptability of soil-based agroecological management practices, and whether this depends on their ecological identity.

the complexity of applying integrated policies in soil-based agroecological systems; and options for developing EU strategies, opinions, and actions into national sectoral policies.

the bundles among farms characteristics, farmers ecological identity, barriers to adopt sustainable management practices and policy measures (following the methodology of EJP-Soil SERENA project).

the role of farmers, decision-makers, stakeholders and end users, and the benefits that the postulates of citizen science can bring to the visibility of the soil resource in the management practices recommended by Agroecology.

The study area covers a broad range of agricultural realities of the EU and Turkiye, including various climatic regions and social contexts (that's why the project gives a special emphasis to the ecological identity of farmers). In the different contexts, it is first explored the objective dimension of the problem that makes it possible to identify solutions but not to explore their practicability. The practicability of the required solutions is then investigated through the analysis of farms' structural characteristics, farmers' conditions, the existence of facilitating policies that can contribute legitimating farmers roles and attitudes and finally, farmers perceptions of soil-related challenges and responsibility. All these elements justify the multidisciplinary nature of the research team, made up

of scientists from various disciplines: agronomists, foresters, biologists, geographers, economists, life sciences and political sciences.

Currently, the project is about to end, almost all deliverables are completed. Thus, an overview of main methodologies and key messages from project results are provided with the main purpose to set the general framework from where other contributions from this project are expected to be discussed during the breakout session.

Keywords: Participatory methods; Soil health, Driving forces, Policy solutions, Multi-actor approaches

Living Labs to support sustainable soil management practices and the implementation of decision-support Tools in Europe

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Keywords: Living Labs; decision-support tools, implementation, multi-stakeholder, soil management.

Individual decisions taken by farmers determine the change towards more sustainable agriculture and resource management. Sustainable local and regional development may be accelerated by improving farmers' knowledge and capacity to define and decide on sustainable systems. To achieve this, an entity at local level is needed that is legitimate for all stakeholders to support the process of transferring knowledge and innovations, and that ensures the participation of all the legitimate parties concerned by resources management. In this context, the EU has identified Living Labs as a key and legitimate actor in local development, to involve farmers in sustainable resource management, to enable the sharing of knowledge about local resources and decision-support systems, to make it possible to consider the relevant scales of stakeholders: i) the decision-making scale of farmers (plot and farm scale), and ii) the decision-making scale of decision-makers (regional scale) and to ensure the bridge between the different levels. The implementation level of decision-support tools (DSTs) for sustainable soil management in Europe varies among farmers and regions. The aim of this study is to explore, within the EJP SOIL project PRAC2LIV, the main factors that explain why the use of the available tools to improve resource use efficiency and management is still insufficient in Europe, while the necessary tools in many cases are freely available. This study also focused on a case study in Sweden conducted within a Swedish regional project (VGR-project). Within the EJP SOIL project PRAC2LIV, a wide range of DSTs has been identified in Europe: 38 DSTs were reported for soil water availability and retention, 46 DSTs for soil organic carbon and 72 DSTs for soil nutrient use efficiency. Making these tools operational and relevant for farmers is a challenge, let alone for stakeholders in

general. In order to have reliable and accurate input and output data for farmers, the scope and implementation of DSTs must take into account local specificities. Based on farmers' interviews in the Swedish case study conducted as part of the Swedish VGR-project, there is a knowledge gap between farmers and tool developers related to the proposed use and interpretation of tools. Farmers indicated that they receive too little or too much information which effect their capacity to decide whether to use DSTs or not. Instead, many farmers perform on-farm experiments as a method to enhance their decision-making capacity. This underlines the importance of identifying the drivers for sustainability in a real-life context, in order to produce scientific knowledge and make the most of this knowledge at the intervention level. Indeed, experimentation practices might support farmers' transition towards more sustainable practices. The analysis of the interview-results showed that acceleration of sustainable soil management requires efforts by multiple stakeholders, at different organization levels. Living Labs can be key to connect stakeholders in the articulation of tailored interventions for sustainability at the regional level. Furthermore, they can support innovation processes around experimentation to foster sustainable soil management practices and the implementation of DSTs for sustainable development from local to national and European levels.

Advancing carbon farming in Europe: Insights and challenges from research and policy perspectives

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Carbon farming, a key strategy for mitigating climate change and enhancing soil ecosystem services, holds immense promise in Europe. This presentation synthesizes findings from multiple research papers and deliverables within the EJP SOIL - Road4Schemes project to provide comprehensive insights into the landscape of carbon farming schemes in Europe.

Drawing from the inventory and analysis conducted in Work Package 2 (WP2), we evaluate the diversity of carbon farming schemes across Europe, examining their organizational structures, payment models, and adherence to critical principles such as additionality and long-term carbon storage. Additionally, we explore the implications of private versus public schemes and the challenges in standardization and monitoring.

Furthermore, insights from Thorsøe et al. 2024 shed light on the design and implementation of carbon farming schemes, emphasizing the need for credible schemes that ensure quantifiable carbon removal, additionality, and sustainability. While result-based schemes hold promise, the predominant use of activity-based incentives presents a notable observation.

Hönle et al. 2024 delves into the integration of carbon farming into national policies, highlighting the evolving role of carbon farming in achieving national climate targets. Disparities among European countries in policy emphasis, assessment of carbon farming options, and strategies for monitoring and verification underscore the need for harmonization and coherent strategies.

Additionally, insights from farmers' perspectives, as explored in WP3, provide valuable considerations for scheme design and implementation. Farmers' varying levels of interest, adoptability, and opinions on result-based schemes underscore the importance of tailoring schemes to meet their needs while addressing measurement challenges and providing adequate support.

Finally, the roadmap outlined in WP4 offers a decision-making tool for the further introduction of carbon farming, considering local characteristics and environments. This holistic approach integrates natural, economic, technical, and regulatory factors to facilitate informed choices in implementing carbon farming schemes. By synthesizing these insights, our presentation contributes to the ongoing discourse on advancing carbon farming in Europe, addressing challenges, and informing policy and decision-making processes for a sustainable future.

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Keywords: carbon management; scheme design; decision making tools; MRV

Policy gaps and inconsistencies in addressing agricultural soil health challenges in the EU and Türkiye

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This study focuses on the analysis of policies addressing soil health challenges which have been recently designed and implemented in six EU countries and in Türkiye. To this end, researchers involved in the Into-DIALOGUE project have developed a common research framework consisting of five key policy areas: Incentivising the adoption of sustainable practices, with special reference to voluntary measures supported by agricultural policies (i.e., the CAP for EU countries and IPARD for Türkiye); Enabling participatory processes, with particular reference to regulations empowering collective actions (e.g. Bio-districts, Land associations, Rural districts); Regulating the protection of the environment and the landscape, which includes both nitrate, water, and biodiversity directives, as well as regulations and rules aimed at protecting landscape features; Co-creating and sharing innovation and knowledge, with special reference to EIP-Agri Operational Groups, lighthouses and living labs and advisory services; Triggering new market opportunities, which encompasses rules on geographical indications of origin, short food chain initiatives and voluntary certification schemes.

A comparative analysis based on descriptive statistics and qualitative information was performed in order to: highlight convergences and divergences of the policy interventions adopted in different countries, assess the relevance of the policies compared to current soil health challenges, and identify policy gaps and inconsistencies in the design of policy interventions.

The results show that, in general, policy decisions and the agro-ecological practices promoted by these policies are not supported by robust evidence regarding the extent of soil-related issues at the

territorial level. Moreover, they frequently lack rigorous conditionality requirements, posing a risk to their effectiveness, particularly in certain types of farming systems. In addition, the different national soil health strategies are generally still characterised by a number of weaknesses, partly due to the flexibility with which EU regulations and directives can be implemented, which has often led to weaker commitments, and partly due to deliberate infringements, which have a direct impact on the ability of governments to monitor and control compliance. Conclusions summarise the main findings, discuss the limitations of the policies examined and provide some policy recommendations to address the existing gaps due to the lack or poor design of relevant policy instruments.

Keywords: Policy instruments; soil degradation indicators; agroecology; CAP; conditionality.

Enhancing Soil health through values-based business models

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Keywords: soil health, business models, payment for ecosystem services

Soil is a key asset for farmers and land managers and requires continuous investments to prevent land degradation and increase farm resilience[1]. In addition, soils are important for society as a whole, generating key ecosystem services such as clean water, carbon sequestration and biodiversity[2]. However, the importance of well-functioning 'healthy' soils is often not recognised, neither in business decisions nor by the general public, resulting in a lack of incentivesfor private and public land managers to adopt practices supporting soil health[3]. Thus the question rises: *What conditions need to be met in order to develop succesful business models which include soil health and get them adopted by land managers?*

the Horizon Europe project SoilValues comprises six case studies across Europe (Belgium, The Netherlands, Denmark, Germany, Poland and Portugal), in which researchers identify the relationships between farming practices, income, soil health and the ecosystem services provided by land managers.

Land managers then work together with their stakeholders in each case study to formulate implementation plans detailing how they will explore or test options for adaptation of their current business model. The goal is to recognise and capture value from (improvements in) soil health and the delivery of ecosystem services and collaborate with stakeholders on how to distribute this value. This is done in a co-creative setting, involving a wide range of stakeholders through interviews, workshops, focus groups and field visits.

The preliminary results highlight the necessity and added value of including a diverse group of stakeholders to identify new business opportunities and tackle the various accompanying financial, legal and practical obstacles. Besides the possibilities for adapted business models, the various stakeholder interactions are increasing awareness on soil health and related concepts through regional networking. At the same time, the many perspectives represented by these stakeholders demonstrate the subjective nature of attributing (economic) value to concepts such as soil health, of which the benefits in the short- and long-term can be complex and challenging to quantify.

In conclusion, a co-creational approach to developing business models for soil health is promising due to the need for a consensus on the (economic) valuation of soil health and ecosystem services within a specific value chain. This approach recognises the involved nature of business models which have land

management decisions at its core. At the same time, involving many stakeholders is not without challenges and possible pitfalls.

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Identifying farmers' priorities in soil management for climate adaptation to develop attractive support measures

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Climate change and the associated increase of extreme weather events pose serious challenges for crop farmers across Europe. Climate-smart soil management practices can mitigate these challenges at the farm level. However, adopting such practices requires farmers to change their production system, acquire new equipment, deal with new challenges in pest management, and more, which might result in farmers being reluctant. A widespread uptake of climate-smart soil management practices thus requires supporting the on-farm transformation process. However, farmers, like society, are not a uniform group and their decisions are driven by factors such as social and cultural norms, values, and attitudes. As a result, farmers have different priorities in their soil management. To identify suitable support instruments, it is therefore necessary to identify the soil management priorities of different farmers.

We used a mixed-method approach to answer the following research question: "What priorities do different farmer types have in their soil management?". We conducted a total of 130 Q-methodological interviews with farmers (operators of crop or mixed farms) in five European countries (Austria, Denmark, Spain, Sweden, Switzerland). Q Methodology centres around on a set of statements on a topic (here: soil management priorities), derived from literature, pre-tests and stakeholder interviews. Respondents sort these statements according to their level of agreement with each statement. In the analysis, we then statistically identify typical ways how the statements have been sorted and qualitatively interpret these typical sortings.

We identified five different farmer types or viewpoints, with differing priorities in soil management: Farmers that share viewpoint 1, "sustainability of soil and environment", prioritize soil health and environmental aspects to preserve their farm for future generations. Viewpoint 2, "efficient farm management" is shared by farmers who strive to optimize their farm business for economic sustainability. Accordingly, they focus on soil water retention and an efficient organization of the farm work in their soil management. Farmers aligned with Viewpoint 3, "farming the triple bottom line",

prioritize the long-term economic viability of their farms, while also considering social and environmental impacts. They are open to novel practices and, above all, want to enjoy their work as farmers. Farmers sharing viewpoint 4, “traditional farm work”, strongly believe in providing food for the world through hard and accurate farm work and enabling their successors to continue farming. Moreover, viewpoint 5, “striving for financial stability”, gives top priority to the avoidance of risks that could endanger the farm’s continuation.

Based on these priorities, each viewpoint will also respond differently to different support measures for adapting their soil management. To identify which types of support will be attractive to different viewpoints, we also conducted country-specific workshops with farmers. These show that some farmers will likely respond to financial support, while others might need information campaigns, field days, or societal recognition for their work with the soil. These results can inform policy makers, farm advisors, and other stakeholders to provide tailored information and support measures.

Keywords: Farmer typology, policy recommendations, sustainable soil management, climate adaptation, farmer priorities

Assessing Agri-Environmental Footprints and Pathways to Net-Zero: Insights from Process-Based and Whole-Farm Models

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Agriculture, with its significant environmental footprint, notably in greenhouse gas (GHG) emissions, presents a crucial arena for achieving climate action goals primarily carbon-neutral farms by 2050. Achieving a sustainable future requires strategies aimed at mitigation and offsetting of GHGs through increased carbon sequestration. The labour-intensive measurements of all inputs and outputs at a farm-to-country level trigger to find tools for accounting, and evaluation, and thereby find alternative options for decision making.

Process-based models (PBMs) and whole-farm models (WFMs) emerge as potential solutions to this challenge, offering unique strengths to tackle this complexity. PBMs, like DNDC, excel at dissecting specific agricultural practices like fertilization. By simulating underlying biophysical processes, they shed light on the "why" behind emissions, generating crop-specific and management-specific emission factors (EFs). However, their reliance on site-specific calibration and potential lack of transparency in source code can limit their wider application. WFMs, in contrast, offer a holistic view of the farm ecosystem, encompassing crops, livestock, agroforestry, and management practices. This comprehensive approach allows the assessment of mitigation strategies and explores pathways towards carbon-neutral farms. While WFMs offer a powerful tool for solutions, their data-driven nature and potential complexity can be daunting, particularly for smaller farms with limited resources. Bridging this gap lies in leveraging the synergies and trade-offs of both approaches. PBMs can provide research-grade insights and refined EFs tailored to specific farm contexts. These insights can then be seamlessly integrated into WFMs, enhancing the accuracy and realism of farm-level assessments. This paves the way for targeted intervention strategies and more precise estimations of a farm's environmental impact.

Digital platforms like HOLOS-IE (www.ucd.ie/holos-ie) could play a crucial role in facilitating this synergy. This digital platform, under development, offers a user-friendly interface, transforming the complex modelling process into an accessible tool for farmers and other stakeholders. By streamlining data input and offering intuitive visualisations, HOLOS-IE empowers stakeholders to gain a deeper understanding of their agri-environmental footprint and choices for its reduction. Automation of soil and climate parameters through mapping, along with the integration of default inputs/EFs from PBMs,

could significantly reduce input requirements. This empowers actively track and manage carbon footprint, paving the way for more sustainable agricultural practices.

This paper presents a preliminary version of HOLOS-IE, leading to HOLOS-EU for wider application across Europe, showcasing its potential to be an invaluable tool in the pursuit of net-zero emissions in agriculture. By providing accessible and user-friendly environmental assessment tools, we can empower farmers and other stakeholders to become active participants in the fight against climate change, fostering a more sustainable future for agriculture.

This ongoing research is funded by the Science Foundation Ireland via GOV.IE, and ECRRF (HOLOS-IE)

Keywords: Sustainable Agriculture, Greenhouse Gas Emissions, Modelling, Net-Zero Emissions, Decision Support Systems

Developing a Carbon farming framework supporting Ireland to meet its climate targets.

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The European Commission defines carbon farming as "a green business model that rewards land managers for taking up improved land management practices, resulting in the increase of carbon sequestration in living biomass, dead organic matter, and soils by enhancing carbon capture and/or reducing the release of carbon into the atmosphere, in respect of ecological principles. Carbon farming can enable the facilitation of certified climate action which has the potential to be rewarded through result-based contracts/approach with other actors in the value chain or through public support." In its role of helping Ireland meet its Climate targets, a fit for purpose National Carbon Farming Framework will provide opportunities for Irish farmers/land managers to derive a new and diversified income stream for their farm. It is essential that this Framework provides confidence, trust, fairness, verification and certification to support rewarding Irish farmers/foresters for the actions they take to remove and store carbon in our soils, forests, grasslands, croplands, peatlands and hedgerows.

The Framework will create the structures needed to leverage appropriate financial incentives to scale up adoption of measures by land managers that will result in Ireland achieving its ambitious targets on emissions reductions, biodiversity and water quality improvements. The Core Carbon Principles (CCPs), have been adopted to set out fundamental principles for high-quality credits that create real, verifiable climate impact, based on the latest science and best practice. Following input through public consultation, the CCPs have been adapted to include biodiversity/water quality improvements in the Irish context. Two additional overarching principles have also guided the development of this Framework; Just Transition & Learning By Doing.

This research presents the outcomes of a public consultation, elements of policy lab and describes the process to develop the national framework and outlines the framework that will be submitted for approval by the government. Elements of the new policy identified as key by various stakeholder groups will be described, as well as areas of concern and implementation conditions that should be ensured. Analyzing qualitative data from the entire policy creation process as well as quantitative data from the public consultation stage itself, we use the Transformative Innovation Policy approach, trying to understand what forms of creating climate policies have the greatest potential to activate various resources. **Keywords: Carbon farming, ecosystem, public consultation, climate policy, governance.**

Soil health challenges and farmers adaptation strategies: transition pathways in Türkiye and the European Union

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The degradation of agricultural soils in the European Union (EU) and Türkiye poses a significant threat to both human well-being and ecosystems, with around 60-70% of agricultural soils found being unhealthy due to one or diverse soil threats. While agriculture has the potential to mitigate soil degradation through adequate practices, relevant stakeholders are not enough motivated to drive meaningful change, even in the presence of facilitating policies. This underscores the need for a coherent soil strategy that integrates agricultural and environmental policies, tailored to regional realities and equipped with effective instruments to address contingent problems and drive the transition of agricultural systems towards more resilient agroecological states. In this regard, a survey involving 70 farmers from 5 regions around Europe and Türkiye with agricultural soils under threat, is carried out to investigate farmers adaptation strategies. A Data Envelopment Analysis followed by a regression analysis, complemented with qualitative information, is carried out to investigate inefficiencies, barriers, and driving forces. Results reveal the existence of different factors that contribute influencing farmers adaptation strategies. From a preliminary analysis (data analysis is still ongoing), Implementation cost barriers appear particularly strong for small farms, while market barriers for large farms with high income share from agriculture and with leased land. Inefficiencies are also strongly influenced by the territory where farmers operate for both small and large farms. Discussions follow arguing around the driving forces, with special reference to the influence of the territory on a social and biophysical perspective. This is because the different reference territories of the selected farms reflect different forms of social constructions farmers are embedded in and

influenced by, such as markets and governments. The interplay of such forces is thought to influence farmers adaption more than their structural characteristics. The paper is expected to conclude with some policy implications addressing the influence of local governments in recognizing the role of farmers in contributing protecting the environment through appropriate incentive policies followed by facilitating policies to accompanying the transition towards more resilient agroecological systems, such as the provision of advisory services, demonstration fields and better rules to protect the environment and favour the collaboration between farmers, the absence of which can compromise the efficacy of facilitating policies when present.

Keywords: Soil health; Data Envelopment Analysis, Farmers' survey

Knowing and needs on soil quality indicators for agroecological practices: results from a systematic review of long-term experiments in Countries participating in "Into Dialogue" EJP Soil project

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The study insight into the assessments of the relationships between agroecological practices and soil quality through a literature review of studies carried out within the countries involved in the Into-DIALOGUE project (Italy, Poland, Spain, Czech Republic, Latvia, Lithuania, Turkey). The focus was on the soil quality properties and related soil ecosystem services in relation to agroecological practices in each country.

The results showed how conservation practices are useful for improving soil quality in general and supporting soil ecosystem services, particularly in terms of regulatory and support functions influenced by organic amendment.

Moreover, the results showed the need for a comprehensive dataset including physical, chemical, and biological properties to assess soil quality and to address current needs regarding soil functions and ecosystem services. Biological data should be used more in soil quality assessment due to their completeness of information and faster response compared to physical and chemical aspects of the soil. For this reason, it would be necessary to invest in the harmonization and clarification of methodological aspects required for proper soil quality monitoring. In conclusion, the review sustained that agroecological practices have a strongly positive effect on soil quality and emphasized

the importance of increasing long-term experiments focusing on conservation practices, especially in environmentally sensitive European and Turkish agricultural landscapes.

A novel method to support the discussion of soil management PRACtices and development of decision support TOols through LIVing labs in EU (PRAC2LIV)

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The project PRAC2LIV explores how Decision Support Tools (DSTs) for soil management could support soil health in living labs. The DSTs in this case were constrained to those addressing soil organic matter, water retention, and nutrient use efficiency. Assessing the potential of DSTs to support soil health in living labs is a complex issue, given that all the various aspects of context will play a key role. Therefore, there is a need to not only collect information on DSTs but to inspire conversations to understand the needs and expectations of different stakeholders within the different contexts of living labs across Europe. To address that need, we used the novel participatory pictorial approach which include the visualization and short justification text. This method consists of (1) extracting a visualisation out of a team discussion, (2) presenting these visualised key points in expert groups and (3) using the visualisation as a source for discussion. Throughout the process, the visualisation goes through several iterations, all with the end goal of igniting fruitful discussions. Shown here is a pictorial highlighting a set of key topics around DSTs for soil health in living labs within the EJP Soil PRAC2LIV project. We presented the visualization to several expert groups at various scale levels both national and international. In the discussions, the visualization bridged communication gaps between living lab stakeholders with different values and needs. For instance the suggestion to include a digital twin for living labs and to consider financial aspects of soil health. The visualisation approach was found to be useful to generate new directions for programmes such as EJP Soil including important topics that could be (re)evaluated.

Keywords: Decision Support Tool, sustainable soil management, Living Lab, visualisation, pictorial, novel participatory method

Identification of drivers and barriers to the acceptability of agroecological land management practices for farmers in the EU and Turkey

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With the new 2023-2027 Common Agricultural Policy (CAP), Member States were called to prepare their own Strategic Plans providing support to the agricultural sector and rural areas with specific common objectives and especially greater environmental ambition. The aims involve conditions for sustainable farming in the European Union (EU), targeted support to farms, and increased flexibility for EU countries to adapt measures to local contexts. Into-DIALOGUE project, funded by the European Joint Programme on SOIL, is focused on exploring eco-schemes' potential impact on climate- and environment-friendly farming practices and biodiversity improvements. Targeted agri-environmental measures strongly support conserving managed areas of significant natural value, natural resources, biodiversity, and landscape maintenance. Similar supporting measures focused on sustainable agriculture and farming practices are realised in Turkey.

In the Into-DIALOGUE project, a questionnaire survey was carried out in the seven participating countries (Czech Republic, Spain, Italy, Lithuania, Latvia, Poland, and Turkey) to identify the drivers and barriers farmers face in adopting sustainable farming practices. The results of the questionnaire survey on a sample of farms provide valuable information on farmers' attitudes towards different agri-

environmental measures. The status of farms (individual farmers or legal entities), type of management (conventional; organic), area of cultivated land, the age structure of management, the labour force (family labour; non-family labour), and other indicators were assessed as classification criteria.

Farmers' attitudes regarding the current status and estimation of the short and medium-term outlook of their farming in relation to the introduction of agroecological practices and possible barriers were surveyed. Details on risk assessment of biodiversity loss, soil erosion, soil compaction, or loss of organic matter were investigated. The evaluation of the data concerning each agri-environmental measure provides results in terms of assessing the financial benefits to the farm, the improvement of soil conditions, the improvement of agroecological parameters, including biodiversity, the assessment of the time and workload on the field, and the administrative burden associated with the implementation of the measures.

Keywords: CAP eco-schemes; agroecology; farmers’ survey; financial benefits; participatory approach

Block B

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

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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.

Acknowledgment: This research was funded by the Research Council of Lithuania (LMTLT), agreement No. S-MIP-23-6.

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

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

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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

Block C

C1 Carbon sequestration, roots and amendments

Session Description

Involved projects: MIXROOT-C, MaxRoot C

Conveners: Henrike Heinemann, José A. González-Pérez

Climate change mitigation and adaptation is a major challenge of modern agriculture. Increasing the incorporation of atmospheric carbon (C) as organic matter into soils through improved crop management seems to be a promising agricultural management option for supporting climate change mitigation. In order to build up soil organic C increased organic C inputs to the soil are urgently needed. In agricultural soils, crop roots are the major source of C inputs and pivotal for long-term C storage compared to aboveground biomass as their turnover is 2 to 3 times slower. Thus, sequestering carbon in soils through increased belowground C inputs from cropping systems, specifically increasing root carbon inputs could play a major role in mitigating climate change. The most viable yet to date neglected option to increase root carbon inputs is an increased and deeper root production of both main and cover crops in extensive and intensive cropping systems.

In MIX and MaxRoot-C we are developing assessment methods to estimate root C inputs of both staple and novel crops in cropland, grassland and agroforestry systems across Europe. In this session we seek contributions which cover topics such as: measuring root traits, root biomass, root stoichiometry, root architecture, isotope labelling and rhizodeposition, in conjunction with environmental factors, such as soil type, strength and fertility, to predict the effect of root systems on SOC stocks. We would also like to see results from the ongoing projects that might be of interest to the root community and the initial data or approaches from those working on modelling. In this session we hope to go beyond current knowledge, to evaluate the potential impact of promising C sequestering management interventions, such as: cover cropping, targeted breeding, and soil management in these diverse agricultural production systems aiming at widespread adoption of more sustainable carbon sequestering and soil restorative practices.

What is the stability of additional organic carbon stored thanks to alternative cropping systems and organic wastes products application? A multi-methods evaluation

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Purpose: The implementation of agroecological practices often leads to an additional soil organic carbon storage in these soils, of which we aimed to assess the biogeochemical stability. Different methods are available in the literature, insufficiently compared.

Methods: We used particles size and density fractionation, Rock-Eval® thermal analyses and long-term incubation (484 days), applied to topsoil samples (0-30 cm) from temperate Luvisols that had been subjected, in > 20 years long-term experiments in France, to conservation agriculture (CA), organic agriculture (ORG) in La Cage experiment, and to organic wastes products (OWPs) applications (biowaste composts, residual municipal solid waste composts or farmyard manure) in QualiAgro experiment. Conventional agriculture plot served as a reference.

Results: The additional soil organic C mineralized faster than the baseline C at La Cage but slower at QualiAgro. In OWPs-treated plots at QualiAgro, 60-66% of the additional carbon was stored as mineral-associated organic matter (MAOM-C), and 34-40% as particulate organic matter (POM-C). In CA and ORG systems at La Cage, 77-84% of the additional carbon was stored in MAOM-C, versus 16-23% as POM-C. Utilizing the PARTYSOC model with Rock-Eval® thermal analysis parameters, we found that most, if not all, of the additional carbon belonged to the active carbon pool (MRT ~ 30-40 years).

Conclusion: this comprehensive multi-methods evaluation indicates that the additional soil organic carbon is less stable over decadal and pluri-decadal time-scales compared to soil carbon under baseline practices. Divergent results observed between methods can be explained by the fact that they address different kinetic pools of organic C and care must be taken to specify which range of residence times is considered when using these methods, as well as when using the terms stable or

labile. The results observed in the different management options also highlight the need to maintain agroecological practices to keep these carbon stocks at a high level over time.

Using direct analytical pyrolysis (Py-GC/MS) to characterize SOM and explore processes and humification drivers

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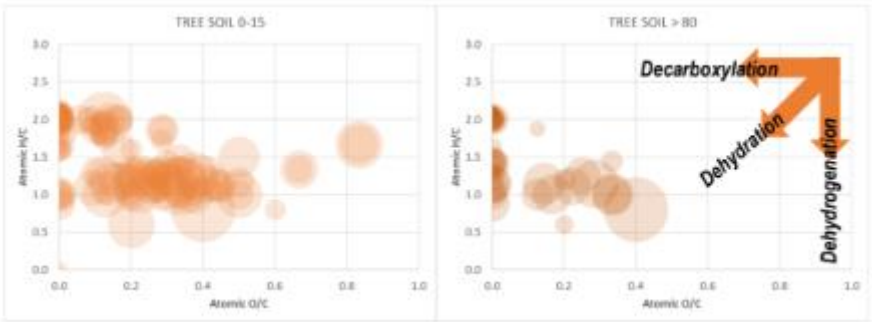
Soil organic matter (SOM) is an important factor in carbon sequestration that helps mitigate global change. Human activities such as land-use changes, agriculture, and forestry management can affect SOM dynamics. For example, practices like no-till agriculture or reforestation can lead to the accumulation of organic matter (OM) (Davidson et al., 2007). However, the changes made to the chemical structure of OM during the humification process in the soil, is what is critical to enhancing soil carbon sequestration. Differences in the molecular composition of SOM, resulting from its origin or evolution in soil, confer varying degrees of resistance to biodegradation, which is crucial for effective carbon sequestration in soils (Lal, 2004). In this work, we present a rapid and direct technique that can be used to characterize the chemical structure of soil organic matter and to evaluate the primary chemical processes that occur during organic matter evolution in soils. The technique combines analytical pyrolysis (Py-GC/MS) with a graphical statistical approach based in Van Krevelen diagrams (Van Krevelen, 1950). The Van Krevelen plots have the advantage of displaying the different SOM chemical components released during the pyrolysis in different regions of the H/C vs. O/C surface, which facilitates comparisons between samples and the possibility to infer main biogeochemical processes that may be involved in the stabilization of the SOM i.e. dehydration, aromatization, dealkylation, decarboxylation, etc. (Almendros et al., 2018).



Van Krevelen diagrams of soil pyrolysis products (400 °C) at two depths. Dot size indicates relative compound abundance

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Van Krevelen 1950. Fuel 29: 269–284.

Keywords: SOM dynamics, carbon sequestration, analytical pyrolysis, soil profile, humification

Root derived carbon input to soil: a case study for wheat varieties using a stable isotope approach.

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Promoting cropping systems with higher carbon sequestration in soils is an indispensable climate change mitigation and adaption measure. Crop roots are the major source of soil organic carbon (SOC) as belowground C inputs, namely root biomass C and rhizodeposition C, reside in soil longer than C derived from above ground crop residues and organic soil amendments. Hence, selecting varieties of main crops with increased belowground inputs has been proposed as a viable option to enhance SOC stocks without yield losses. However, little is known about the variability in root biomass C and rhizodeposition C of modern, commercial crop varieties. Moreover, there is a lack of data on the impact of different pedoclimatic conditions across Europe on this variability and few studies consider C allocation in deep soil layers.

Within the European Joint Programme Soil (EJPsoil) project MaxRoot-C, an in-situ multiple-pulse labelling with $^{13}CO2$ of four selected winter wheat (WW) varieties was carried out in the field in a replicated pan European experiment to determine belowground C inputs. We isotopically labelled the WW varieties throughout the active growth period. We sampled aboveground biomass and soil and roots after harvest by taking soil cores to 1 m depth. The separation of soil and roots is done by a series of soil sieving and root washing steps to end with crown roots, a coarse root fraction (>2 mm) and a fine root fraction (> 0.5 mm) to determine root biomass. Bulk isotope analysis is performed in the recovered roots and the sieved soil (<0.5 mm) to determine root biomass C and rhizodeposition C.

Results will include how the selected species differ in belowground C inputs and how the complex pedoclimatic conditions affect the amount of both root biomass C and rhizodeposition C. In addition,

we will report the aboveground biomass and the grain yield to investigate whether genotype selection meets the needs for both food production and increased SOC build up.

Keywords: roots, rhizodeposition, winter wheat, isotope labelling.

Modelling belowground C inputs in agricultural soils: key processes and current limitations

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Root systems are a crucial source of stable C into soils. Quantitatively, belowground C inputs can be proportionally large in agricultural systems where biomass yields and possibly aboveground residues are exported. Qualitatively, it has been demonstrated that, per unit C input, root-derived C is stored more than twice efficiently in soils as compared to C from shoot origin. In a climate smart management perspective, enhancing belowground C inputs associated with plant growth appears much more feasible than manipulating intrinsic soil conditions favouring C stabilisation. Modelling belowground C allocation is therefore a powerful tool to exploring venues for increasing C storage in soils with enhanced root activities. Here, we first reviewed the key processes driving belowground C allocation and how some of these have been implemented in soil and agroecosystem models so far. We reviewed 31 mechanistic models used to simulate C dynamics in cultivated soils. Of these models, 19 considered root biomass inputs through allometric relationships, while 12 models used dynamic plant growth modelling. Rhizodeposition, i.e. the release of organic matter by living roots, was considered by 14 models, while 17 did not take it into account. Rhizodeposition is an important mechanism as a source of labile C, which can be stabilized in microbial biomass but also induce priming effect of the SOC. More than half of the models did not take soil N dynamics into account, while soil N has been shown to be a key driver of belowground C allocation. Most of the reviewed models were still single-soil-layer models, which is a strong limitation to simulating the dynamics and fate of root-derived C. The limited progress in the modelling of belowground C dynamics appears linked to the high degree of variability and the paucity of data on belowground C allocation. For example, our investigations of the EJP database of root-to-shoot biomass ratio for the main cereal crops in Europe show a high degree of variability. In light of such recent and ongoing studies, we analyse limitations and opportunities for better predicting belowground C allocation in a climate-smart soil management perspective.

Keywords: belowground allocation, root growth, rhizodeposition, modelling

Improving the sustainability of arable cropping systems by modifying root traits: a modelling study for winter wheat

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Crop breeding to increase below-ground production and inputs of organic matter into soil has been attracting increasing attention as a potentially effective strategy to enhance soil organic matter (SOM) stocks and thus the quality of soil and sustainability of arable cropping systems. We used the new soil-crop model USSF (**U**ppsala model of **S**oil **S**tructure and **F**unction) to investigate the potential for increasing SOM whilst maintaining or improving yields by modifying the root system of winter wheat in terms of below-ground allocation of carbon (C) and some specific key root traits. USSF combines physics-based descriptions of soil water flow, water uptake and transpiration by plants, with a crop growth model and a model of the interactions between soil structure dynamics and organic matter turnover that considers the effects of soil physical protection and microbial priming on decomposition.

The model was first calibrated against field data on soil water contents and both above-ground and root biomass of winter wheat measured during one growing season in a clay soil in Uppsala, Sweden. Based on five acceptable calibrated parameter sets, we created four model crops (ideotypes) by modifying root-related parameters to mimic winter wheat phenotypes with improved root traits. 30-year simulations were then performed to evaluate the potential effects of cultivating these winter wheat ideotypes on the soil water balance, soil organic matter stocks and grain yields.

Our results showed that a winter wheat variety that allocated ca. 25% more assimilate below-ground without affecting leaf area (i.e. reduced allocation to stem biomass) increased SOM storage in the soil profile by ca. 1.4% in a 30-year perspective without impacting grain yields. Ideotypes with deeper root systems or root systems that are more effective for water uptake were predicted to increase grain yields by ca. 3%, as well as increasing SOM stocks in the soil profile by ca. 0.4 to 0.5%. Combining all three improved root traits showed even more promising results: compared with the baseline "business-as-usual" scenario, grain yields and SOM stocks in the soil profile were predicted to increase by ca. 7% and 2% respectively in a 30-year perspective (as an average of the five parameter sets).

Keywords: soil organic matter, crop growth, roots, water balance, ideotype

Cover Crops Affect Pool Specific Soil Organic Carbon in Cropland – a Meta analysis

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Cover crops (CC) offer numerous benefits to agroecosystems, particularly in the realm of soil organic carbon (SOC) accrual and loss mitigation. However, uncertainties persist regarding the extent to which CCs, in co-occurrence with environmental factors, influence SOC responses and associated C pools. We therefore performed a weighted meta-analysis on the effects of CCs on the mineral associated organic carbon (MAOC), the particulate organic carbon (POC) and the microbial biomass carbon (MBC) pool compared to no CC cultivation in arable cropland. Our study summarized global research of comparable management, with a focus on climatic zones representative of Europe, such as arid,

temperate and boreal climates.

In this meta-analysis, we included 71 independent studies from 61 articles published between 1990 and June 2023 in several scientific and grey literature databases. Sensitivity analysis was conducted and did not identify any significant publication bias. The results revealed that CCs had an overall statistically significant positive effect on SOC pools, increasing MAOC by 4.8% (95% CI: 0.6% - 9.4%, n = 16), POC by 23.2% (95% CI: 13.9% - 34.4%, n = 39) and MBC by 20.2% (95% CI: 11.7% - 30.7%, n = 30) in the top soil, compared to no CC cultivation. Thereby, CCs feed into the stable as well as the more labile C pools. The effect of CCs on MAOC was dependent on soil clay content and initial SOC concentration, whereas POC was influenced by moderators such as CC peak biomass and experiment duration. For MBC, e.g., clay content, crop rotation duration and tillage depth were identified as important drivers.

Based on our results on the effects of CCs on SOC pools and significant moderators, we identified several research needs. A pressing need for additional experiments exploring the effects on CCs on SOC pools was found, with a particular focus on MAOC and POC. Further, we emphasize the necessity for conducting European studies spanning the north-south gradient.

In conclusion, our results show that CC cultivation is a key strategy to promote C accrual in different SOC pools. Additionally, this meta-analysis provides new insights on the state of knowledge regarding SOC pool changes influenced by CCs, offering quantitative summary results and shedding light on the sources of heterogeneity affecting these findings.

Keywords: effect size, MAOC, MBC, POC, synthesis

Rooting for roots: Climate change adaptation and mitigation potential by variety selection of winter wheat

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Climate change mitigation and adaptation is a major challenge of modern agriculture. Increasing the incorporation of atmospheric carbon (C) as organic matter into soils through improved crop management seems to be a promising agricultural management option for supporting climate change mitigation. In order to build up soil organic C increased organic C inputs to the soil are urgently needed. Furthermore, more and deeper roots can serve as a critical climate change adaptation measure.

This suggests, that variety selection towards increased root biomass can enhance root C inputs to the soil and could therefore increase C stocks and potentially facilitate C sequestration in soils. At the same time there is a potential to sustain yields under climate change, pointing out that increasing root biomass and selection for an adapted root system might be a win-win situation. As biomass production and allocation is driven by both, genetics and environmental factors it is necessary to conduct multi-site studies when broad conclusions should be drawn. To quantify whether biomass allocation and root system architecture (RSA) are affected by variety x environment interaction, we assessed root biomass, root distribution to 1 m soil depth and root:shoot ratios in a set of 10 different varieties grown at 11 experimental sites, covering a large European climatic gradient from Spain to Norway.

We found a broad variety-specific variation in biomass production and its allocation between roots and shoots. The median root biomass across all sites and varieties was 1.4 ± 0.7 Mg ha^{-1}. Root biomass could be increased by 20% by variety selection compared to the average root biomass without compromising yield. RSA showed high variability among varieties and sites, with certain traits varying up to a factor of 2 in a single site. Root to shoot ratios varied between 0.04 and 0.58 with a mean of 0.16. Higher root biomass has neither a clearly positive nor a clearly negative effect on yield depending on the site. Instead, the potential of variety selection depended on the site-specific yield level, indicating a high potential for increasing root biomass at moderate yield levels. More roots in deeper soil layers showed to be beneficial for yield, especially on warmer, dryer sites.

Increased root biomass and deeper roots may stabilise yields under future climate change conditions where increased frequency of drought events during vegetation periods are expected and may therefore be a climate change adaptation measure that increases crop resilience towards changing environmental conditions. Thus, improved variety selection can help to achieve both goals of modern agriculture: climate change mitigation and adaptation. This study sets an example for pan-European variety testing to identify varieties and their adaptation strategies that are best suited for different agroclimatic regions.

Keywords: root biomass, root system architecture, wheat, deep soil, variety choice

Soil carbon sequestration: insights from different farming practices

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Soil organic matter (SOM) accumulation and decomposition are influenced by various soil management practices such as crop rotation and fertilization. This study investigated the impact of different soil management practices on SOM dynamics over a ten-year period (2008–2018). Specifically, it compared conventional farming with mineral fertilization to organic farming with cover crops, with or without composted manure addition. Results showed that organic farming, especially with cover crops and composted manure, led to the highest soil organic carbon (SOC) sequestration rate. Soil fractions containing particulate organic matter (POM) (63–2000 µm) and mineral-associated organic matter (MAOM) (<63 µm) were separated. The highest concentrations of POM-C and MAOM-C were found in systems with cover crops and composted manure. This suggests that these practices promote SOC accumulation, potentially reaching saturation levels in the MAOM fraction. The formation of SOC stock related to the POM fraction was lower in conventional systems compared to organic systems, likely due to the promotion of POM decomposition by mineral N fertilizer fertilization. The cover cropping system exhibited the highest proportion of SOC stock related to POM. Simultaneously, it showed the lowest SOC stock related to MAOM compared to other treatments. In conclusion, it can be stated that organic farming methods, particularly the utilization of cover crops and composted manure, significantly promote the accumulation of soil organic carbon, potentially serving as crucial means for maintaining soil health and fertility while sequestering carbon in the soil.

Keywords: cover crop; carbon sequestration rate; organic farming; conventional farming

A simple profile-scale model of soil organic matter turnover accounting for physical protection and priming: calibration and sensitivity analysis

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Implementing soil and crop management practices to mitigate losses of organic matter in agricultural soils (SOM) would enhance the sustainability of agro-ecosystems under the pressure of climate change. Accurate prediction of the effects of alternative management strategies relies on the development of models that capture the important interactions between organic matter (OM) inputs and the physical and biological processes in the soil environment driving the decomposition and stabilization of SOM. We present such a model based on the simple two-pool model ICBM (Andrén and Kätterer, 1997). ICBM was further developed by Meurer et al. (2020) to account for interactions between soil structure dynamics and SOM turnover. Here, we extend this model to account for the effects of SOM on microbial activity (i.e. priming) according to Wutzler and Reichstein (2013) and to the soil profile scale in order to consider the vertical distribution of both root OM inputs and SOM.

The model was applied to a long-term experiment at Ultuna (Uppsala, Sweden) in which soils have been treated with different organic amendments since 1956. Three treatments were studied: a bare fallow with no OM amendment and two treatments with mineral-fertilized crops where all above-ground residues were removed. One treatment only received root residues, while the other was amended with a known amount of straw. This dataset is therefore well suited to test the ability of the model to estimate long-term changes in SOM contents with strongly contrasting OM inputs, both in terms of quantity and type, particularly as the measurements suggest that root-derived residues are more stable in soil. A GLUE (Generalized Likelihood Uncertainty Estimation) procedure was used to calibrate the model. The model could accurately match the measurements in the three treatments using a common parameterization. This suggests that the combined effects of physical protection and microbial priming may be important reasons for the greater persistence of root-derived OM compared with above-ground residues. As expected, significant correlations between three of the model parameters (ε, retention coefficient for SOM, k_o, the rate constant for decomposition of microbially-processed SOM and A_o, the microbial uptake limitation factor) were found. Nevertheless, all three parameters could be constrained, since a narrow optimum range of values of ε was clearly identifiable.

A sensitivity analysis was also performed for an analytical solution of the model that predicts steady-state SOM stocks. This showed that parameters regulating decomposition rates through the effects of priming and physical protection are among the most sensitive, followed by parameters controlling OM

inputs, especially crop yields and the fraction of net primary production allocated to roots. The outcome of this sensitivity analysis is a simple multiple linear regression equation that could be used as a statistical model to predict SOM stocks under contrasting agro-environmental conditions, providing the decomposition rate constants in the model are adjusted for contrasting soil climates.

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Keywords: SOM turnover model, priming effect, physical protection, soil profile, sensitivity analysis

The impact of cover crop roots in soil carbon input across a European gradient

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Cover crops have been identified a key component for achieving both soil health and carbon sequestration EU Soil Mission goals. Currently they are cultivated on about 10% of the arable land area in Europe with large differences across regions, presenting ample opportunities for expansion. Cover crops provide soil coverage and protection and can contribute to the build-up of soil organic carbon. In many countries, cover crops were initially introduced to fulfil other specific objectives, for example, to achieve erosion control or as catch crops to reduce N-leaching. Thus, in recent years interest in cover crops has broadened to realize their role in fulfilling multiple ecosystem services, among other carbon sequestration, a source of biodiversity and acting as refugia for beneficial insects. They are also acceptable low-cost interventions for both conventional and organic farmers.

Increasing the mass and depth of cover crop roots could be a pioneering option for breeding for carbon inputs. Establishing an effective management for increasing below ground carbon inputs requires information on root quantities, location, and longevity as well as information on the impacts on following crops. Currently there is scant data on cover crop root carbon inputs across Europe and even less data on how inputs such as rhizodeposition and turnover contribute to increasing soil organic carbon stocks. This was highlighted in several recent review papers. One reason for this could be that cover crops use is often context specific, with different cover crop mixtures used to address farm specific issues. This adds complexity to assessing their benefits particularly in pan European experiments and design om cover crop mixtures for farming difficult.

To address the lack of root and rhizodeposition data to follow cover crops inputs to soil, we employed a suite of methodologies to quantify root inputs and turnover that could eventually be fed back into a cover crop design program. We also ran a pan-European experiment to get some initial assessment and range of the potential carbon inputs from cover crop and test the ease of implementation and utility of the methodologies developed. We standardised the methods for measuring sampling and

measuring root carbon and applied these on a series of cover crop trials in Denmark, Lithuania, Czech Republic, Austria and the south of France with both low and high diversity cover crop treatments, providing unique dataset as an output of MaxRoot-C, WP4. We showed that cover crops can add up to 2 Mg C ha^{-1} into the soil pool and that up to 50% of carbon can be in the form of rhizodeposits. We also showed that cover crop mixture composition has an impact on below ground inputs. This suggests there is scope for management and optimisation of cover crops performance as well as selection for traits for enhanced carbon farming.

Keywords: cover crops, crop diversification, roots, soil organic carbon, isotopic labelling

Impact of grassland management on soil carbon storage, CarboGrass

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Grasslands and pastures, spanning 40% of Earth's ice-free land, store 20% of global carbon (C). However, overuse and inadequate management, driven by food demand, have led to degradation and desertification. Addressing this presents significant climate protection opportunities, potentially sequestering up to 150 Tg of soil C annually through improved grazing or silvopastoral systems (SPS). Realizing this potential necessitates understanding carbon sequestration (CS) mechanisms across diverse environments and grassland systems. Despite various restoration and management attempts, a common framework to assess their CS impact is lacking. This project aims to i) assess improved grassland management's impact on soil C, nitrogen (N) cycling, and health globally; ii) analyze how environmental changes and management affect grassland CS; iii) provide standardized, high-quality datasets for benchmarking ecosystem models and iv) develop methods to enhance soil C stocks while improving productivity and livelihoods. Ten paired grassland sites across tropical and temperate regions will be selected to assess: management and environmental impacts on soil C stocks, CS potential, and soil C/N cycling; potential of improved management and restoration measures to mitigate land degradation. Standardized methods are applied to soil samples collected down to 30cm depth, analysing soil organic C, total N, texture, bulk density, pH, temperature, plant biomass and plant growth. Data will be related to soil characteristics, ecosystem management, restoration strategy, and environmental conditions. Comparing management practices' effects in diverse climates will elucidate their potential for enhancing soil organic C stocks, productivity, and ecosystem services.

Modeling CS with LandscapeDNDC, RothC, or other models using project data will inform decision tools to promote productivity while maintaining or enhancing soil organic C stocks.

Keywords: Soil health; Soil organic matter; Silvopastoral systems

A trans-European decomposition index study in arable soils, focusing on the impact of plant diversity using a common ^{13}C-labelled litter.

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Root carbon has been shown to be one of the most dominant forms of soils carbon inputs in agricultural systems. New paradigms about the decomposition of soil organic matter suggest the role of root derived soil carbon may have been overlooked. Current data and knowledge do not allow for prediction of the fate of root derived SOC storage in agricultural soils, specifically in relation to soil-depth and the complexity of the standing crop or intercrop.

Mixed species systems are currently gaining traction Europe providing opportunities for sustainable intensification of agriculture and other ecosystem-service co-benefits. Agroforestry systems cover about 9% of the utilized agricultural area and integrated crop livestock systems are both historically and culturally important in European agriculture, as they include perennial forage grasses and grasslands. Intercropping and other mixed cash crop systems are currently less developed in the EU. The aim of the EU EJP-SOIL funded MIXROOT-C and MAXROOT-C projects (2021-2024) is to gain a management-oriented understanding of the effect of mixed-species root systems on carbon flow and organic matter accumulation in European agricultural soils.

As part of the project, we have conducted a pan-European in-situ field experiments across pedo-climatic conditions. Treatments include:((i) monoculture (1 species), (ii) low diversity (2-4 different plant species in the mix culture) and (iii) high diversity (≥ 5 different plant species in the mix culture)) and different soil depths. The goal is to determine the impact of increased plant diversity organic matter breakdown to develop a trans-European decomposition index. To achieve this, we monitored the decomposition of ^{13}C-labelled maize litter in mixed agroecosystems and in the main crop monocultures across Europe. Using a hub spoke design, a common ^{13}C-labelled maize material was supplied to each participant and was mixed in a similar manner with the local soil from the treatment plots, packed in mesh bags and buried in the treatment plots. This was then excavated after six months and returned to Tulln for analysis.

This experiment, which includes many sites, climates and cropping systems, will provide key information on the rate of litter decomposition and the inclusion of litter C in different soil OM pools depending on the climatic condition, soil type and management. Furthermore, the experiment will provide information on litter turnover and link this process to soil C storage. We tested the null hypothesis that increased plant diversity does not increase the decomposition rate in the field. Initial results suggest that decomposition rates were 40-65% across sites and that diverse cover-cropping mixtures lead to lower decomposition rates.

These data and results could be used to guide model predictions of the fate pf belowground C inputs in single and mixed species systems at different soil depths.

Keywords* Mixed cropping, Diversity, ^{13}C labelled, Maize litter, Monoculture, Carbon

C2 Soil biodiversity and ecosystem services

Session Description

Involved projects: AGROEcoSeqC, EnergyLink, ARTEMIS

Conveners: Julia Schroeder, Dylan Warren Raffa , Klaus Jarosch

Healthy soils can provide important ecosystem services and habitat for soil biodiversity. Crop diversification could support the provision of ecosystem services through its effects on soil fauna and microbial communities, and thereby represent a management practice to mitigate climate change in agroecosystems. However, how soil diversity relates to soil multifunctionality is not yet understood.

This breakout session will focus on the mechanisms by which above- and below-ground biodiversity drives key ecosystem functions in agroecosystems, such as biomass production, nutrient cycling, and SOC accumulation.

We invite submissions that explore the influence of plant diversity on soil fauna, microbial communities and soil organic matter quality. We particularly welcome research that investigates the relationship between biodiversity and functional diversity, microbial physiology, and carbon stabilisation, employing techniques such as isotopic labelling, molecular methods, biomarkers, greenhouse gas measurements, and modelling.

Response of spontaneous flora to ecological intensification in a fruit and arable system in Mediterranean conditions: an overview of the communities' potential contribution to soil C input and storage

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Spontaneous plants in agroecosystems (i.e. weeds) are commonly considered to negatively impact provisioning services, reducing crop yield through competition. Instead, spontaneous plants can drive beneficial services such as enhanced biological control, pollination, providing supporting services (soil formation, nutrient cycling and soil stability). In the AGROECOseqC project, spontaneous flora communities are studied in agroecosystems managed in an ecological intensification perspective in comparison to local business as usual. Main focus is to assess their potential contribution to C sequestration.

Results on two project Case Studies are here reported: 1) the MAIOR Long Term Experiment (LTE, CREA) in Central Italy, an organic apricot orchard where: (i) Business As Usual (BAU—soil tillage and organic commercial fertilizer), is compared with (ii) Innovative diversified system with Cover crops, Compost and soil tillage (ICC), (iii) Innovative diversified system with Natural cover, Compost and soil tillage limited to transplanting furrow (INC); 2) La Canaleja LTE (INIA-CSIC), in Alcalá de Henares (Madrid, Spain), where (i) wheat in monoculture under minimum tillage (BAU) is compared with (ii) wheat in monoculture under no-till (No_till_M) and (iii) wheat in a 4-year rotation (fallow-wheat-vetch barley) under no-till (No_till_R).

Flora vegetational surveys were conducted during autumn 2022 (T1) and spring 2023 (T2), corresponding to minimum and maximum plant nutrient uptake.

We assumed that two main factors may drive C sequestration by the plant community: high C inputs through biomass production and low C outputs (losses) through slow decomposition (high C:

N of plant biomass). Therefore, plant functional characteristics linked to the two drivers were selected and, then, their distribution in the communities was studied through a trait analysis approach. Communities' Shannon H' diversity index was calculated and the Principal Component Analysis (PCA) on species distribution was also performed to characterize flora ecological niches.

The PCA separated the BAU communities respect to those of the other treatments in Italy at T2 and in Spain at both T1 and T2. As expected, the H' was higher in BAU at T1 in both sites, while at T2 it was lower in ICC in Italy, while a trend with lower values in BAU was recorded in Spain. No-till in both sites resulted in communities with greater ability to mycorrhize (higher values of the trait Supporting Arbuscular Mycorrhization), meaning the promotion of the rhizosphere mycorrhizal network, acting as a source or sink for C. Higher communities' Specific Leaf Area and Canopy Height (used as proxy of biomass productivity) were also recorded under no-till in both sites, suggesting potential higher C input

to the soil. In Italy, no-till resulted in higher perennials percentage, especially at T2, meaning higher soil capability to store C in plants' propagules, with ICC showing intermediate values. No clear trend was find in Spain. In INC (Italy), the communities showed also higher percentage of grass-like species (i.e. higher C:N ratio than forbs), meaning lower C outputs through slow decomposition.

In both sites, no-till seems to drive the spontaneous plant communities through a better potential for C sequestration. No effect was observed respect to the systems' diversification/diversity.

Keywords: Agroecology; Functional biodiversity; Conservation agriculture; Weed management; Ecosystem services

Microbial Carbon Use Efficiency of Plant Root Exudates Depends on the Substrate and Relative Nitrogen Availability

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Microorganisms play a crucial role in soil organic matter (SOM) dynamics. While microbial activities contribute to SOM loss, microbial products are essential precursors of stable SOM. Microbial carbon use efficiency (CUE) is defined as the ratio of carbon (C) allocated for microbial growth to the total assimilated C. It describes the balance of SOM loss and stabilization, and even a slight change in the CUE may have significant consequences for C sequestration. Microorganisms are generally more efficient in utilizing labile organic compounds, such as plant primary root exudates. However, despite its implicated importance, our understanding of the microbial utilization of root exudates, and thus their contribution to SOM formation, remains limited. Furthermore, few studies on root exudates have been conducted at scales relevant to the real rhizosphere processes.

In this study, we conducted soil incubation experiments to investigate the CUE of low-molecular-weight compounds commonly found in root exudates. We used a microdialysis system to mimic the hotspots of microbial activity created by primary metabolite exudation into the rhizosphere. We added ^{14}C-labeled compounds (two carbohydrates, two organic acids, and two amino acids) to the soil individually, and measured the ^{14}C recovery in respiration, microbial biomass, and soil to assess the CUE. Additionally, we selected three compounds and repeated the experiment with compound mixtures (with one compound ^{14}C-labeled and the other two unlabeled) to assess how the CUE of each compound was affected by different C and N availabilities.

We observed that the microdialysis system effectively created a small volume of soil with high microbial activity, and the microbial respiration significantly differed between the microdialysis system and the commonly used single-pulse addition method. We also found significant differences in microbial respiration and biomass between compounds, as well as between individual compound additions and compound mixture additions.

Our findings suggest the CUE of root exudates depends on the substrate as well as C and N availabilities in the exudates. This implies the potential of managing plant community composition to enhance the buildup of stable SOM from root exudates.

Keywords: microbial carbon use efficiency (CUE), plant primary root exudation, microdialysis

Functional and taxonomic microbial diversity profiling across soil depth in a diversified cover cropping system in the Netherlands

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Considering the important role microbial processes play in carbon cycling, it is crucial to grasp how agricultural management, in this case cover crop diversification, affect microbial physiology and its relationship with carbon dynamics. Diversifying cover crops might change the microbial community composition by increasing the chemical complexity of organic matter input from cover crop residues. This, in turn, could impact the microbial carbon use efficiency (CUE) and potentially increase carbon storage in the soil.

Furthermore, it is unclear how this effect may expand into deeper soil layers. With soil depth, the amount of soil organic carbon (SOC) and the C:N ratio of organic material decrease. While a narrower C:N ratio may positively influence CUE, nutrient scarcity may negatively affect CUE. Gradient studies within soil profiles have reported different trends in microbial CUE. Other factors, like microbial diversity, may play an important role in regulating microbial CUE.

In the EJP Soil-EngeryLink project, our main hypothesis is that greater crop diversity results in more efficient microbial use of carbon, thus enhancing soil carbon storage. To understand the link between crop diversity and the processing of organic carbon by the soil microbiome, we studied the effect of cover crop diversification on microbial CUE, microbial diversity, and carbon storage (SOC) in the top- (0-30 cm) and subsoil (30-60cm) of the Dutch long-term experiment Clever Cover Cropping.

This experiment was set up as a randomized block-design with 5 blocks of 8 plots. Each block consists of 8 cover crop treatments: three single species (radish: *Raphanus sativus*, black oats: *Avena strigosa*

and vetch: *Vicia sativa*), all possible 2- and 3- species combinations of these single cover crops and a fallow treatment. Soil samples were taken in both soil layers in December 2022 when the cover crop biomass had reached its maximum. We have analysed microbiome diversity, biomass and function and microbial CUE.

Some first results of 16S and ITS sequencing show that cover crop diversification did not significantly affect richness and Shannon diversity of the microbiome. However, the effect of soil layer was significant. Both richness and Shannon diversity were higher in the topsoil, compared to the subsoil. The correlation between microbial diversity and microbial CUE appears to have different directions in the top- and subsoil. In the topsoil microbial CUE is lower with increasing microbial diversity. In the subsoil microbial CUE is higher with increasing microbial diversity, however in the subsoil this correlation is not significant. The results and correlations for the other measurements will be presented at the EJP Soil Annual Science Days.

Preliminary results of 16S and ITS sequencing data show that cover crop diversification did not significantly affect microbial alpha diversity (richness and Shannon indices). However, the soil layer effect was significant. Both alpha diversity indices were higher in the topsoil, compared to the subsoil. The correlation between microbial alpha diversity and microbial CUE appears to have different directions in the top- and subsoil. In the topsoil microbial CUE is lower with increasing bacterial diversity, where fungal alpha diversity correlation values with CUE were small and not significant. In the subsoil microbial CUE is higher with increasing bacterial diversity, however in the subsoil this correlation is not significant. Regarding beta diversity, bacterial community also showed a big difference between top and sub soil, where the fungal community did not differ that much, though the differences between top and sub soil were significant for both, bacteria and fungi. The results and correlations for the other measurements will be presented at the EJP Soil Annual Science Days.

Our results may give indications that the relationship between microbial diversity and CUE is stronger in topsoils, but not in subsoils. Further, a higher diversity does not seem to result in increased CUE.

Keywords: cover crop diversification, subsoil, microbial diversity, microbial carbon use efficiency

Assessing the Influence of Long-term Agroecological Practices on Soil Microbial Functional Diversity and Metabolic Activity

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Promoting agroecological management practices such as minimal soil disturbance and greater plant diversity significantly enhances the soil microbial community. The current focus on the composition and structure of the soil microbial community, and the changes it undergoes due to various environmental factors, is noteworthy. Furthermore, microbial activity is a reliable indicator of soil health because soil microorganisms are crucial for the breakdown of organic matter and the biogeochemical cycles that affect soil fertility. Therefore, this study aimed to assess the influence of long-term agroecological practices such as different tillage systems, along with cover crop usage, on the functional diversity and metabolic activity of the microbial community. The experimental site located in central Lithuania, at the Lithuanian Research Centre for Agriculture and Forestry (LAMMC) (55°23'50"N, 23°51'40"E). A split-plot design with three treatments, including no-tillage (NT), no-tillage + cover crop (Persian clover) (NTC), and conventional tillage (CT), was selected to evaluate the effects of agroecological practices. Microbial Community Level Physiological Profiles (CLPP) were determined using Biolog EcoPlates™ (Biolog Inc., Hayward, CA), which contain 31 different carbon sources. The average well color development (AWCD), substrate richness, and Shannon diversity index (H') were determined to quantify the metabolic capabilities and functional diversity. After 48 hours of incubation of the EcoPlates, it was noted that there were statistically significant differences (with $P \leq 0.05$) among the treatments, in total AWCD and H' index, where NTC showed the highest AWCD and H' index values. However, the picture changed after 96 hours of incubation; there were no statistically significant differences among soils from different agroecological practices and CT, but NTC showed comparatively higher values of AWCD and H' indexes. Carbon substrate groups' utilization patterns differed among the soils. The highest carbon substrate groups, including carbohydrates, carboxylic acids, amino acids, polymers, amines, and miscellaneous utilization, were detected in the soil of NTC. The results also revealed that NTC significantly increased microbial biomass carbon (MBC) compared

to NT and CT treatments ($p = 0.0101$). Pearson's correlation analysis showed moderate, statistically significant positive correlations between AWCD and MBC ($r = 0.630$, $p = 0.028$), as well as between H' index and MBC ($r = 0.576$, $p = 0.050$). These results suggest that increases in AWCD and H' index values are associated with higher microbial biomass carbon in soil. Overall, our findings demonstrate that NTC exhibited comparatively higher microbial functional diversity and enhanced metabolic activity, compared to both NT alone and CT practices. These improvements are likely due to the increased organic inputs and minimal soil disturbance, which favor a more stable and functionally diverse microbial community.

Keywords: soil, tillage, cover crop, community level physiological profiles, microbial biomass carbon

Effect of agroecological intensification on root mycorrhization, soil aggregate dimension and related C content by SEM-EDS

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Fostering agroecological management practices, based on reduced soil disturbance and increased plant diversity in field, can play a pivotal role on soil fine macroaggregates and related C pools. In AGROECOseqC project, we hypothesized the no till and the crop diversification (as cover crop or rotation) can improve the physical stabilization in soil aggregates through development of mycorrhizal

root network, making SOM recalcitrant to fast degradation. To verify it, soil samples were collected from three AGROECOseqC experimental sites: S1-CREA (IT), S2-INIA-CSIC (ES), S3-LAMMC (LT). In each 4-blocks randomized experiments, following practices were tested: T1 - no tillage (NT), no crop diversification (no-Div); T2 - tillage (T), crop diversification (Div); T3 (control) – tillage (T), no crop diversification (no-Div).

At S1, Div was based on wheat+vetch cover crops sowed in apricot orchard interrow, at S3 on Persian clover cover crop after oilseed rape, while at S2 Div was the wheat-vetch-barley rotation. Twelve undisturbed soil samples in each experimental site (3 treatments x 4 blocks) were collected and sent to CREA, refrigerated. Soil samples were analysed by Scanning Electron Microscopy (SEM) and by Energy Dispersive X-ray Spectroscopy (EDS), a non-destructive technique used for morphological and chemical characterization of soil aggregates. Mycorrhizal colonization intensity (M%) was measured on undisturbed roots collected in the same 12 plots (3 plant root systems/treatment/block). Mycorrhizal colonization intensity (M%) of roots was determined using Trouvelot method (Trouvelot et al., 1986).

Agricultural practices differently affected the distribution of soil fine (250µm<Ø<1.0mm) and coarse (1.0mm<Ø<2.0mm) macroaggregates, depending on experimental sites. In apricot orchard interrow (S1), the highest percentage of soil fine macroaggregates was recorded in tilled system with cover crops (T2), as such as in S2 wheat cropping system under no-tillage (T1): as expected, in S2 the soil microaggregates (<250µm) were predominant in tilled plots (T3). Contrastingly, in S3 oilseed rape cropping system the highest percentage of soil fine macroaggregate were found in tilled plots

(T3), while no-tillage gave the highest percentage of soil microaggregates. By evaluating together all the tested sites, a decrease of soil microaggregates in favour of 250µm÷500µm fine macroaggregates was observed under no-till and crop diversification. M% was reduced by tillage compared to no-tillage in the tested experimental sites, while no effect of crop diversification on root mycorrhization was observed, except in S3, where Persian clover was introduced as cover crop. SEM analysis gave also evidence of no-till to maintain the root mycorrhizal extra-hyphal mycelium intact. M% was also positively correlated to soil aggregates diameter (linear regression: R^2 = 0.6106). Contrastingly, semi quantitative analysis of C% in soil aggregates did show neither a significant correlation with average diameter of soil aggregates, nor with M%.

In conclusion, no-till practice corresponds to an increased root mycorrhization in field and to a predominance of soil fine macroaggregates, probably due to the mycorrhizal extra-hyphal mycelium increasing the soil particles adhesion. In no-tilled systems, a trend to C% increase in studied soil aggregates was recorded also.

Keywords: no tillage, crop diversification, SEM-EDS, soil aggregates, mycorrhization.

Soil nitrogen pool dynamics in an agroecological gradient

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One of the main targets of agroecology is the reduction of fertilizing application while maintaining crop productivity, resulting in less fertilization costs for the farmer and a decrease in nitrogen leaching and its derivate ecological impacts (e.g. water eutrophication, biodiversity loss or toxic algae growth). This could be achieved by increasing the synchrony between the plant nutrient demand and the nitrogen cycle. In soil, the two main processes involving nitrogen are mineralization (N transformed from organic N to mineral N forms, available for plats but also leached) and immobilization (N transformed from mineral to organic forms), whose balance determine nitrogen leaching or accumulation in soil. In this frame, the AgroecoseqC project aims to study the soil nitrogen supply resulting from soil organic nitrogen dynamics at low and high nutrient demand under different agroecological intensification conditions. We collected soil samples on 9 European experimental sites with 3 equivalent treatments (1 control, and 2 levels of agroecological improvements) at two dates corresponding to low and high plant nutrient demand. Besides, the practices applied on the different sites constituted a gradient of agroecological intensification, from low to high intensity management practices. We estimated soil nitrogen mineralization and immobilization by the ^{15}N isotope dilution method of Davidson et al. (1991). After an addition of $^{15}NH_4^+$ to soils, this method allows to quantify 1) the gross N mineralization using the dilution of $^{15}NH_4^+$ pool by the $^{14}NH_4^+$ released from soil organic nitrogen and 2) the gross N immobilization using the incorporation of ^{15}N in soil organic nitrogen. Here we present some preliminary results for the already available data, showing differences between demand periods, sites and agroecological practices.

Keywords: nitrogen cycle; stable isotopes; soil microbials; plant/soil interactions, nutrient cycling, nitrogen mineralization and immobilization balance

Cover crop diversification can alter microbial life-death cycle and enhance carbon sequestration in agricultural soil

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Sequestering atmospheric CO2 within soil organic matter via shifts in agricultural practices represents a compelling strategy for enhancing soil ecosystem services and mitigating global change. Traditionally, the perception of soil carbon (C) stability is focused on intrinsic characteristics of organic matter inputs, such as lignin content. Recent studies, though, challenge this perspective, proposing a more effective approach centered on managing how the soil microbiome processes C inputs (Sokol et al., 2019; Poeplau et al., 2019).

This change of perspective prompts the exploration into the intricate connection between aboveground plant communities and belowground diversity of the microbiome, as well as the associated metabolic processes governing C sequestration. Building on this, Lehmann et al. (2020) presented a theoretical framework, interpreting the persistence of C in soil as a consequence of interactions between the molecular variability of organic matter input and the spatio-temporal microbial heterogeneities within the soil system. This perspective emphasizes the need of a comprehensive understanding of the dynamic interplay shaping C sequestration, moving beyond static views of organic matter stability.

Consequently, within the EnergyLink framework a range of microbial markers were investigated to illuminate potential physiological changes at a microbial level across several European agricultural field sites with different cover crop management types. Specifically, to discern shifts in microbial necromass composition and quantity, we focused on amino sugars (galactosamin, gluctosamine, mannosamine and muramic acid). To assess effects on potential growth rates, we quantified 14C incorporation into ergosterol for fungi and 3H-leucine incorporation for bacteria. To investigate shifts in nutrient acquisition strategies, we also examined extracellular enzyme activities for different nutrient classes. Additionally, we determined C:N:P ratio for bulk soil and microbial biomass. Here we present first results and discuss implications of diversified cover crops on soil carbon properties.

Keywords: Cover cropping; microbial necromass, microbial growth, amino sugars, microbial turn over

The effect of crop diversification and season on microbial carbon use efficiency across a European gradient

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Given the critical role of microbial carbon (C) transformations in C cycling, it is important to understand the influence of land use and management practices on microbial physiology and its connection to C dynamics. Crop diversification may alter microbial physiology by altering the chemical complexity of plant-derived organic matter inputs to the soil and eventually microbial community composition. This in turn could influence the mean residence time of plant-derived C in soil. The microbial carbon use efficiency (CUE) describes how much of the metabolised C is directed to microbial biomass or lost as CO_2 to the atmosphere.

Within the EJP SOIL project EnergyLink, we investigated the effects of crop diversification on microbial CUE across a pan-European pedo-climatic gradient. In total, topsoil from eight long-term experimental sites representative for different crop diversification measures (i.e. cover crops, ley farming, vegetation stripes) across Europe were sampled and analysed for microbial CUE, growth, respiration and biomass C using the ^{18}O-labelling method. On a subset of five sites, a second sampling was performed to test whether the effect of crop diversification was influenced by the growing season.

The general response of these microbial parameters and SOC stocks to overall crop diversification and individual measures was calculated extracting weighed effect sizes for each sampling (i.e. site and season), accounting for site clusters. We tested for differences in CUE between sampling time points using a site-wise ANOVA and TukeyHSD.

Crop diversification did not cause a distinct alteration in microbial physiology. The establishment of vegetation stripes between rows of olives or vines increased overall microbial abundance and activity (i.e. microbial biomass C, respiration and growth), without changes in CUE. Higher abundance and activity were likely related to higher C inputs in vegetation stripes as compared to bare soil. Most noticeable, CUE was significantly different for samples taken at different time points, potentially implying a seasonality effect on microbial physiology. This should be considered when comparing CUE values across sites sampled at different time points.

Furthermore, a numerical approach to extract seasonality information from weather data (i.e. temperature and precipitation) to account for different climatic conditions across the pan-European gradient is presented. This information can help to further investigate the drivers of the observed seasonality effect.

Keywords: crop diversification, microbial carbon pump, carbon stabilisation, isotopic labelling, microbial physiology

A guideline for estimating carbon use efficiency with the ^{18}O method

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The carbon use efficiency (CUE) of soil microorganisms is the fraction of absorbed carbon that is allocated to microbial growth, with the remainder being released as CO_2. The CUE provides information on the carbon metabolism of soil microorganisms, and on the carbon storage function of soils, since the microbial biomass contribute to soil organic matter building. One of the aims of the AgroecoseqC project is to estimate CUE in soils under a gradient of agroecological intensification, to disentangle if they act as source or sink of carbon during the low and high plant nutrient demand periods. Among all the multiple methods available to estimate CUE, In the AgroecoseqC project we will use the ^{18}O method, which aims the estimation of microbial gross growth in short periods of time. The greatest difference with the methods based on C substrate addition, is that with this method we avoid bias in CUE estimation due to the stimulation of microbial populations that were previously dormant. The main assumption of this method is that all the oxygen in DNA of soil microorganisms comes from water. Hence, the method consists on the addition of ^{18}O labelled and to trace the incorporation of ^{18}O in DNA in order to estimate microbial growth. Simultaneously, microbial respiration is measured by gas chromatography. Then these measures are used in a series of equations for estimating CUE. At the time of testing these methods for their application in AgroecoseqC, we have identified some unclear points in the published literature, introducing potential uncertainty in the final CUE estimates. These unclear points involve the quantity of oxygen and the impurity levels in the DNA extractions, the needed of spiking those samples with salmon DNA (to reach the minimum oxygen levels measurable by the mass spectrophotometer), the variability of the replicates performed with the same soil sample and the use of different equations for estimating CUE from the measurements obtained. Here we propose a synthesis of the method, and a guideline to help future users to take the right decisions depending on the situation.

Keywords: carbon cycle; stable isotopes; soil microbials; plant/soil interactions, nutrient cycling

Integrated modelling of microbial-plant interactions in multi-species agroecosystems: the project MODIMIV

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The MODIMIV ("Modeling relationships between microbial and plant diversity in multi-species agroecosystems") exploratory project (2024-2025) within the INRAE Biosefair meta-programme (https://biosefair.hub.inrae.fr) sets out to refine our understanding of biotic interactions within multi-species vegetation stands (https://biosefair.hub.inrae.fr/rubriques-verticales/nos-actions/projets-exploratoires/modimiv-projet-exploratoire-2024-2026). Recognising the pivotal role played by soil microbial diversity and plant diversity in governing carbon and nutrient cycles, MODIMIV is committed to unravelling these complex interactions, with grasslands serving as revealing case studies for broader multi-species ecosystems.

Conventional modelling approaches often compartmentalise plant and microbial components, overlooking their dynamic interplays. MODIMIV challenges this view by integrating the dynamics of microbial and plant diversity into simulation tools, thereby offering key insights for sustainable agricultural management practices. Microbial diversity significantly shapes processes such as nitrification, denitrification, nitrogen fixation and carbon sequestration, while plant diversity holds promise for optimising microbial carbon and nitrogen use by harmonising nutrient supply and demand.

At the core of MODIMIV lies the ambition to develop integrated simulators capable of capturing the material flows both within and between microorganisms and plants. By aligning the availability of nutrients with the needs of plants and microbes, this approach seeks to shed light on the nuanced interplay of biological compartments within ecosystems.

The main objectives of MODIMIV include:

- Investigating how biodiversity shapes carbon and nutrient cycling across diverse, multi-species vegetation cover to enhance our understanding of ecosystem dynamics.

- Developing advanced simulation tools that seamlessly integrate plant and microbial diversity to enrich the modelling of ecological processes associated with herbaceous covers.

- Assessing the effects of plant and microbial diversity on nutrient cycling and carbon sequestration, highlighting their central role in supporting ecosystem sustainability.

- Providing long-term prediction models: Equipping stakeholders with reliable and easy-to-use predictive models to strengthen sustainable agricultural practices by offering foresight for sustainable management strategies.

To enhance the refinement of modelling prototypes, MODIMIV will leverage data from multi-year mesocosm studies and replicated field experiments conducted on grassland and agro-grassland treatments in Clermont-Ferrand (France). Moreover, the project actively welcomes collaboration with other initiatives, including the EJP Soil AGROECOSeqC project. With grasslands as its primary focus, MODIMIV aims to show the effectiveness of its simulators, particularly in low-input agroecosystems. These ecosystems serve as compelling examples of how diverse plant communities modulate nutrient availability to soil microbiota, with benefits for plant growth. Through these collaborative efforts, MODIMIV seeks to transcend conventional modelling paradigms and advocates for the adoption of sustainable agricultural practices across a diverse array of multi-species vegetation covers.

Keywords: grasslands, integrated modelling, microbial-plant dynamics, multi-species agroecosystems

Exploring the interplay of plant and soil biodiversity in mediating soil organic carbon dynamics in European agroecosystems

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Plant and soil biodiversity are critical for soil health and ecosystem stability. The interactions between soil and plant biodiversity mediate essential processes that underpin multiple ecosystem services. In the last decades the study of functional biodiversity emerged as a new lens to analyse, monitor and promote the role of the soil life and plant assemblages on ecosystem services. However, the mechanisms underlying these interactions and how farmers can manage biodiversity to balance environmental and productive goals remain unclear.

In the AGROECOseqC project we have been collecting plant and microbial biodiversity data in order to investigate their effects on soil organic carbon dynamics from several locations across Europe. Specifically, we conducted phytosociological survey of plant communities and applied Next Generation Sequencing analysis to characterize the soil microbial (bacteria and fungi) communities. Based on these data we have studied the functional diversity of those communities by selecting functional traits linked to soil carbon dynamics. The statistical analysis employed alternative strategies, including partial least squares structural equation modelling.

Our preliminary results indicate that specific plant traits, such as Specific Leaf Area and taproot presence, significantly affected organic carbon content in soil. These plant traits also influenced microbial functional groups, particularly bacterial groups involved in carbon degradation and mycorrhizal fungi. Some selected bacterial and fungal groups exhibited significant negative effects on soil carbon, including soil organic carbon and water-extractable carbon. Additionally, farm management practices were found to influence both plant and microbial functional groups.

This functional approach offers a valuable tool for exploring the impacts of plant and soil microbial biodiversity on soil health and ecosystem services. Understanding these interactions can help in developing strategies for managing biodiversity to achieve both environmental sustainability and agricultural productivity.

Regional Assessment of Soil Organic Matter Stability under No-till and Diversified Agricultural Management Practices

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The relationship between soil structure and the ability of soil microbiome to stabilize soil organic matter is a key element in soil carbon (C) dynamics. Water extractable organic carbon (WEOC) pool can be used as prompt indicator of soil organic matter stability, associated to soil microbial C (SMBC). Therefore, this study aims to validate the established correlation between the water stable aggregates (WSA, %), soil organic carbon (SOC, %), WEOC (g kg^{-1}), and SMBC (µg g^{-1}) in bulk soil and different soil aggregates (fine: 0.25-1 mm and coarse: >1mm) under no-till and diversified practices across different environmental conditions at experimental sites in Italy (S1-CREA), Spain (S2-INIA-CSIC), and Lithuania (S3-LAMMC). Soil samples were collected from 3-blocks with three sub-replications in two no tillage treatments: T1 - no crop diversification (no-Div) and T2 - crop diversification (Div). At S1, Div was based on wheat + vetch cover crops in-between apricot tree rows, at S2 - on the wheat-vetch-barley rotation, and at S3 - on Persian clover cover crop grown after oilseed rape. Undisturbed soil samples (0-20 cm in depth) were taken for the aggregate stability analysis. Dry sieving was performed by Retch sieve shaker: mesh sizes 8.0, 5.6, 4.0, 2.0, 1.0, 0.5, and 0.25-mm and soil aggregates of 0.25-1 mm and >1mm were subjected to SOC and WEOC analysis. Aggregates from 1 mm sieve were wet sieved by Ejkelkamp apparatus (Velykis, Satkus, 2018). Bulk soil samples for the SOC, WEOC, and SMBC analysis were sieved through a 2 mm sieve. The content of SOC was determined according to the Nikitin-modified Tyurin method (Nikitin, 1999), WEOC - by the IR detection method after UV-catalyzed persulphate oxidation, SMBC - by the chloroform fumigation extraction method (Vance et al., 1987).

Soil aggregate stability differed among sites, but not among treatments, with highest WSA at S1 (93.9%) followed by S3 (77,0%), and S2 (47.1%). Highest content of SOC and WEOC were obtained in bulk soil at site S1 (2.2% and 0.30 g kg^{-1} respectively), and lowest - at site S2 (1.1% and 0.16 g kg^{-1} respectively) and S3 (1.6% and 0.17 g kg^{-1} respectively). No significant differences among different soil

aggregate fractions and treatments for SOC and WEOC were found at any site. SMBC differed among the S1, S2 and S3 (367.6 µg g^{-1}, 267.3 µg g^{-1} and 92.6 µg g^{-1} respectively) and Div' - at S1 and S3. Higher SMBC was found in no-Div (433.1 µg g^{-1}) compared to Div (313.4 µg g^{-1}) at S1, and opposite, less SMBC - in no-Div (238.9 µg g^{-1}) compared to Div (291.4 µg g^{-1}) at S3. Positive and statistically significant correlations were detected among all variables tested. Most of the very strong correlations (r> 0.8**l) were found among SOC and WEOC and its amounts in different soil aggregates. SMBC strongly correlated with WSA (r= 0.87**l), SOC and WEOC in bulk soil (r=0.67**l and r= 0.62**l respectively). Strongest WSA correlations obtained with SOC in fine aggregates (r=0.73**l) and WEOC in bulk soil (r=0.69**l).

This study emphasizes the complex relationship between soil structure, microbial activity, and carbon cycling across diverse environmental conditions and agricultural practices. The strong correlations observed among SMBC, WEOC, SOC, and WSA highlight the pivotal role of soil organic matter stability in regulating soil carbon processes. Integrated agricultural management strategies are essential for improving soil carbon dynamics in response to these findings.

Keywords: soil aggregate stability, soil microbial carbon, soil organic carbon, water extractable organic carbon

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Soil-, management-, and climate-related drivers of yield stability in organic and conventional farming systems

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Soils provide multiple ecosystem services that enable a continuous production of crops. This ability is largely affected by the actual land management system in place. Farming systems that promote ecosystem services are also expected to be more resilient against external stressors, enabling a more stable crop production. To better understand the soil-, management- and climatic- related drivers of yield stability in different farming systems, the EJP SOIL ARTEMIS project is analysing different long-term field experiments across Europe on these parameters. Here we present the results of the Swiss DOK-experiment, that continuously compares organic and conventional farming systems since more than 45 years at two fertilisation levels (standard and halved).

We calculated different yield stability indicators including the coefficient of variance for the main crops of winter wheat, maize, soy bean, potatoes as well as grass-clover leys that are part of the 7-year crop rotation. Yield stability showed no general treatment trend, i.e. in some years organically managed crops performed better and vice versa. To better identify treatment differences, we then decoupled climate-related drivers from soil-related drivers (such as soil organic carbon, pH and nutrient available N) using linear mixed effect models. We further included different management practices for pest management that are strongly differing between these systems into the statistical modelling.

Preliminary results indicate a strong relationship between yield productivity and agroclimatic data, especially for estimates for the whole growing season of each specific crop. We further show that the positive effects of standard fertilisation levels on yield levels are for both systems significantly stronger during adverse climatic stress events.

Keywords: yield stability; organic farming; long-term field experiment

Effects of different agriculture practices on ecosystem services in cereal fields worldwide

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Cereals are critical to support food production and energy across the globe, occupying the largest crop acreage in the world. Advancing our knowledge about the effects of the different agricultural practices on the ecosystem services provided by these cereal crops is critical to support food production and ecosystems sustainability. Here, we put together a global database to investigate the effects of conventional agricultural, organic and sustainable management in driving multiple ecosystem services from nutrient cycling to carbon stocks. Our meta-analysis reveals that different agricultural practices affect soil microbial communities and nutrients, leading to variations in their activities and composition.

Specifically, we found that sustainable agriculture has a significant positive effect on fertility, soil habitat, and carbon sequestration, while organic agriculture only shows a significant positive effect on soil habitat compared to sustainable agriculture. Despite this, no significant effect of these practices on crop production is observed, indicating that both soil management practices maintain agricultural production while promoting key ecosystem services.

Our study demonstrates the critical role of farm management in supporting food production in a world facing such major changes.

Keywords: soil fertility, soil biodiversity, crop yield, ecosystem services

ANALYSIS OF SOIL MICROBIAL COMMUNITY ASSOCIATED WITH CEREAL CROP UNDER SUSTAINABLE MANAGEMENTS IN DIFFERENT EUROPEAN COUNTRIES

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Abstract

Climate change poses an escalating threat to food security and overall life, with significant effects on crops and ecosystems. Adaptation and mitigation strategies are imperative to safeguard agricultural production and ensure the sustainability of food systems and human well-being. This comprehensive European study compares biodiversity and functionality across different regions of Europe in cereal crops, applying different ecological scales in terms of eco-efficiency. Furthermore, some studies recently revealed that even rare bacterial and fungal species may be highly important for soil function, which should be identified and monitored. The experiments consisted in testing three different treatments: sustainable farming (T1), consisting in the use organic fertilizers, crop rotation, and reducing the chemical inputs; agroecological farming (T2), adopting organic and environmental-friendly practices; conventional farming (T3), taken as control. We observed that both the structure and predicted functionality of fungal and bacterial communities were differently affected by T1 and T2 treatments, compared to conventional farming (T3) across the different regions. These results indicate that both sustainable and agroecological agricultural practices may have a similar, great

impact on soil microbial composition and functionality in different European regions, thus benefiting the agroecosystems through increasing soil heath and fertility.

Keywords: biodiversity, functionality, sustainable managements, soil

Exploring Endophytic Bacteria from Artemisia spp.: Antagonistic Potential Against Pathogens and Contributions to plant growth promotion

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Endophytic microorganisms might present sustainable alternatives to environmental concerns associated with conventional agricultural practices. Therefore, our study focused on the isolation, identification, and characterization of endophytic bacteria from the root, stem, and leaf tissues of four Artemisia plant species. A total of eighty-four endophytic bacterial isolates were selected based on morphological characteristics, and their molecular identification was performed using a 16S rDNA gene sequence-based method. The isolated bacteria belonged to diverse genera, including *Bacillus, Pseudomonas, Enterobacter*, and *Lysinibacillus.* Inhibition growth tests revealed that 61 bacterial isolates inhibited the growth of two pea root rot pathogens. AR11, and VR24 strains, isolated from *A. absinthium* and *A. vulgaris* roots, respectively, exhibited significant inhibition growth activity, against *Fusarium sp*. Root rot agent of pea. Furthermore, twenty-two strains demonstrated phosphate solubilization ability, with AR11 displaying the highest Phosphate Solubilization Index (2.93) after 10 days. Additionally, thirteen isolated strains exhibited positive reactions for indole production. The majority of effective strains belonged to the *Bacillus* genus, particularly from the root parts of *Artemisia* spp. The study underscores the multifaceted benefits of endophytic bacteria in sustainable agriculture, providing valuable insights into their role in pathogen suppression and plant growth promotion.

Keywords: Endophytic bacteria, Artemisia plants, *Fusarium* sp. Plant growth promotion

INCREASES of ORGANIC CONTENTS OF SOILS THROUGH *Taloromyces funiculosus* APPLICATION

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ABSTRACT

Soil nutrient status tend to decrease gradually over the years even if fertilization is made. Inorganic and organic compounds tend to accumulate and lead to pollution if they are not decomposed. These compounds also increase the soil electrical conductivity (EC) level and pose a threat to crop plants especially in the seedling stages. In this study, over a 3-year period between 2021-2023, we applied *Taloromyces funiculosus* to the soils cultivated with barley or soybean as cover plants in winter seasons. We observed that total organic carbon (TOC) contents and soil organic matters (SOM) increased significantly over a 3-year period. The soils cultivated with barley or soybean without the fungus application exhibited a gradual increase in TOC and SOM contents. We evaluate that *T. funiculosus* has a significant role for improving and maintaining the soil chemical and physical properties. We are in the process of elucidating if the fungus acts as a biofertilizer due to possible synthesis of soil enzymes. But much more proof is needed in this area.

Keywords: *Taloromyces funiculosus,* total organic carbon, soil organic matters, barley, soybean.

C3 Sustainable soil management

Session Description

Involved projects: SoilCompaC, SCALE, SoilX

Conveners: Lisbeth Johannsen, Olivier Heller, Alejamdro Romero

Sustainable soil management requires consideration of the multifunctionality of agricultural landscapes, where the need for efficient production of agricultural products may be in conflict with environmental and climate-related requirements. The multiple land uses place high demands on soil functions and the involvement of multiple stakeholders require an integrated approach between policy and practice to achieve sustainable soil management. The challenges presented by projected increases in the occurrence and severity of extreme events due to climate change add further complexity to achieving sustainable soil management.

Strategies for sustainable soil management that aim to prevent and mitigate soil compaction, improve soil water retention and infiltration capacity, as well as mitigate soil erosion, may be well known, but require further understanding to assess the possible gains and trade-offs with other sustainability targets.

Soil compaction is a major threat to soil productivity and ecological and hydrological soil functioning. Although adverse impacts of compaction on soil properties and functions are relatively well documented, estimates of the extent and severity of compaction in Europe remain elusive, we have limited knowledge on how compaction changes the carbon cycle, and we lack information on compaction risks for different pedo-climatic zones and cropping systems in Europe and how the risks evolve due to climate change. Especially, research results quantifying interactions between soil compaction and climate, and presenting information on how to assess, detect, recover and minimize soil compaction, thereby providing a basis for sustainable soil management in Europe, are urgently needed.

Soil management impacts the soils' structure and the soils' ability to infiltrate water during heavy precipitation events and to store plant available water for dry periods. With climate change, both drought and heavy precipitation are becoming more frequent and are threatening crop productivity and other vital ecosystem services. New evidence from field experiments, model simulation and farmer interviews identifies soil management strategies for climate change adaptation and approaches for their promotion.

The challenge of soil erosion, where on-site soil management of agricultural fields also has potential off-site impacts, is emphasized by connectivity and highlights the impact of landscape elements on

the transport of water and sediment during hydrological events. Implementation of targeted mitigation measures and encouraging changes in land use practices can ensure sustainable soil protection. Improved modelling of soil erosion processes with focus on connectivity at different scales and ensuring empirical validation of erosion risk maps is essential for effective decision-making tailored to regional circumstances.

In the present session, focus is on evaluation and development of sustainable soil management, especially with regard to soil threats as soil erosion and soil compaction. We kindly invite interested parties to submit an abstract with results from their novel research dealing with any of the knowledge gaps mentioned above.

SCALE – Managing Sediment Connectivity in Agricultural Landscapes for reducing water Erosion impacts

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The SCALE project intends to improve the knowledge of sediment connectivity and how to model it at different scales and locations, to enhance our understanding of soil erosion by water, sediment transport and landscape connectivity. This will help to advance the efficient implementation of mitigation measures, which account for regional differences in erosion damages supported by erosion modelling at different scales. We present the results of the project, which contribute to an enhanced knowledge on soil erosion processes, connectivity modelling, the implementation of mitigation measures and policy adaptation across landscapes in Europe.

These results include an overview of the current implementation of connectivity elements and mitigation measures in specific soil erosion models, as well as how to improve their model representation for improved soil erosion risk assessment and mitigation planning. Further, we developed guidelines for model users on the practical use of the connectivity approach in modelling developed via several mitigation scenarios for various soil erosion models. Our work shows that integrating erosion mitigation measures and sediment connectivity elements into models suitable for landscape scale simulations enhances our understanding of erosion and sediment transport and its management. However, it also highlights the necessity for further developments to improve the incorporation of sediment connectivity in modelling. Further, we analysed the effect of different treatments of the input and output grid resolution of soil erosion risk maps and how this affects the zoning of non-tolerable soil erosion as a basis for areas to implement regulatory measures. The local costs of implementing erosion mitigation measures and the diverse perspectives of farmers and other stakeholders from focus group meetings reveal the need for targeted mitigation strategies which consider the different perceptions on soil erosion risk, farm system sustainability and the feasibility of mitigation measure implementation.

The outcomes of the project highlight the need for targeted erosion mitigation measures in areas of heightened risk of erosion, as well as more appropriate protocols including sediment connectivity modelling to improve accuracy in soil erosion risk assessment, particularly when employing soil erosion risk maps for policy or planning purposes.

Keywords: soil erosion, sediment connectivity, mitigation measures, sustainable soil management

Predicting soil carbon removal by erosion in hillslope environments by erosion-deposition modelling could improve C cycle assessment

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Enhanced erosion - and sediment transport - in consequence of wrong soil management practices represents one of the most important threats in all the European countries, declined in different ways according to landscape, land use, climatic and pedoclimatic patterns. The erosion of the first topsoil layer does not involve only the loss of the mineral fraction, but also the mechanical removal of the organic carbon (C) from the soil, and the fraction of microbial biomass contained in it, with a decline in soil fertility.

This process interacts with soil C sequestration by biochemical activity, negatively affecting the balance among humified substances, mineralization, and CO_2 emissions. Indeed, the problem of soil C removed by water erosion and deposited somewhere along the watershed is still a matter of discussion among the soil experts' scientific community. Understanding the processes governing soil organic C turnover is confounded by the fact that C feedback driven by soil erosion has not been fully explored at large scale, yet (Lugato et al., 2018).

The present study aimed to verify the weight of the different processes involved in soil C sequestration (physical-mechanical vs biochemical) and their importance in soil C stock balance in a watershed in Central Italy. Soil erosion rates - as yearly average – were predicted by applying the RUSLE model coupled with Unit Stream Power-based Erosion Deposition methodology, together with the sediment reallocation both in other agricultural parcels (on-site erosion) and out of the watershed (off-site erosion), with the final prediction of the quantity (mass/surface) of soil C losses by mechanical removal and deposition fate (on-site and off-site).

A final comparison with the balance of soil C stock via a process-based model (RothC) allowed to assess the ratio between erosion and deposition, and to evaluate the importance of soil organic C removal by erosion.

Keywords: soil C loss; water erosion; erosion-deposition models; soil C stock

Buffer Zone Efficiency under Ploughing, Direct Drilling and Grazing in Boreal Conditions

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Establishing buffer zones (BZ) under perennial plants between cultivated arable land and receiving waters is a supplementary way of reducing sediment and phosphorus (P) losses in surface runoff.

Buffer zones have several roles in minimizing water loading. They decrease the area of tilled and fertilized soil near water bodies, reduce soil erosion in slopes, and remove sediment and nutrients from runoff water. In Jokioinen, SW Finland, a six-plot experimental field was established in clay soil to study long-term changes in functioning of BZ and their retention capacity for total solids (TS), total (TP) and dissolved reactive P (DRP).

Ten-meter-wide BZ located in the slope (*c*. 10%), whereas 60-m-long upper source area was quite flat. Grassed BZ (GBZ) were harvested annually, whereas vegetated ones growing natural bushes, trees and plants (VBZ) were not managed. Two 70-m-long field areas were cultivated without BZ (control. NBZ). The source field and the slope of NBZ were under spring crop and they were ploughed in autumn (1991–2001). Following three years the source field was grazed by cattle (2003–2005) and after that it was under direct drilling (Sept. 2006–Sept 2021). In the end of September 2021, composted pulp mill sludge (30 t/ha) was spread on the field and tilled into depth of 10 cm. Surface runoff (0–30 cm) was collected from the lower end of the BZ and piped to an observation building where water volume was measured with a tipping bucket, and representative subsamples were taken for laboratory analyses. The loads of TS, TP and DRP from GBZ and VBZ were compared to ones collected from the control (NBZ).

In autumn ploughing, the GBZ and VBZ halved the annual load of TS (1 t/ha) in the surface runoff from the NBZ whereas the decrease of TP load of 1 kg/ha was 36% and 28%, respectively. The load of DRP, however, was 70% higher from the VBZ than from the other treatments being the highest in spring. During pasture years, erosion was small (0.3 t/ha) in NBZ, and TP load of 0.7 kg/ha was decreased by 13% and 21% in the GBZ and VBZ, respectively. During grazing years, the DRP load was higher in all treatments compared to cereal years.

Under direct drilling, annual TS load was 0.5 t/ha in the NBZ; the GBZ and VBZ decreasing the load by 24% and 31%, respectively. In direct drilling, the annual load of DRP (0.30 kg/ha) from the NBZ was

twice as high as in autumn ploughing (0.15 kg/ha). During last three months in 2021, the load of TS (0.6 t/ha) and TP (0.7 kg/ha) were high due to the increased erosion events after soil tillage.

When modelling the effectiveness of BZ in water protection, the management of both the source fields and the BZ need to be considered. Soil type, topography, cultivation managements, type of BZ and weather conditions have a strong influence on surface runoff and erosion. To decrease DRP losses from plants to spring runoff, annual harvest of BZ is recommended.

Keywords: buffer zones; erosion; phosphorus; cultivation managements

Collaborative Design of erosion and sediment transport control measures at watershed scale in agricultural landscapes: Insights from stakeholders

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The current wave of protests in the EU agricultural sector, extending all over Europe, underscores profitability problems and the administrative burden as key issues that should be addressed by the EU to facilitate the better sustainable management of farms. Therefore, the issue of erosion and connectivity cannot be addressed separately from this general context. There is a need for increased sector participation in the design and implementation of regulations and their technical specifications.

We present the results of focal group meetings conducted in representative catchments of the SCALE Project located in Austria, Belgium (Flanders), Denmark, Finland and Spain to identify and select mitigation measures considering the perspective of the stakeholders and evaluate the social and economic barriers hindering their implementation.

The meetings were attended by local stakeholders: farmers and public servants connected with the agricultural and environmental sectors. Participants were asked to assess the relevance and their perception of soil erosion risk and sediment transport, the usefulness of erosion models and maps to implement erosion control measures, and how to improve these tools. They were also inquired about the most suitable measures to be implemented and the actions needed to overcome the barriers for wider adoption.

Farmers expressed different perspectives about erosion risk. While there was a group of farmers in the Austrian, Flemish, and Spanish catchments who were aware of the impacts of erosion on soil quality, crop yield, and water quality, the farmers from Nordic countries do not perceive soil erosion as a significant threat. In general, farmers mistrust assessments based on erosion models and maps and would prefer to advocate for more intense field monitoring to obtain reliable and precise data.

The implementation of erosion control measures largely depends on farmers' experience and "tradition" and profitability analysis. Subsidies were considered as a promising tool to foster the

adoption of new voluntary measures, but improving subsidy schemes, particularly by streamlining the administrative process, was remarked as a priority by all participants.

The diverse perspectives among farmers and stakeholders emphasize the need for tailored mitigation strategies considering the different perceptions of the relationship between soil erosion, crop yield, and the sustainability of farm systems, and the feasibility of implementing measures.

Given that many of the EU policies and regulations are driven by scientists' concerns and warnings, we question how much these concerns align with and are shared by farmers. To explore this, new group discussions involving representatives from the scientific community and academia, aiming to compare their perspectives on soil erosion and sediment transport issues with those of farmers are in course.

Keywords: sustainable soil management; co-design approach, Common Agricultural Policy

Soil management impacts on soil structural properties in ten European long-term experiments

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Abstract

Soil structure plays a crucial role in determining functional soil properties essential for crop growth, including water infiltration, water retention, and mechanical resistance, which directly impact water availability to crops and accessibility of resources by roots. Soil management affects soil structure directly through loosening by tillage and traffic compaction, as well as indirectly, for example by influencing soil organic carbon (SOC) content, earthworm abundance and activity, and root growth.

In the SoilX project, we evaluated how soil hydraulic and mechanical properties respond to differences in soil management. Our assessments encompassed measurements of saturated and unsaturated

hydraulic conductivity, water retention, aggregate stability, and penetration resistance in the topsoil and in subsoil layers. In addition, we measured earthworm abundance and visually assessed the soil structural quality. Basic soil properties including texture and SOC were also measured. We sampled over 100 experimental plots across ten long-term field experiments (LTEs) in Europe. To compare soil management across LTEs, we calculated numerical soil management indicators.

Preliminary data analysis of the Swiss LTEs revealed that tillage intensity had a negative and soil cover a positive impact on earthworm biomass, and that saturated hydraulic conductivity was positively correlated with earthworm biomass. Higher carbon inputs were associated with increased SOC contents, higher unsaturated hydraulic conductivity, and slightly larger amounts of plant-available water. Comprehensive analyses of data from all ten LTEs are currently on-going.

The preliminary findings underscore the significant impact of soil management on soil structure and function. Quantitative relationships between soil management and soil structural properties derived in the SoilX project will help guide the development of sustainable soil management strategies aimed at enhancing soil health and resilience to climatic extremes.

Keywords: long-term experiments, soil structure, soil management, soil hydraulic properties, soil mechanical properties

Consequences of soil compaction on yield and the environment: a modelling study

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Soil compaction is an important environmental and agricultural hazard, affecting at least 68 Mha of agricultural lands in worldwide. Soil degradation by compaction is increasing due to agricultural intensification that relies on the usage of heavy machinery, under mechanically vulnerable soil conditions. This agricultural trafficking leads to a disruption of soil structure and concurrent change in soil hydraulic and mechanical properties. Such soil structure degradation may have negative consequences for soil functioning, affecting both agricultural production and key soil environmental functions such as carbon and nitrogen cycling, which are crucial in the context of climate change mitigation. While it is generally known that soil compaction will have adverse negative effects on crop yield, impacts on nitrogen leaching, nitrous oxide emissions and carbon storage are less well quantified. Understanding relationships between these quantities remains challenging, as this involves complex interactions between soil physical, chemical and biological processes controlling soil functioning, which are in turn affected by agricultural management and depend on pedoclimatic conditions. In this study, we used a soil-structure based modelling approach to systematically assess the consequences of soil compaction on agricultural production and environment services and disservices. We coupled a soil compaction model that simulates compaction-induced changes in soil bulk density, macroporosity, and saturated hydraulic conductivity for different levels of soil compaction (i.e., mimicking different tractor weights and passages), with an agroecosystem model to simulate agricultural soil functioning. The model was used to analyse how different levels of compaction influence crop yield, nitrogen leaching, nitrous oxide emissions and carbon storage. Simulations were performed for different (1) soil textures, (2) soil structure recovery rates, (3) crop types and (4) climate regimes. We compared our simulations with field observations found in the literature. Despite the limitations in the modelling approach, our study sheds lights on relevant soil processes and scenarios that could help informing agricultural managing strategies.

Keywords: agroecosystem modelling, nitrous oxide; carbon stocks, nitrate leaching

Soil compaction risk under climate change: an analysis for different pedoclimatic zones in Europe

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Climate change affects the agriculture in manifold ways. One important point is the change of the weather conditions, which results in variation of precipitation and temperature. Both, precipitation and temperature changes, will affect plant and root growth as well as the available water content in the soil. In addition to many other soil and plant processes, soil moisture has a major influence on soil strength. A change in soil moisture due to climate change will therefore have an impact on the trafficability of soils and the risk of soil compaction. However, it is currently not known to what extent and in what direction the trafficability and soil compaction risk may change as a result of climate change.

In this study, we used a modelling approach to analyse the behaviour of soil compaction risk in times of climate change. First, we collected soil, crop and weather data from 13 different pedo-climatic zones in Europe. Using a new version of the SaSCiA model (Spatially explicit Soil Compaction risk Assessment), we calculated the wheel load carrying capacity (WLCC) for the last two decades. To model the effects of climate change, we selected 10 different climatic models and 2 SSP-scenarios (SSP1-2.6 and SSP5-8.5). For each pedo-climatic zone, we calculated the WLCC for each climate model and each SSP-scenario from present to 2100 on a daily basis.

The results show that climate change will affect the WLCC and thus the soil compaction risk. Although the extent and direction of WLCC-change depend on the pedo-climatic zone, there are some overall trends. In summer, the WLCC will increase due to lower precipitation and higher temperature drying out the soil. In late summer and fall, the behaviour is different. In some pedo-climatic zones the WLCC increases, in others it decreases. As maize and sugar beet harvest takes place at this time and both processes are accompanied by high wheel loads, the soil compaction risk will increase here in future. Late winter and spring show almost no variation in WLCC. At this time soils are often at field capacity which is also expected to be reached in the future. Thus, the soil compactions risk remains high during this period.

In addition to the average long-term effects, the variation in the WLCC between years is significantly high. There is an irregular alternation of dry and wet years within certain periods. The effects of these dry or wet years exceed the long-term changes in WLCC caused by climate change. This is an important point, as the compaction of the subsoil lasts for a long time.

Keywords: soil compaction, modelling, climate change

Potential for carbon sequestration on arable land under the limitations of the Flemish manure legislation

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Several large-scale studies have indicated declining soil organic carbon (SOC) contents in intensively managed cropland soils in Northern Belgium during the last few decades (e.g., Sleutel et al., 2007). As SOC content is regarded as a major indicator for soil health, improved SOC management is required (D'Hose et al., 2014). Almost all soil and crop management practices have implications for SOC but the most obvious way for increasing the SOC content is by using organic fertilizers such as animal manures or compost or decreasing soil disturbance by applying reduced tillage. However, several EU regions have fertilizer regulations to comply with the Nitrates Directive, and these regulations limit the use of organic fertilizers as a source of N and P, and consequently may constrain the built-up of stable SOC. Farmers need to balance the carbon input by exogenous organic matter on the one hand, and the risk of N and P leaching on the other.

We studied the effect of a combination of several measures (i.e., slurry application, compost amendment and non-inversion tillage) on topsoil C content, nutrient leaching and soil quality in the multi-year field trial BOPACT (°2010). The sandy loam soil initially had a suboptimal C content (i.e. 0.81%). After a period of 12 years, the yearly addition of compost (2t C ha^{-1}) resulted in a significant ($p<0.01$) increase of the SOC content in the 0-30cm (+0.15 percentage point on average) compared to no compost, while the application of non-inversion tillage mainly altered the distribution of the carbon in the topsoil. This application of 22.4 Mg C ha^{-1} also buffered the soil pH-KCl (+0.2 units, $p<0.01$) and increased the overall plant available nutrient content (i.e. P, K, Mg & Ca). Further, our research demonstrates that farmers can use compost, for at least 12 years, on top of cattle or pig slurry application to soils with suboptimal C levels to increase C content in the top soil, without inducing a higher risk for N leaching (i.e., NO3-N content in the 0-90cm). However, the $PCaCl_2$ content, which is often used as a proxy for P leaching, was significantly increased ($p<0.01$). The absolute increase was rather limited though (+0.8 mg kg soil).

In the framework of the EJP SOIL - SoilX project, the BOPACT field trial was intensively sampled in the spring of 2023 for biological (earthworm population, PLFA) and physical soil properties (penetration resistance, bulk density, Ksat, plant-available water). At the moment, results are still coming in.

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Keywords: soil organic carbon, compost, non-inversion tillage, soil quality, nutrient leaching

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Towards enhanced adoption of soil improving management practices in Europe

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Sustainable agricultural soil management practices are key to restore, maintain and improve soil health. The European Joint Programme for SOIL (EJP SOIL) has identified twelve main soil challenges in Europe. To assess the potential and eventually increase the adoption of soil-improving management practices, it is necessary to know i) the current levels of adoption of the practices, ii) socio-technical barriers influencing their adoption, and iii) their bio-physical limits.

This study compiled an inventory of soil improving management practices relevant for European conditions, and used a survey among soil scientists to assess the levels of adoption of these practices in Europe. In total, 53 soil management practices were identified that address one or several of the soil challenges. The adoption of most practices was low or spatially heterogenous across Europe, highlighting region-specific limitations to sustainable soil management. Qualitative interviews were conducted to explore the importance of socio-technical aspects of adoption. Using conservation agriculture as example, factors that can hinder adoption included the availability of knowledge and adequate machinery, financial risks, and farming traditions. Through a modelling approach, 54% of arable land in Europe was found to be suitable for cover cropping, indicating that the adoption of soil management practices is frequently limited by climatic constraints.

We propose a region-specific approach that recognises the importance of identifying and overcoming socio-technical barriers, and by acknowledging bio-physical limits that may be expanded by innovation.

Keywords: conservation agriculture, cover crops, EJP SOIL, soil challenges, soil degradation, soil health, soil restoration, soil threats, sustainable soil management

The FAST method for visual assessment of soil aggregate stability

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The strength of the soil structure is a key parameter in determining the susceptibility of the soil to erosion and in allowing for proper water infiltration. One way to assess soil structural stability is to measure the stability of soil aggregates in water. Methods already exist, such as the ISO-certified standard by Le Bissonnais et al., but it is rather time-consuming and can introduce operator-related biases.

We present a rapid and cost-effective tool for assessing soil structural stability: the Fast Aggregate Stability Test (FAST). Originating from the work of Fajardo et al. in Sidney, the FAST principle involves visually monitoring the spread of slaking aggregates upon wetting, and has already been implemented in the SLAKES smartphone application (now renamed Moulder). Although attractive due to its minimal equipment requirements, this method could not easily sample enough individual aggregates to meet the statistical needs of soil research. The goal of our work was to develop a robust, adaptable, and sufficiently representative method that could be widely used in soil science laboratories.

The protocol has been modified to use a 3D-printed plate that allows the simultaneous immersion of up to 96 individual aggregates in water. This amount of soil used per test is similar to that used in the Le Bissonnais tests, ensuring representative results. The increase in projected area of the aggregates during slaking is tracked using image recognition software, ImageJ. The final stability index is determined based on this area increase. Soil structural stability can be assessed within one hour using a procedure that involves placing aggregates on a plate, filming and analyzing. This method provides an objective assessment of soil stability in a timely manner.

The FAST index shows the expected behavior of aggregate stability, as evidenced by its correlation with other soil characteristics and its ability to discriminate between soils that have undergone different tillage practices. An indicative classification of the FAST index into four categories of soil stability, similar to the Le Bissonnais tests, is proposed.

The FAST method is expected to facilitate a wider implementation of structural stability studies.

Keywords: aggregate stability; soil health monitoring; 3D-printing; image analysis; method development

Effects of Long-Term Soil Compaction on Physical Parameters and Carbon Stocks under Pannonian Conditions

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The majority of agricultural soils experience compaction due to numerous factors such as the use of heavy machinery, cultivation under inappropriate conditions, or repeated passage of machinery on headlands. This compaction alters mechanical and hydraulic soil properties, leading to changes in key soil functions such as water and air flow, as well as carbon and nitrogen stocks, ultimately impacting plant growth and yields. This study aims to investigate the effects of long-term compaction compared to less trafficked areas of a field. As part of the SoilCompaC project (EJP SOIL), a field with a history spanning several decades was selected for this experiment. Featuring a crop rotation predominantly comprised of grains, the field represents the agricultural landscape of eastern Austria under Pannonian climate conditions and Calcaric Chernozem of alluvial origin. Three sampling points were selected in the headland (HL) and in-field (IF), respectively.

Soil penetration resistance was measured four times, consistently revealing higher resistance levels on the headlands on each sampling date. Crop yield of spring durum wheat was determined by collecting one square meter of aboveground biomass from each sampling spot and separating it into grain and straw yields. We found higher yields in the headland. After harvest, six pits - each two meters deep - were excavated using a backhoe attached to a small excavator. Three pits were located on the HL while the remaining three were IF. Visual soil profile evaluations were conducted, followed by taking soil samples measurements of bulk density, total carbon and nitrogen content, total organic carbon and nitrogen content, calcium carbonate ($CaCO_3$) levels, p*H*, saturated hydraulic conductivity, and air permeability. Selected results show that the mean total organic C stock (0-100 cm) was 231 Mg ha^{-1} for IF and 162 Mg ha^{-1} for HL. The bulk density differed between IF (=reference) and HL: 0-10 cm: -4%, 10-20 cm: +1%, 20-30 cm: +1%, 30-40 cm: +7%, 40-50 cm: +5%, 50-70cm: 0%, 70-100 cm: +1%.

For understanding of the complex system in compacted soil, long-term field experiments are necessary.

Keywords: long-term soil compaction; headland; bulk density; Pannonian conditions; calcaric chernozem

Linking soil resistance and earthworm abundance

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Earthworms are considered ecosystem engineers and show a strong interaction with soil structure. In addition, earthworms and soil structure depend on soil tillage, and earthworm abundance usually decreases with soil tillage intensity. Thus, earthworm numbers are lowest under a ploughing regime and highest under no-till. Similar applies for soil bulk density and causes higher soil moisture and soil penetration resistance in no-till than for plough. Earthworms depend on soil moisture and burrow deeper under dry conditions and/or aestivate until soil moisture increases. Also, soil penetration resistance is affected by soil moisture with higher values under dry conditions across soil tillage systems. These complex interactions of tillage, soil moisture and resistance also affect earthworm abundance. We hypothesised that earthworm abundance decreases with increasing soil penetration resistance for ploughing, whilst abundance increases with decreasing soil penetration resistance for no-till, as a function of soil moisture.

The hypothesis was tested with preliminary data from Hollabrunn, Austria, a long-term experiment (LTE) in north east of Austria with chernozem soil of loamy silt texture (clay 217; silt 570; sand 213 g kg^{-1}, total organic carbon 23.5 g kg^{-1}). The LTE consists of plough (25 cm depth) and no-till (0 cm) for 18 years. We took earthworm (4 soil monoliths 20 × 20 × 20 cm) and soil resistance (15 points per plot)

samples in April 2022, 2023, 2024 and October 2023. Soil penetration values were measured by 1 cm, 1 N accuracy, with penetration speed of 2 cm s^{-1}, with a 1 cm^2 cone. Maximum soil penetration depth was -40 cm, partly restricted by dry soil. Soil moisture was measured gravimetrically at 0 - 20 cm.

For no-till, preliminary results showed a higher soil moisture content and lower soil penetration depth than plough. Earthworm numbers responded as hypothesised, showed higher abundance with increasing soil penetration depth for no-till, related to higher soil moisture than for ploughing. These preliminary results showed that earthworm abundance can be predicted by maximum soil penetration depth. This could become a novel approach for farmers to estimate earthworm abundance. We seek to broaden our simple earthworm estimation for different soil textures and include data sampled in the SoilX project. We further hypothesise that earthworm number and soil penetration depth are affected by soil clay content and climatic boundary conditions.

Keywords: soil penetration resistance, soil penetration depth, soil management, earthworm, soil moisture, soil texture, SoilX

Effect of Agricultural Management on Soil Properties of Two Different Soil Types in the Czech Republic

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The aim of this contribution is to present the results of soil properties obtained in the Czech Republic as part of the SoilX project. The main research questions of the SoilX project are: 1. How exactly has soil management altered soil hydraulic properties in long-term field experiments across Europe? 2. To what extent can soil structural improvements enhance the resilience of cropping systems to future precipitation extremes? 3. Which socio-economic factors enable soil management improvements? Contrasting soil management treatments in 12 long-term agricultural field experiments (LTE) across Europe are investigated. To fulfil the objectives of the project from the Czech side the field measurements and sampling were carried out in the spring of 2023 at two locations, Čáslav (Luvisol) and Lukavec (Cambisol). Two contrasting variants were investigated at both sites: control (no fertilizers and other enrichments) (MIN), and manure and N2PK fertilized soil (FYM). In the field, a penetration resistance, soil CO_2 efflux, field soil water content (SWC), earthworms' abundance, and unsaturated hydraulic conductivity for pressure head of –2 and –0.5 cm, respectively were measured. Grab soil samples were taken in the depth of 5, 30 and 50 cm to evaluate basic soil properties (e.g., soil pH, soil organic carbon content (SOC)) and stability of soil aggregates (WSA index). Intact 100-cm^3 soil samples were taken in the same depth to measure the hydraulic properties using the multistep outflow method, and the pressure plate apparatus. In laboratory, the minidisk tension infiltrometers were used to measure the unsaturated hydraulic conductivities for pressure head of –5 and –0.3 cm, respectively.

Results indicate apparent differences in most of the parameters measured for the different variants and soils. For example, the higher WSA index, SOC, or field SWC were found for FYM variant than for MIN variant in both sites. On the other hand, earthworm abundance or field soil CO_2 effluxes were higher in FYM variant in Čáslav and surprisingly higher in MIN variant in Lukavec. Used fertilisation decreased soil pH in Čáslav (however, it had no effect in the control variant of Lukavec, which is naturally more acid soil). Some soil properties were not affected using fertiliser, e.g., penetration

resistance, or the field unsaturated hydraulic conductivities. We can see from the achieved results that the effect of fertilization can have different effect on different soil type.

Data obtained within this project and data gained before during LTE will be used as inputs into selected biophysical models to estimate the benefits of soil structural improvements for mitigating the impacts of increasing precipitation extremes (i.e., drought and heavy precipitation) under climate change. Synthesized project results will improve the basis of knowledge and evidence to provide better soil and crop management advice for both farmers and policy makers at European and regional levels.

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Keywords: long term experiments; fertilisation; soil structure; soil management; SoilX

The use of computed tomography to study the effect of fertilization on soil structure during a long-term experiment

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The aim of this contribution is to present the results of soil properties (porosity) obtained in the Czech Republic as part of the SoilX project. The main research question of the SoilX project is: How exactly has soil management altered soil hydraulic properties in long-term field experiments across Europe? Contrasting soil management treatments in 12 long-term agricultural field experiments (LTE) across Europe are investigated. In order to fulfil the objectives of the project from the Czech side, field measurements and sampling were carried out in spring 2023 at two locations, Čáslav (Luvisol) and Lukavec (Cambisol). Two contrasting variants were studied at both sites: control (no fertiliser and other amendments) (MIN) and fertilised with manure and H+N3PK (FYM). Plastic columns with a diameter of 7 cm and a height of 12 cm were collected at a depth of 1-13 cm (Ap horizons) and 30-42 cm (Bw and Bt horizons in Lukavec and Čáslav, respectively). These samples were used for porosity measurements using computed tomography (CT) NIKON XTH 225 ST. In addition, set of three 100-cm^3 undisturbed soils samples were taken from each horizon to measure porosity and soil hydraulic properties using standard methods.

The results from the Lukavec site show that the porosity determined from the plastic column samples obtained by CT is higher in the Ap horizon in the control than that in the fertilized variant, while no effect of fertilization is observed in the Bw horizon. Whereas at the Čáslav site, the effect of fertilisation is evident. The fertilised variant showed higher porosity in the Ap horizon and lower porosity in the Bt horizon compared to the control. The results obtained on the 100-cm^3 correspond to the CT observations.

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Keywords: computed tomography, porosity, soil structure, image analysis, long-term experiments

Soil properties and wheat yield in headlands: results from field scale experiments in *Cambisol* and *Retisol* in Lithuania.

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Continuous usage of heavy machinery, especially when soil is wet, often results in soil compaction in headlands, which can lead to wors soil conditions and at the end the yield loss. Many studies have shown the yield decrease as affected by soil compaction, but still lack of data reported on soil carbon and nitrogen cycles due to enhanced soil bulk density in headlands. Investigations of compacted headlands are important not only to assess the magnitude of the problem, but also to find the solutions for the sustainable use of such areas and mitigation of soil compaction. The aim of this study was to evaluate soil parameters in compacted headland and cultivated field down to 1m depth as well as their influence on wheat yields in two soil regions in Lithuania in 2022–2023. Experiments were located in Akademija, Kėdainiai distr. (Central part), in winter wheat (55°23'15.5"N 23°52'16.7"E in 2022) and spring wheat (55°24'38.4"N 23°51'00.1"E in 2023) fields and in Vėžaičiai, Klaipėda distr. (Western part) in winter wheat fields (55°43'26.1"N 21°30'15.8"E and 55°41'16.7"N 21°34'20.3"E in 2022 and 2023 respectively). According to WRB the soil in Central Lithuania was classified as *Endocalcari-Epihypogleyic Cambisol* and in the Western Lithuania as *Bathygleyic Dystric Glossic Retisol*. Soil texture in both experiments was indicated as a loam soil. SubVESS, soil texture, pH, total C (organic and inorganic), total N, bulk density (BD), total porosity, soil water retention curve, hydraulic conductivity (Ksat, constant head), aggregate stability (water stable aggregates) were measured down to 30 cm (0–10, 10–20, 20–30 cm) in 2022 and to100 cm in 2023 (0–10, 10–20, 20–30, 30–40, 50–70, 70–100 cm depth), penetration resistance down to 80 cm (every 1 cm), soil biological activity, root length, diameter and density per cm^3 were assessed in a top soil (0–20 cm), above ground biomass (wheat and spontaneous flora), wheat grain yield and quality were also evaluated. Greenhouse gas fluxes of N_2O, CO_2 and CH_4 were measured in both experimental sites in 2022 during winter wheat development in spring at stem elongation, at wheat flowering and before the harvest. All data were collected from headland and normal field from 5 replications in 2022 and 3

replications in 2023 (10 and 9 plots respectively) in two regions – soil types (*Cambisol* and *Retisol*). Gross area of each experimental plot was 25 m^2 in Akademija and 36 m^2 in Vėžaičiai. The results obtained in both experiments and in both years showed that the values of the soil physical and chemical parameters describing the soil condition were essentially worse within the soil profile in the headland than in the mid-field. Soil BD in the headlands exceeded the critical limit of 1.65 Mgm^{-3} within the whole profile, while in the cultivated field it was below the limits down to 50 cm in *Cambisol* and to 40 cm in *Retisol*. Soil organic C and total N tended to decrease in headland compared to normal field in both locations, while C/N in *Retisol* was significantly lower in 20–50 cm soil layer. Such conditions affected the wheat grain yield, which decreased by 9% (spring wheat) and 12% (winter wheat) in *Cambisol* and by 13% to 31% (in 2022 and 2023 respectively) in Retisol, when compared grain yield in compacted headland to non-compacted field.

Keywords: soil compaction, bulk density, organic carbon, total nitrogen, grain yield.

A Review On Microplastics In European Soil: Occurrence, Sources, Analytical Methods, And Potential Ecological Risk

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In North Europe, microplastics are a pervasive issue, as in the rest world. Microplastics in North Europe have raised concerns due to their potential environmental and health impacts. Efforts to address microplastic pollution in North Europe include research initiatives to understand its sources, distribution, and potential ecological risk.

We systematically compare last decade's studies on microplastic pollution in different Baltic Sea region countries (Denmark, Sweden, Finland, Estonia, Latvia, Lithuania, Poland, and Germany).

The focus is identifying the recent knowledge level and status quo of the mentioned research, mapping potential pollution sources, and identifying hotspots to get a wider view of possible ecological risks in the future of the Baltic Sea region.

A review of scientific papers was performed by Google Scholar and Scopus databases. Research terms were entered to identify relevant scientific papers: microplastic, soil, and selected country. Only the country of the first author was considered. A total of 66 publications in English were considered relevant to the objectives of this review. More than 89% of the articles were published in the last 5 years.

After performing the analysis, we observed a lack of information on the regional release of microplastics to agricultural soils, no clear classification of factors affecting the concentration of microplastics in soil, and no observations of possible effects on the environment in the target regions.

Keywords: microplastic, soil, pollution, Baltic Sea region, Europe

Carbon dioxide (CO_2) and Methane (CH_4) annual emissions from drained and undrained forest Terric Histosols

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In Lithuania, Histosols cover about 8–10% of the terrestrial territory, and the largest part, 513 kha (about 78%), is occupied by nutrient-rich organic soils classified as Terric Histosols (WRB, 2014 [2015]). Greenhouse gas (GHG) emissions from drained Histosols contribute more than 25% of emissions from the Land Use, Land Use Change and Forestry (LULUCF) sector. In this study we measured heterotrophic CO_2-C, and CH_4-C emissions from drained and undrained forest nutrient-rich organic soil (Terric Histosols) in 2021-2023. The study was conducted in the stands of native tree species as silver birch (*Betula pendula* Roth), black alder (*Alnus glutinosa* (L.) Gaertn.), and Norway spruce (*Picea abies* (L.) H. Karst.).

Three subplots (area of each subplot were 500 m^2) were established for gas measurements at studied forest stands, and the distance was 30 m between subplots. Gas samples were collected using 65 L non-transparent chambers. Sampling frequency was 2-3 times per month during the growing period and once per month during the cold season. The collected samples were analysed by gas chromatography in the laboratory of the University of Tartu (Estonia). Heterotrophic respiration was estimated as a proportion and accounted for 65% of soil total CO_2-C.

In drained forest Terric Histosols, the total annual heterotrophic CO_2-C emissions ranged from 2.9 to 4.6 t $ha^{-1}yr^{-1}$, while the total annual CH_4-C emissions were negative and varied from -1 to -5 kg ha^{-1} yr^{-1}. In undrained Terric Histosols the annual heterotrophic CO_2-C emissions were lower and varied from 2.7 to 2.8 t ha^{-1} yr^{-1}, meanwhile the total annual CH_4-C emissions were positive and reached 40 kg ha^{-1} yr^{-1}.

Keywords: Forest land, Terric Histosols, GHG, emissions.

ClimateCropping: Climate Smart Management for Resilient European Cropping Systems

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The large-scale adoption of sustainable soil management practices (SMPs) potentially mitigating GHGs still include substantial uncertainties in soil carbon (C), nitrogen (N) and phosphorus (P) balances, economic profitability and farmers' willingness to adopt new SMPs, particularly under climate change. ClimateCropping aims to provide scientific evidence, mainly based on long term experiments (LTEs), on how management of agricultural soils can contribute to climate change adaptation and mitigation, better cycling of nutrients and other associated co-benefits in European (EU) cropping systems and pedo-climatic conditions. This project is implementing an interdisciplinary approach that includes meta-analysis of historical LTE data, field observations, life cycle assessment, ecosystem modelling, agro-economic assessment and stakeholder engagement to evaluate the contribution of alternative SMPs such as 1) reduced tillage, 2) cover cropping, 3) organic fertilisation and 4) crop residue retention, to climate change mitigation and adaptation in cropping systems along a North-South climate gradient across Europe. Historical data will be complemented with new measurements and modelling of LTEs in seven EU countries (Austria, France, Germany, Ireland, Spain, Switzerland and the

UK). The focus will be on studying soil C stock, soil C sequestration potential, effects on N and P cycling, GHG mitigation, C footprint and potential trade-offs with yield at local to regional scales. Additionally, a selection of soil C decision support models will be evaluated for the above SMPs. The soil assessment will be complemented with an evaluation of economic and social sustainability including practical feasibility, and socio-cultural factors on farmers' willingness to accept a single or a combination of SMPs. Specific objectives are the following:

Determine soil C sequestration potential for alternative SMPs considering C, N and P inputs and inherent soil properties;

Evaluate the influence of climate change on soil C sequestration, N and P cycling under conventional and alternative SMPs;

Quantify climate change mitigation at field, farm and regional scale associated with alternative SMPs using ecosystem and LCA modelling;

Assess the climate change adaptive capacity and economic profitability associated with alternative SMPs;

Identify socio-cultural structural factors that enable or disable the adoption of alternative SMPs and policies that could accelerate the adoption of these SMPs in the EU.

Research is underway to prepare for activities of the project including collation and processing of data from 13 LTEs to feed forward to soil C stock assessment, ecosystem modelling, LCA and socio-economic analysis. Profiling and validating of decision support tools for soil C assessment is in progress. Literature review of LCA methodologies for use in cropping systems and on farmers' willingness to adopt alternative SMPs have been conducted. The first farmer interviews have been completed in Spain incorporating SMPs in olive production systems.

This project will develop holistic understanding of the GHG mitigation impacts of selected SMPs, alone and in combination, in main cropping systems across relevant climate regions and enable their uptake in EU agriculture. Results will contribute to the achievement of the national and international climate goals and will be highly relevant for European and national scale climate change policies.

Keywords: Sustainable soil management; Long term experiments, Life Cycle Assessment, Ecosystem modelling, Socio-economic assessment

Teaching agricultural soil biology to support sustainable crop production under pending climate change conditions by semi-saline irrigation

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Saltwater contamination is a major contributor to agricultural soil degradation. With rising sea levels and increasing summer droughts due to climate change, ground water and soils in temperate coastal areas are increasing in salinity. This is compounded as growers are forced to use the increasingly saline ground water to irrigate crops in summer. In arid areas, saltwater contamination has been reported to decrease crop yields, but the short- and long-term effects of soil saltwater contamination in temperate areas has not yet been thoroughly investigated, and especially little is known of the effects of increased salinity on soil microbial communities. Here we developed a 3-year experiment to study the effects of different levels of semi-saline irrigation on crops and soil microorganisms and test the hypothesis that deliberate semi-saline irrigation across the growing season applies a selection pressure and serves to pre-adapt soil organisms to increased soil salinity. The aim is to determine if we can we pre-prepare soils for future climate change conditions. After the first year the data show that irrigation with higher levels of semi-saline water (6 dS/m) had a negative impact on potato and spinach yield, but that irrigation with medium levels of salinity (3 dS/m) had no negative impact on crop yield compared to the control using ninety 30-liter mesocosms. Our results also show that increased salinity levels had an impact on the structure of soil bacterial and fungal communities from metabarcode DNA sequencing, as well as the function of soil microbes via gene expression from RNA sequencing. The lack of effect on crops at 3 dS/m part-saline irrigation but the change in microbial community structure and function suggests the selection pressure imposed by this part-saline irrigation level across the growing season has driven the soil biology community change to a state where it is better adapted to the increased salinity, and this supports crop yield. This is in line with the hypothesis that soils can be taught to be more tolerant of future climate change conditions. The outcome of this work will provide evidence to support growers' decisions on the levels of semi-saline

irrigation that can be used safely to irrigate crops to sustainably rescue yields in increasingly dry summers. More generally, as far as we are aware, this is the first proof in principle of the concept of pre-adapting soils to future conditions: this presents a method of mitigating the effects of climate change to ensure sustainable food production and soil health for future generations.

Keywords: soil, microorganism, crop, salinity gradient, climate change

The Impact of Ploidy on Daylily Plant Resilience in Drought Conditions

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The correlation between soil moisture levels and water availability significantly impacts how plants respond to environmental stress, especially during drought conditions. This study analysed the complex correlation between soil moisture content and morpho-physiological traits of daylily plants with different ploidy levels. The study examined various morphological and physiological parameters like relative water content (RWC), dry weight, plant height, leaf characteristics, accumulation of reactive oxygen species (ROS), chlorophyll and flavonoid levels, and nitrogen balance indices. The research findings show how diploid and tetraploid daylilies adapt to limited water resources.

The study observed the daylily plants' response to water deficit stress under abnormally dry conditions where soil moisture was 25%. Diploid and tetraploid varieties showed reductions in RWC, an essential indicator of their water status. However, the extent of RWC decline differed between the two ploidy levels, suggesting the potential for future research to explore the role of genetic factors in regulating water retention mechanisms. This finding underlines the complexity of the topic and the exciting avenues for further investigation.

As soil moisture levels dropped to 10% under severe drought conditions, the impact on the daylily plants became more pronounced. Diploid and tetraploid plants experienced significant decreases in RWC, with tetraploid varieties exhibiting slightly higher resilience to water scarcity. Notably, specific genotypes within each ploidy group displayed remarkable water retention capabilities, maintaining higher RWC percentages even under severe drought conditions. This variability underscores the genetic diversity in daylily populations and the potential for practical application of the research in selecting drought-tolerant cultivars through breeding programs.

The study highlights the crucial role of understanding soil-water dynamics in shaping plant responses to drought stress, with significant implications for horticultural practices. The findings provide valuable insights into enhancing crop resilience to water scarcity and optimizing water management strategies by unravelling the physiological mechanisms governing water use efficiency in daylilies. This knowledge empowers breeders and researchers to target critical traits associated with drought

tolerance, paving the way for developing water-efficient plant varieties capable of thriving in changing environmental conditions.

In conclusion, this study provides a foundation for advancing sustainable agriculture practices and fostering resilience in greenery cultivation amidst escalating water scarcity challenges.

Keywords: Tetraploid Plants; Plant Physiology; Water Deficit; Adaptation Strategies; Morphological changes

C4 Innovation and methods for data acquisition

Session Description

Conveners: Emmanuelle Vaudour, Luboš Borůvka

The session will focus on proximal and remote sensing of soils with special attention to soil spectroscopy and to soil organic carbon as the target soil characteristic. Presentations will be considered dealing with: 1) methods of data collection (lab/field proximal/UAV/ airborne/ satellite; tools/instruments/platforms; standard procedures and/or protocols; spectral/spatial/temporal resolution; spatial extent etc.); 2) data processing (pre-treatment, model development and calibration, machine learning methods, downsaling/upscaling; building and exploitation of soil spectral libraries including transfer options between lab, field and remote data); 3) elimination of the effect of disturbing factors (soil moisture, texture, vegetation and plant residues, atmospheric conditions); 4) accuracy assessment and uncertainty (validation methods and approaches, criteria, ground truth determination, comparison of methods and models).

Influence of soil texture on the possibilities to estimate soil organic carbon using Sentinel-2 data

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Remote sensing using satellite data is frequently put forward as a possible tool for estimating and monitoring soil properties such as soil organic carbon (SOC). SOC affects soil spectra in the visible and near-infrared region due to specific vibrations in chemical bonds in organic molecules. This has been successfully used for modelling SOC content under laboratory conditions often using high spectral resolution data. Encouraging performances have also been obtained using multispectral Sentinel-2 satellite data. However, results are variable. Several factors affect the satellite data, including other soil properties. Clay minerals influence the spectra in similar spectral regions as SOC, with the risk of masking important information. This is especially problematic in multispectral data (low spectral resolution). Soil texture also affects the visibility of SOC, with lower visibility of SOC in clay soils, and both SOC and soil texture influence the water holding capacity and soil moisture, affecting soil colour.

To study the effect of variation in soil texture, especially clay content, on the performance of modelling SOC content using Sentinel-2 data, a joint study was conducted within the STEROPES project, including 34 sites in 10 European countries. The countries covered various pedoclimatic conditions and cropping systems across Europe and included Türkiye, Spain, Italy, Switzerland, France, Czech Republic, Poland, Lithuania, Denmark, and Sweden. The sites were individual or neighbouring fields ranging from a few hectares to more than 500 ha at two sites, with a median size of 20 ha.

A pixelwise temporal mosaicking described by Castaldi et al. (2023) was used for the satellite data. Best condition bare soil Sentinel-2 images from the time series 2019-2022 were selected using cloud filters in Google Earth Engine and a combination of Normalized Difference Vegetation Index (NDVI) and Normalized Burn Ratio 2 (NBR2). Two approaches for calculating the pixel values from the retrieved images were included, the median value and the 90th percentile. The reasoning behind the 90th percentile was to use as dry soil conditions (bright images) as possible without including extreme values. Local models for SOC and clay content were developed for each site using Partial least squares regression and random forest. SOC was modelled using satellite data with or without adding information on soil texture and soil sampling location (geographic coordinates).

Results showed large variations in SOC modelling performance between the 34 sites, from very poor performing models to models with Lin's concordance correlation coefficient (ccc) of 0.8-0.9. However, at 50 % of the sites, SOC models using satellite data resulted in ccc < 0.5. Models predicting clay content also resulted in similar variable performances, although, clay content was easier to predict at a majority of the sites. There were no general explanations apparent for the SOC results related to possible clay interference. However, good models for both soil properties were generally achieved when they followed similar or reverse spatial patterns.

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Keywords: remote sensing; SOC; clay content; soil moisture; time series

Semi-automatic supervised bare soil pixels retrieval: impact of different classification approaches on soil organic carbon prediction

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Green and dry vegetation can cover agricultural soils and hence interrupt the acquisition of surface reflectance by remote earth observation sensors. Several spectral indices have been introduced to detect and discriminate bare soil from different types of vegetation. Spectral unmixing has also been under special consideration to estimate the fractional abundance of each soil surface cover class at the sub-pixel level. This study aims to compare the performance of the index-based and unmixing-based classification approaches as well as their integration on discrimination of the bare soil pixels on Sentinel-2 (S2) and Landsat 8-OLI (L08-OLI) single-date scenes from dry and green vegetation within four local agricultural sites in the Czech Republic. A reference soil cover RGB image representing the percentages of the three cover classes in each band (R: bare soil, G: green vegetation, and B: dry vegetation) was created using an airborne hyperspectral imagery along with the same date ground truth photos taken at the sampling points. A reference bare/non-bare soil binary map was also produced after classification of the reference image pixels to bare and non-bare, with an 80% of bare soil fraction threshold. The bare soil fraction images obtained by applying different classification approaches on different satellite data were compared with the reference image at 400 points evenly distributed all over the area. Accordingly, the best bare soil fractions estimations were obtained when using the integrated approach (R^2 0.81 and RMSE 0.02 for L08-OLI and R^2 0.87 and RMSE 0.01 for S2).

Furthermore, bare/non-bare soil binary maps produced by the integrated approach were more accurate than the others (overall accuracy 76% and 85% for L08-OLI and S2, respectively). In addition, random forest (RF) models were developed to predict SOC using sample-pixels retrieved as bare soil by each of the classification approaches. Models performed best on outputs of the integrated approach with average RMSE of 0.17 and 0.14 for L08-OLI and S2, respectively. The highest average prediction errors were yielded by the index-based approach (RMSE 0.24 and 0.20 for L08-OLI and S2, respectively). Considering all approaches, results obtained on S2 data were more accurate than those delivered on L08-OLI. In brief, classification of soil cover using the integrated approach led to a more accurate extraction of bare soil and higher performance of SOC prediction models on both types of satellite data.

Keywords: soil cover classification; spectral indices; linear spectral unmixing; soil organic carbon; airborne and satellite data

Effects of Vegetative Covers on Soil Properties in Semi-Arid Areas: Insights from the SANCHOSTHIRST Project

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Integration of remote sensing data with ground-based measurements approaches can enhance our understanding of the relationships between soil management, soil health, and landscape-scale processes. In our study on the impact of vegetative covers on soils, we sampled 15 pairs of plots of woody crops, vineyards, and olive groves in semi-arid areas of Spain. These areas typically suffer soil degradation and erosion under tillage management, but vegetative covers offer a solution. Yet, their adoption remains low in semi-arid regions. We present data from the ongoing SANCHOSTHIRST project. We compared soil conditions between covered and tilled plots, noting variations in soil types, terrain, and management practices. This diversity provides insights across different contexts that ultimately will help to assess the potential for remote sensing to monitor these changes over time. Parameters analyzed include physical, chemical, and biological soil characteristics. Cover crop (CC) age ranges from two to over twenty years, impacting soil conservation indicators such as porosity, water content, organic carbon, humification, and enzymatic activity.

The results obtained are variable, just as the types of soil and management practices are. Overall, it has been found that CC significantly increase carbon content, potentially doubling it in cases where the covers have been in place for more than ten years. This data is important because in these crops, the organic carbon content is usually less than 1%. This increase refers to fresh organic matter (SOM), but its humification is also being analyzed to assess the carbon sequestration capacity of these management practices. As expected, fresh SOM increases in management with CC, and in some cases, humification also increases, but not in others. Not all analyses have been completed yet, so conclusions cannot be drawn completely. Regarding soil structure, total porosity also tends to increase in soils with CC, even in subsurface layers, but this only occurs in crops managed with CC for the

medium term. Variation in total available water has been observed in some crops with CC compared to tilled crops, which must be analyzed based on soil textures, whose values are still to be fully determined.

Several enzymes pivotal in assessing nutrient cycling, SOM decomposition, and overall soil fertility are analyzed. Phosphatase enzymes, facilitating the conversion of organic phosphorus compounds into inorganic phosphates, have not exhibited significant differences across management in the samples analyzed thus far, which comprise only one third of the total. Similar findings have emerged concerning Arylsulfatase, involved in the mineralization of sulfur-containing organic matter. Beta-glucosidase, which catalyzes the breakdown of beta-glucosidic bonds in carbohydrates, plays a crucial role in carbon cycling and nutrient availability have to date shown heightened activity in the topsoil layers (0-10 cm) of CC owing to elevated SOM content and oxygen levels. Dehydrogenase enzymes, serving as indicators of microbial activity, exhibit notable variances across management practices. Likewise, Urease enzymes, key for nitrogen cycling in soils by catalyzing the hydrolysis of urea into ammonia and carbon dioxide, generally demonstrate significantly higher activity in soils with CC.

Keywords: woody crops; carbon sequestration, enzymatic activities, soil health

In-situ measurement of surface soil reflectance with SoilPRO® apparatus

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The general aim of the ProbeField project is to develop a novel protocol for robust in field monitoring of carbon stocks and soil fertility based on proximal sensors and existing soil spectral libraries. This study introduces an innovative approach for the accurate assessment and harmonization of undisturbed soil surface spectra under field conditions, achieving laboratory-grade precision, while minimizing systematic discrepancies. The SoilPRO® assembly was employed for its efficacy in precisely measuring seven different soil samples under similar field and laboratory conditions in six different laboratories. While some discrepancies were noted in and between field and laboratory measurements, aligning the laboratory measurements with a reference sample, Lucky Bay (LB) internal soil standard (ISS), significantly reduced variations across different laboratory settings. A similar approach was employed to align field spectra through the use of a field ISS (FISS), which could be practically applied in the field and adjusted to the laboratory reference LB before utilization. Correcting to the FISS facilitated the alignment of field reflectance among the six laboratories and closely matched with laboratory ISS measurements adjusted to the LB standard. This alignment of field reflectance with ISS-corrected laboratory measurements represents a ground-breaking achievement in field soil spectroscopy, which suffers from instabilities. It not only ensures preservation of the soil surface condition in the field, but also enables objective comparisons with all soil spectral library (SSL) measurements and robust harmonization of field spectral data from different sources. This study marks the first use of a controlled method for soil-surface spectroscopy measurements, opening a path for the construction of in-situ SSLs. This development is a significant stride forward in obtaining more accurate and standardized soil analyses.

Keywords: soil field spectroscopy; standard and protocol; harmonization; internal soil standards; SoilPRO®

Adjustments of the Rock-Eval® thermal analysis for SOC and SIC quantification: application on calcareous soils and soil fractions

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Standard methods to quantify both soil organic and inorganic carbon (SOC & SIC) in calcareous soils requires pretreatments (carbonate or organic matter removal), at least two aliquots, and calculations. This procedure can lead to i) analytical bias due to pretreatment, ii) measurement deviation stemming from the heterogeneity of the bulk and pretreated aliquots, and iii) cumulative errors associated with the calculation. Thus, thermal analyses may be useful tools for quantifying SOC and SIC content on a single non-pretreated aliquot. Originally developed in the 1970s by IFPEN for studying oil-bearing rocks, the Rock-Eval (RE) analysis has been increasingly used to quantify and characterize SOC. Previous work has also used the RE to estimate both SOC and SIC contents from the TOC and MINC standard parameters respectively, calculated from the carbonaceous effluents emitted during the ramped pyrolysis of the aliquot and the ramped oxidation of the residue. In literature, statistical corrections of the TOC and MINC parameters have been proposed to improve SOC and SIC content estimations using the RE analysis, but no adjustment of the RE standard analysis cycle has been investigated.

This study aims at adjusting the RE standard cycle to quantify SOC and SIC without using statistical corrections and exploring the impact of these adjustments on the indices used to characterize SOC (*e.g.*, Hydrogen index, Oxygen index, I-index, R-index). A panel of calcareous soil samples and soil fractions with a wide range of SOC and SIC contents was analyzed by both standard and adjusted RE cycles. Results from the soil samples were also compared to SOC and SIC quantifications by an Elemental Analyzer (EA) after carbonate and organic matter removal, respectively.

First, the total carbon content measured by RE systematically underestimated the total carbon content assessed by EA for samples with high SIC contents. The CO_2 signal obtained for crucibles containing more than 4 mg of SIC dropped suddenly at the end of the oxidation, suggesting a stop of the SIC thermal breakdown. To address this issue, the final oxidation isotherm was extended to complete the SIC thermal breakdown.

Secondly, the pyrolysis thermograms showed that, after 550°C, a part of thermoresistant SOC and a part of SIC, decomposed simultaneously. To avoid the mixing of fluxes and the need for statistical corrections, the pyrolysis was stopped at a lower temperature to decompose SIC exclusively during the oxidation, where the separation of SOC and SIC was clearer.

The new analysis cycle (extended oxidation and low temperature pyrolysis) improved the estimation of C contents compared to EA without any statistical corrections. The SOC indices are little affected by the cycle adjustments and are correlated to those obtained with the standard cycle. This new cycle of RE analysis provides more accurate estimations of SOC and SIC contents and characterizes SOC with a single analysis. Such an analysis is particularly relevant to explore SOC and SIC in soil fractions as it requires small sample amounts of a single aliquot and no sample pre-treatment.

Keywords: C data acquisition; SOC characterisation; lab methodology

Advancements in non-invasive soil salinity monitoring: integrating electromagnetic induction, inversion, and remote sensing techniques

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Keywords: Soil Salinity; Electromagnetic Induction; NDVI; Inversion; Monitoring

Soil salinization poses a significant threat to agricultural productivity worldwide, leading to soil degradation, hindered plant growth, and even desertification. Addressing this issue is crucial due to its adverse social, economic, and environmental impacts. As agricultural practices intensify and global warming progresses, it becomes critical to adapt management strategies to mitigate and manage soil salinity effectively. To achieve this, there is an increasing need for efficient field-assessment methods capable of mapping and monitoring soil salinity dynamics.

Traditional methods have often limitations in addressing the soil salinity dynamics at a field scale, due to a small scale of investigation. Hence, our study aims to evaluate the effectiveness of non-invasive, cost-effective Electromagnetic Induction (EMI) sensors and emerging inversion techniques in monitoring soil salinity across various irrigated agricultural lands in several Mediterranean countries. Additionally, we assessed the possibility of using Sentinel-2 NDVI imagery in combination with EMI to further study the impact of salinity on crop development during the crop season.

Our methodology involves several key steps: conducting repeated (time-lapse) EMI surveys to measure soil apparent electrical conductivity (ECa), inverting ECa data to evaluate spatiotemporal soil electrical conductivity (σ) distribution, calibrating σ with proxies for soil salinity (ECe), converting σ distribution into salinity cross sections using calibration equations, and comparing NDVI imagery with σ distribution. We also assessed the prediction ability of in-situ established calibrations across different spatial and temporal scales.

Our findings reveal that the EMI can predict soil salinity with reasonable accuracy in most study sites. However, efficacy of our methodology depends on the soil salinity levels and spatial variability of other soil properties, such as soil texture and moisture content (θ), which influence the EMI signal. While accurate predictions of soil salinity were achieved in regions with higher salinity levels and less

variability in soil texture, challenges arose in predicting soil salinity dynamics over large areas due to the variability of dynamic parameters like θ, soil temperature, and groundwater salinity. In one case study where the NDVI was assessed for the growing season, the observed spatial distribution of EC exhibited a steadily increasing inverse correlation with NDVI throughout the growing season. This finding confirms the potential of EMI tomography in conjunction with NDVI imagery for providing a detailed spatial assessment of soil salinity impacts on crop development throughout the growing season.

Predicting soil salinity dynamics over large areas from time-lapse EMI data proved more challenging due to the substantial variability of dynamic parameters, including θ, soil temperature, and groundwater salinity, all of which significantly impact the EMI signal and complicate the inference of soil salinity changes. This challenge was particularly pronounced in assessing soil salinity in topsoil in most of our study sites.

Mapping compost and digestate spreadings from Sentinel-2 and Sentinel-1 on a farm scale

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According to few recent studies, exogenous organic matters (EOM) can be detectable on either emerging vegetation or bare soil using optical and radar remote sensing techniques. Nevertheless, these image processing approaches considered one single EOM, one season and/or year only and were limited to one surface condition prior to spreading. So far no method addressed the simultaneously tracking of both liquid and solid EOM applications using satellite imagery, for several years and surface conditions. Relying on Support Vector Machine (SVM) classifier, this study aimed to track applications of both composted manure and liquid digestate over three periods and years in agricultural fields on a farm scale with distinct surface conditions (grassland, winter crop, bare soil) in Nouzilly, France. Various combinations of covariates from Sentinel-2 and Sentinel-1 data served to train SVM in a bootstrapping approach in order to assess the uncertainty of map results. Classification performance was higher for pre- and post-application image pairs compared to post-application images alone and slightly improved when adding Sentinel-1 data. While the areal percentage of the highest uncertainty class covered less of 10% of the mapped area regardless of the year, the best models showed accuracies higher than 93% in 2020 and 2021. In 2019, the overall accuracy did not reach more than 79%, probably due to rainfall events and considerable time lags between the image pairs. This study underscores not only the potential of Sentinel-2 and 1 for monitoring EOM applications, but also the requirement of better understanding the spectral behaviour of the EOM spreadings, in line with a thorough characterization of the sequence of crop technical management.

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Keywords: compost; digestates; spreadings; Sentinel; machine learning; SVM

The impact of different fertilization on total organic carbon content and the spectroscopic properties of soil organic matter after fifty five years of rye and maize monocultures

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The research was related to the issue of carbon sequestration, and aimed to determine the impact of long-term diversified cultivation on the content of soil organic matter and the properties of its most persistent fraction. They were carried out on plots of the long-term field experiment established in 1967 in the Norekiskes1 area of the Experimental Station of the Vytautas Magnus University, Agricultural University in Kaunas, Lithuania. The experiment was established on loam Cambisol and included plots on fallow and two cultivation variants: rye monoculture and corn monoculture. Three fertilization variants were used for each crop: no fertilization as a control (CON), NPK fertilization (NPK) and NPK fertilization with manure and legumes (NPK+MAN+LEG).

Soil samples were collected from A horizon and analysed for total organic carbon (TOC), fractional composition of humic substances, and spectroscopic properties of isolated humin fraction (HUM). HUM was obtained after discarding humic and fulvic acids, and digesting the mineral residue in an HF-HCl mixture. The obtained HUM was purified by dialysis, and then freeze-dried. To analyse HUM spectroscopic properties absorption spectra in the UV-Vis range and fluorescence spectra (synchronously scanned SSF and three-dimensional EEM matrix spectra) were recorded.

Compared to fallow, both the cultivation of rye and maize monoculture exhibited the increase in TOC content, which was especially evident in the case of maize fertilized with manure accompanied by the application of legume. However, in relation to CON, application of manure with legume resulted in a statistically significant increase in the TOC content only in the case of maize monoculture. No clear statistical dependencies were found in the fractional composition of SOM, but there was a significantly lower % share of HUM in fallow soils. The application of manure and legume in both crops caused a

reduction in the share of HUM in humic substances, however, this management did not result in a decrease in HUM total amount, when expressed in g kg^{-1}.

The UV-Vis properties of HUM isolated from NPK+MAN+LEG objects indicated the lower polymerization degree of this fraction, compared to CON. This is related to the presence of chemically young aromatic structures originated from lignin introduced with organic components applied. The fluorescence spectra of this HUM indicated its enrichment in protein- and/or phenol-like fluorophores.

The results confirmed the beneficial effect of long-term organic fertilization on carbon dioxide sequestration, especially compared to fallow. However, it is strongly depended on cultivated plant type. The most beneficial changes were found in maize monoculture as a result of fertilization with manure and legume application. UV-Vis and fluorescent properties indicate that this kind of management contributes to the formation of a HUM fraction with less complex structure, enriched in the protein- and/or phenol-like fragments.

The research was financed by the EJP SOIL program (NCBR project EJPSOIL/I/78/SOMPACS/2022, and the Ministry of Agriculture of the Republic of Lithuania project TM-22-1).

Keywords: long-term field experiment; carbon sequestration; SOM spectroscopic properties; humin; fluorescent properties, UV-Vis.

Unveiling soil properties from FTIR spectra

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In general, various physicochemical properties of soils can be predicted from spectra of different types (FTIR, vis-NIR, X-ray fluorescence). The EJP Soil ProbeField project (*A novel protocol for robust in-field monitoring of carbon stock and soil fertility based on proximal sensors and existing soil spectral libraries*) proposes innovative techniques for determining SOC stocks and other relevant properties to the health of EU soils. This study aims to predict soil properties using partial least squares regression (PLS) models and identify significant spectral bands for predicting soil physicochemical properties. To achieve this, 28 soil samples from Andalusia were analyzed using infrared spectroscopy (FTIR) (400–4000 cm^{-1}), and various soil properties (calcium carbonate, sand, silt, clay, available P, and available K contents) were determined using conventional laboratory techniques. The applied protocol includes: i) optimizing prediction models for each property using partial least squares regression (PLS) applied to FTIR spectra, ii) testing methods to extract spectral features showing bands with greater importance in prediction, and iii) identifying mineral components acting as surrogate descriptors. Good predictions were obtained for the considered parameters, with cross-validation functions with R^2 and RMSE values of 0.904 and 4.147 for silt content, 0.878 and 4.778 for clay content, 0.813 and 9.451 for sand content, 0.874 and 5.819 for available P, and 0.803 and 139 for available K. The best prediction was for calcium carbonate content, which showed an R^2 = 0.984 and RMSE = 2.789, being notable the fact that, in this case, the highest values of VIP (variable of importance in the prediction) corresponded to the small bands at 2500 and 2900 cm^{-1}, which were the most useful for quantification, higher than that of the most intense carbonate bands (at 1425, 875 and 718 cm^{-1}), which overlap to a greater extent with that of other minerals. Mean centering and multiplicative scatter correction (MSC) were the most satisfactory spectral pretreatments. Spectral patterns of different soil components (carbonates, hydrated oxides and silicates, quartz, kaolinite, and smectite clay minerals) were shown to be influential according to the model for each parameter. Finally, and to illustrate to what extent the different spectral bands were important in the prediction of each soil property, the strategy of

constructing subtracted scaled semispectra (SSS) was used, ie., calculating two spectra, one of which shows the bands that predominate in the samples with high values (above the average) of the property, and the other one, the bands that predominate in the samples with low values. As the profile of these SSSs largely resembles that of the FTIR spectra of wellknown soil minerals, the mineralogical composition associated with the values of different soil properties was tentatively proposed. Although the number of samples in this study is small, it has allowed for pilot exploratory studies on data management strategies that enable the extraction of maximum possible information from spectroscopic patterns in the case of larger databases.

Keywords: MIR spectroscopy, partial least squares regression, PLS, proximal sensors

Temporal S2/S1 mosaics combined with environmental covariates for regional SOC mapping: lessons from la Beauce (France) and the Veskra-Skaraborg (Sweden)

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Satellite-based soil organic carbon content (SOC) mapping over wide regions is generally hampered by the low soil sampling density and the discrepancy of soil sampling collection dates. Some unfavorable topsoil conditions, such as high moisture, roughness, the presence of crop residues, the limited amplitude of SOC values and the limited area of bare soil when a single image is used, are also among the influencing factors. For two contrasted wide agricultural areas in boreal and temperate zones, Veskra-Skaraborg (Sweden) and la Beauce (France), this study compares approaches relying on Sentinel-2 (S2) temporal mosaics of bare soil (S2Bsoil) over ≥5 years jointly with Sentinel 1, SOC measurements data and other environmental covariates derived from digital elevation models and/or lithology maps and/or airborne gamma-ray data.

Prediction models relied on quartile random forest, with 10 fold cross-validation, according to several datasets: i) “Sentinel-2”, the Sentinel-2 bands of a given S2Bsoil; ii) “terrain”, the terrain covariates (Digital Elevation Model and its derivatives, plus oblique geographic coordinates); iii), “Sentinel-2” plus “terrain”; iv) “all”, i.e. “Sentinel-2”, “terrain” and a selection of relevant Sentinel-2 spectral indices.

Lessons from la Beauce (Urbina-Salazar et al., 2023) deal with (i) the dates and periods that are preferable to construct temporal mosaics of bare soils while accounting for soil moisture and soil management; (ii) which set of covariates is more relevant to explain the SOC variability. The models

using all the covariates had the best model performance. Airborne gamma-ray thorium, slope and S2 bands (e.g., bands 6, 7, 8, 8a) and indices (e.g., calcareous sedimentary rocks, “calcl”) from the “late winter–spring” time series were the most important covariates in this model. Our results also indicated the important role of neighboring topographic distances and oblique geographic coordinates between remote sensing data and parent material. These data contributed not only to optimizing SOC mapping performance but also provided information related to long-range gradients of SOC spatial variability, which makes sense from a pedological point of view.

Lessons from the Veskra-Skaraborg deal with the impact of percentile thresholding for temporal mosaicking of bare soils in relationship with soil moisture and cloud frequency. Performance decreased from R90 to R25. Models were highly predictive over both Plain (RPIQ≤1.3) or Till, yet with a slight improvement for Till (best RPIQ 1.4). Results confirm the differences in performances according to soilscape and agricultural system, and the complex interactions due to soil moisture in satellite-based soil property mapping.

For both study áreas, spectral models alone were not well performing, but covariates such as morphometric layers slightly improved the prediction from temporal mosaics of bare soils.

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Keywords: bare soil temporal mosaicking, quartile random forest, Sentinel-2, soil organic carbon

Mapping soil organic carbon content by combining time series of Sentinel-2 and Sentinel-1 with vis-NIR laboratory spectra – Application to study site in Brittany (France)

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Mapping Soil organic carbon (SOC) is essential for continuous monitoring of its spatial and temporal dynamics. In this study, we developed a method using time series of Sentinel-2 (S2) data combined with Sentinel-1 (S1) and vis-NIR laboratory spectra to map SOC content of agricultural soils. The study site, located in Brittany (northwest France), is an agricultural area of 1.5 km². Soil samples were collected from agricultural fields within this site, their SOC content measured and their spectra recorded under laboratory conditions. The SOC content ranged from 15.2 to 49.4 g.kg^{-1}. Deep neural network algorithms were implemented after dividing the data set built up from the time series of S2 and S1 images into calibration (70%) and validation (30%) sets. Three random draws of the validation sets were performed to assess model robustness. Four approaches were tested: (1) models developed using S2 bands as a single input, (2) applying multiple factor analysis (MFA) to select 12 of 40 indices calculated from S2 data and adding them to the S2 bands, (3) adding soil moisture derived from the time series of S1 (SM1), and (4) gradually adding five indices calculated from laboratory spectra, in descending order of their correlation with SOC. Model performance was compared based on validation results, and semi-variograms for observed and predicted SOC were then used to analyze the maps generated. Results showed that only models using approach 4 were validated (RPIQ = 1.78±0.19 - 3.07±0.6). The addition of SM1 improved model robustness since predictive performance remained stable over the 3 random draws of the validation sets. In approach 4, laboratory indices showed significant correlations with SOC content. Thus, we were able to validate our models once we added the two indices with the highest correlation. Semivariograms of the predicted values showed

lower sill-to-nugget ratios but similar shapes to the observed values. Finally, the developed method allowed us to map 70% of the area of the study site.

Keywords: Soil organic carbon content, Sentinel-2, time series, Deep Neural Network,