Annual Science Days 2024

BOOK OF ABSTRACTS

Block C

Contents

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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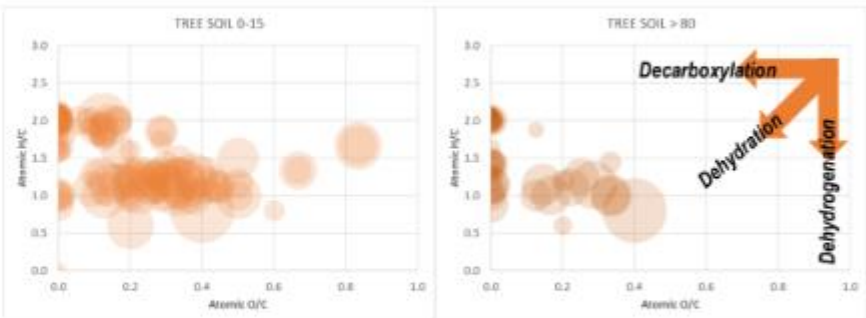
Soil organic matter (SOM) is an important factor in carbon sequestration that helps mitigate global change. Human activities such as land-use changes, agriculture, and forestry management can affect SOM dynamics. For example, practices like no-till agriculture or reforestation can lead to the accumulation 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 $^{13}CO_2$ 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.

Acknowledgment

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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 90^{th} percentile. The reasoning behind the 90^{th} 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,