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Spatially explicit effects of land use change on organic carbon stocks of agricultural soils in Europe

Schneider Florian*, Poeplau Christopher and Don Axel

Thünen Institute of Climate-Smart Agriculture, Bundesallee 65, 38116 Braunschweig, Germany

** Presenting author: florian.schneider@thuenen.de*

Minor alterations in global soil organic carbon (SOC) stocks can cause major changes in the concentration of atmospheric carbon dioxide. In mineral soils, land-use change typically exhibits the strongest anthropogenic effect on SOC stocks. However, site-specific effects of land-use change on SOC stocks may depend on environmental properties such as climate and soil texture. In the present study, we provide spatially explicit, quantitative estimates for the effect of agricultural land-use change on SOC stocks in Europe. Specifically, we addressed the question of how much atmospheric carbon European agricultural soils could sequester if today's cropland were converted to grassland.

Our predictions were derived by applying novel data-driven reciprocal modelling to 3,770 grassland and 6,155 cropland sites of the LUCAS soil survey. In brief, a Random Forest model was trained to predict the SOC stocks of grassland. This model was then applied to cropland soils, with predictions being restricted to the model's space of applicability.

In the remaining croplands, the model predicted SOC stocks to be 12.1 Mg C ha^{-1} (95 % CI, 11.8 to 12.5) higher on average than measured values (Figure 1). This number illustrates the average SOC accrual if European cropland were converted to grassland. Individual effect sizes differed drastically, but their spatial distribution revealed pronounced regional trends. On a country level, the potential SOC accrual from converting cropland to grassland was predicted to be highest in Belgium (mean 27.2 Mg C ha^{-1}; 95 % CI, 24.7 to 29.3) and lowest in Estonia (mean 5.2 Mg C ha^{-1}; 95 % CI, 0.8 to 8.3). Effects of land-use change on SOC stock were strongly related to climate, mineral N fertilisation, C:N ratios of soils and mean annual NDVI values of the land surface.

These results suggest that data-driven reciprocal modeling may offer a promising alternative to existing process-based, mechanistic modeling approaches that still struggle to accurately describe the site-specific effects of land use change on SOC. Data-driven reciprocal modeling allows effect size to be estimated by analyzing associations alone, without understanding causality. They provide the best possible quantitative estimate of the effects of land use change on SOC without understanding every detail of their cause, while achieving a maximum of representativeness.

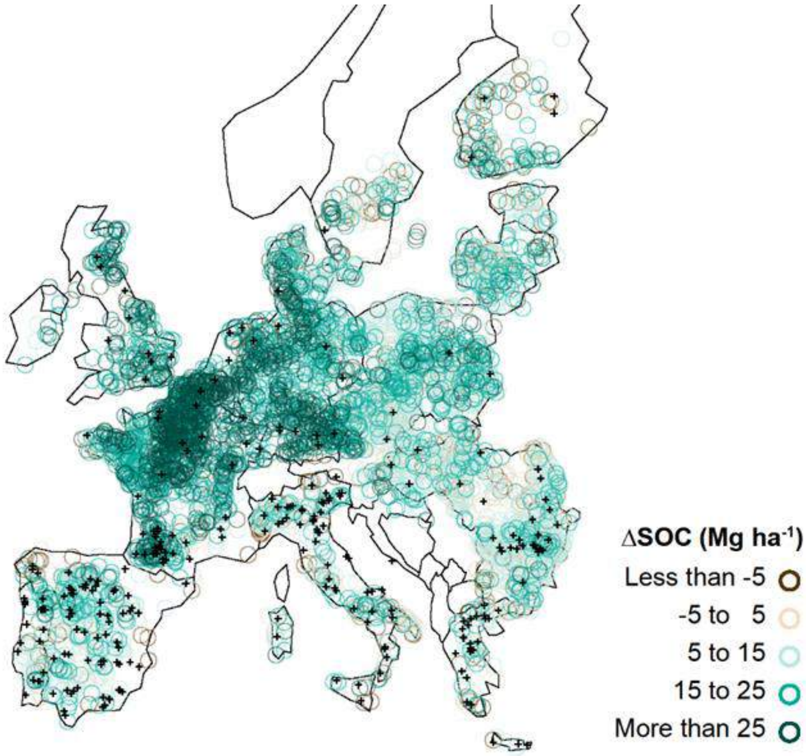

Figure 1. Estimated change in soil organic carbon (SOC) stocks by converting European cropland to grassland. Positive values denote SOC accrual (green colours), negative values SOC losses (brown colours). Crosses represent cropland sites with environmental properties for which no reliable estimate could be made since they were located outside the model's space of applicability. Modified after Schneider et al. (2021) GCB 27, 5670– 5679 (https://doi.org/10.1111/gcb.15817).

Keywords: Soil organic carbon; carbon farming; climate mitigation; machine learning; data-driven reciprocal modelling

Impact of agricultural management on topsoil structure, aggregates and associated organic carbon fractions: Analysis of long-term experiments in Europe

[1,2*]Ioanna S. Panagea, [3]Antonios Apostolakis, [4]Antonio Berti, [5] Pavel Čermak, [1]Jan Diels, [6]Annemie Elsen, [5]Helena Kusá, [4]Ilaria Piccoli, [1,7] Jean Poesen, [8]Chris Stoate, [8]Jenny Bussell, [6]Mia Tits, [9]Zoltan Toth, [1]Guido Wyseure

[1] Department of Earth and Environmental Sciences, KU Leuven, Belgium
[2] Plant Sciences Unit, Flanders research institute for agriculture, fisheries and food (ILVO), Belgium
[3] Max-Planck-Institute for Biogeochemistry, Germany
[4] DAFNAE Department, University of Padova, Italy
[5] Crop Research Institute, Czech Republic
[6] Soil Service of Belgium (BDB), Belgium
[7] Institute of Earth and Environmental Sciences, Poland
[8] Game & Wildlife Conservation Trust, Allerton Project, UK
[9] Institute of Agronomy, Georgikon Campus, Keszthely, Hungarian University of Agriculture and Life Sciences, Hungary

Inversion tillage is a commonly applied soil cultivation practice in Europe, which has been blamed though, for deteriorating topsoil structure and organic carbon (OC) content. This has subsequent negative effects on SOC storage as it increases the outputs through mineralization and leads towards a negative balance between the inputs and outputs. In this study, the potential to reverse these negative effects in the topsoil by alternative agricultural management practices, was evaluated in five long-term experiments in Europe, run by the partners of the Horizon 2020 SoilCare project. Topsoil samples (0 –15 cm) were collected and analyzed to evaluate the effects of conservation tillage (reduced and no-tillage) or increased organic inputs of different origin (farmyard manure, compost, crop residues) combined with inversion tillage on topsoil water retention (SWR), stability, aggregate distribution and within these aggregates fractions, OC distribution. Effects from the treatments on the two main components of organic matter i.e., particulate (POM) and mineral associated (MAOM), were also evaluated. Reduced and no-tillage practices, as well as the additions of manure or compost, increased the aggregates mean weight diameter (MWD) and topsoil OC, as well as the OC corresponding to the different aggregate size fractions. The incorporation of crop residues had a positive impact on the MWD but a less profound effect on OC content both on total OC and on OC associated with the different aggregates. A negative relationship between the mass and the OC content of the microaggregates (53 – 250 μm) was identified in all experiments. There was no effect on the mass of the macroaggregates and the occluded microaggregates (mM) within these, while the corresponding OC contents increased with less tillage and more organic inputs. Inversion tillage led to less particulate organic matter (POM) within the mM, whereas the different organic inputs did not affect it. In all experiment where the total POM increased, the total soil organic carbon (SOC) was also affected positively. The direct impact of the SOC increase on SWR was consistent but negligible, whereas the indirect impact of SOC in the higher matric potentials, which are mainly affected by soil structure and aggregate composition, prevailed. We concluded that the negligible effect of SOC under different management practices during drier conditions, and the increased effect in wetter conditions, implies that the indirect effects of SOC increase in the soil structure, are more important and should be considered and that the negative effects of inversion tillage on topsoil structure and OC content can be mitigated by reducing the tillage intensity or by adding organic materials combined with non-inversion tillage methods, in order to increase the SOC stocks and diminish the decomposition of old OC.

Keywords: soil structure; organic matter fractionation; aggregate distribution; water retention

Why a project on soil organic carbon dynamics in inorganic carbon-rich soils?

Chevallier Tiphaine[1*], Cournac Laurent[1], Sebag David[2], Kowalewski Isabelle[2], Hannam Kirsten[3], Ellert Benjamin[4], Gorzelak Monika[4], Dóra Zacháry[5], Zoltán Szalai[5], Gergely Jakab[5], Tibor Filep[5], Marianna Ringer[5], Lucas Trombino[6], Anna Masseroli[6], Eric Verrechia[7]

[1] *UMR Eco&Sols, IRD, Montpellier, France*

[2] *IFPEN, Rueil-Malmaison, France*

[3] *Agriculture & Agri-Food Canada, Summerland, Canada*

[4] *Agriculture & Agri-Food Canada, Lethbridge, Canada*

[5]*Geographical Institute, Research Centre for Astronomy and Earth Sciences, Budapest, Hungary*

[6] *Università degli Studi di Milano, Milano, Italy*

[7] *Institute of Earth Surface Dynamics - Faculty of Geosciences and the Environment, Lausanne, Switzerland*

** Presenting author: tiphaine.chevallier@ird.fr*

Keywords: Biogeochemistry**,** Carbonates, Organic carbon stabilisation, soil C analysis issues [max 5]

Soil is the largest continental carbon (C) sink and contributes to the global C cycle. Two-thirds of soil C is organic (soil organic carbon, SOC). SOC accumulation or loss results from the balance between the capture of atmospheric CO_2 by plants, the incorporation of C-rich plant litter into the soil, and the re-release of this C as CO_2, via root respiration and microbial activity. SOC plays a well-known role in the physical, chemical, and biological properties of soils and the challenge of maintaining soil fertility while promoting soil C storage is widely recognised. The third of soil C is inorganic (soil inorganic carbon, SIC). SIC consists of lithogenic, or petrogenic (primary) carbonates inherited from the bedrock, and pedogenic (secondary) carbonates precipitated in the soil *in situ*. Because SIC pools are generally considered more stable and less sensitive to human activities than SOC pools in the short term, SIC dynamics have received less research interest. Moreover, analytical difficulties in studying SOC and SIC separately have impeded knowledge on the dynamics of SOC in SIC-rich (i.e., carbonate-containing or calcareous) soils. Consequently, the contribution of calcareous soils to the global C balance are given little consideration, even though they cover one third of the Earth's surface.

Although interactions between SIC and SOC pools have been described in the short-term, they are poorly understood. Isotopic analyses have shown that SIC-rich soils emit CO_2 from both the organic and inorganic C pools. Furthermore, soil biota (bacteria, roots, fungi) have the ability to precipitate bio-minerals (SIC) during the metabolic transformation of SOC (inherited or neoformed origin of SIC). Our project proposes the simultaneous study of SOC and SIC content, composition and dynamics. The unique processes of SOC stabilization in soil containing SIC will be also studied. The main objectives are to propose innovative analytical tools for quantifying and describing SOC and SIC, and to acquire knowledge on C interactions and C balance in calcareous soils, according to the use and management of the soils.

The project is based on 3 scientific work packages: **(1)** Integrated methodology to study SOC and SIC forms: protocols to analyse SOC and SIC pools will be compared and developed **(2)** Processes of SOC stabilisation in carbonate soils: thermal, physical (size), chemical and morphological analysis of SOC in different calcareous contexts will be used to explore the relationships between SOC and SIC. And **(3)** contributions of SIC and SOC to C fluxes between the soil and atmosphere: relationships between soil properties, SIC and SOC forms, and C dynamics will be studied through soil incubation studies; data will be used to develop a model that can be used to explore interactions between SOC and SIC pools in situ. Research will mainly focus on the solid phases of SOC and SIC in a collection of soils with varying SOC and SIC contents. Finally, our ambition is to build a scientific community studying the C cycle in calcareous soils.

[max 500 words]

Retrieving SOC content from space at the detailed scales of small regions: purposes and first results of the EJP-STEROPES project

Emmanuelle Vaudour[1*], Johanna Wetterlind[2], Luboš Borůvka[3], James Biney[1, 3], Diego Urbina-Salazar [1, 5], Asa Gholizadeh[3], Fabio Castaldi[4], Dominique Arrouays[5], Anne C. Richer-de-Forges[5], Mohammadmehdi Saberioon[6, 7], Pasquale Nino[8], Silvia Vanino[8], Fenny van Egmond[9], Renaldas Žydelis [10], Didier Michot[11], Youssef Fouad[11], Artur Lopatka[12], Jose L. Gabriel[13], Nádia Castanheira[14], Ana Marta Paz[14], Muhammed Halil Koparan[15], Cantekin Kivrak[15], Frank Liebisch[16], Raimonds Kasparinkis[17], Mogens H. Greve[18]

[1] *Université Paris-Saclay, INRAE, AgroParisTech, ECOlogie fonctionnelle et écotoxicologie des agroécoSYStèmes, 78850 Thiverval-Grignon, France.*

[2] *Swedish University of Agricultural Science (SLU), PO Box 234, SE-532 23 Skara, Sweden*

[3] *Department of Soil Science and Soil Protection, Faculty of Agrobiology, Food and Natural Resources, Czech University of Life Sciences Prague (CZU), Kamýcká 129, Prague-Suchdol, 16500, Czech Republic*

[4] *Institute of BioEconomy, National Research Council of Italy (CNR), Via Giovanni Caproni 8, 50145 Firenze, Italy.*

[5] *INRAE, Infosol, 45075 Orléans, France*

[6] *ILVO, Flanders Research Institute for Agriculture, Fisheries and Food, Technology and Food Science-Agricultural Engineering, 9820, Merelbeke, Belgium*

[7] *Section 1.4 Remote sensing and Geoinformatics, German Research Centre in Geosciences, Telegrafenberg, 14473 Potsdam, Germany*

[8] *Council for Agricultural Research and Economics (CREA) Via Po 14, - 00198 Roma*

[9] *Wageningen Environmental Research, Droevendaalsesteeg 3, Wageningen, the Netherlands*

[10] *Institute of Agriculture, Lithuanian Research Centre for Agriculture and Forestry (LAMMC), Instituto al. 1, Akademija, LT-58344 Kėdainiai, Lithuania*

[11] *UMR SAS, Institut Agro, INRAE, 35000, Rennes, 65, rue de Saint Brieuc, France.*

[12] *Institute of Soil Science and Plant Cultivation – National Research Institute (IUNG), Czartoryskich 8, 24-100 Puławy, Poland*

[13] *INIA-CSIC, Ctra. de la Coruña km 7,5, 28040 Madrid, Spain.*

[14] *National Institute for Agricultural and Veterinary Research (INIAV), Av. da República, Quinta do Marquês, 2780-157 Oeiras, Portugal.*

[15] *Republic of Turkey Ministry of Agriculture And Forestry General Directorate of Agricultural Research And Policies (TAGEM), Çankaya/Ankara 06800 Turkey*

[16] *Agroscope, Research Division Agroecology and Environment, Reckenholzstrasse 191, CH-8046 Zürich, Switzerland*

[17] *Department of Agroecology, Aarhus University (AU), Blichers Allé20, 8830 Tjele, Denmark*

[18] *Faculty of Geography and Earth Sciences, University of Latvia (UL), 19 Raiņa Blvd., Riga, Latvia*

Conventional high-detail soil maps are static and often based on obsolete data in relation to the time of use. In the framework of the European Joint Programme (EJP) SOIL, the EJP-STEROPES project initiated in February 2021 gathers 14 countries (https://ejpsoil.eu/soil-research/steropes/). As multispectral satellite series such as Sentinel-2 time series are now freely available with a weekly frequency, STEROPES aims to assess the potential to predict cropland soil organic carbon content from such satellite data over various pedoclimatic conditions and cropping systems across Europe. While encouraging performances were recently obtained from Sentinel-2 (S2) for temperate soils of Europe and annual crop systems, little is known about the S2 capabilities for many other soil types and agroecosystems across Europe. Therefore, the focus lays on a detailed mapping that could serve as key information in decision making for farmers, governmental institutions and agricultural advisers, or other stake-holders involved in land planning.

Several datasets have been collected focusing on small regions of some hundreds of km^2 or on detailed scales of farms or catchments of some km^2, for which soil organic carbon samples were already available with an areal density higher than 1-3 samples/km^2. Spectral models were constructed from the reflectance image spectra of optical satellite series, using several commonly used algorithms including partial least squares regression (PLSR), support vector machine regression (SVM) and random forest (RF).

Overall encouraging performances have been obtained (RPIQ >1.7), but vary in time and geographical space according to several factors especially soil moisture, texture, dry vegetation due to management practices, and salinity. The following stages of the STEROPES project include the analysis of each of these disturbing or influencing factors and their joint effect.

The project is closely linked with the achievement of task 6.4 within WP6 in the EJP Soil, which aims at developing methods for accounting, monitoring and mapping agricultural soil carbon, fertility and degradation changes, with particular focus on using innovative inventory techniques such as proximal sensing integrated with current and upcoming satellite products.

Keywords: satellite remote sensing; Sentinel-series, soil organic carbon content; croplands

THE EFFECT OF TWO DIFFERENT ROTATION SYSTEMS ON SOIL ORGANIC MATTER IN ORGANIC FORAGE CULTIVATION

Ulfet ERDAL[1*], Ahmet Esen CELEN[2]

[1]International Agricultural Research and Training Center, Menemen, Izmir, Turkey
[2]Department of Field Crops, Faculty of Agriculture, Ege University, Bornova, Izmir, Turkey
*Corresponding author: ulfeterdal@yahoo.com

Abstract

Crop rotation has a key role in improving the soil and increasing the yield. Crop rotation with legumes, recycling of crop residues and the application of organic manure must form the basis of nutrient management in organic farming. Presence of legumes in rotation may serve as the primary source of nitrogen for subsequent crops. Most deficiencies in the soil are directly linked to low organic matter content. Organic matter has a very crucial significance for soil fertility improvement. The aim of this study was to determine the effects of some plants used in animal feeding on soil organic matter (SOM). For this purpose some certain plants have been selected and tested in two different rotation systems. This study was carried out in Menemen Plain, in Aegean Region, Izmir, Turkey during a period of 5 years between 2012 and 2016. Trial was set up in a randomized block design with four replications. According to the results of soil analysis, organic fertilizer containing 2 % N, 2.5 % P2O5, 2.5 % K2O, 60 % organic matter and 9/12 C/N was given to the plots. Fertilization was carried out so as not to exceed 170 kg / ha nitrogen as stated in the organic farming law. In the study, the fertilizer applications required by the plants were made considering the residual nitrogen from the plant roots. In the first rotation system Persian clover - silage maize, vetch/triticale mixture– cotton, Persian clover - silage maize, vetch/triticale mixture – cotton, in the second rotation system Persian clover - silage maize, triticale (grain) – second crop soybean, Persian clover - silage maize, triticale (grain) – second crop soybean were consecutively cultivated for five years. Soil organic matter (SOM) in soil samples taken from 0-20 and 20-40 cm in rotation system mentioned above was analyzed. According to analysis results, plant in the first rotation system affected SOM better than those of the second rotation system. It can also be stated that selected crops play an important role in SOM.

Keywords: *Crop rotation, Organic forage crop, Soil organic matter* (SOM).

Synergies and trade-offs of carbon sequestration in agricultural soils: a global literature synthesis

Sánchez-Moreno Sara[1], Petersen Søren O.[2], Velthof Gerard[3], Munkholm Lars[2], Ros Mart[3], Feizene Dalia[4], Gómez-Gallego Tamara[5], Jeanbille Mathilde[6], Dammie Nompumelelo[7], Juhanson Jaanis[8], Peixoto Leanne[2], Feiza Virginijus[4], Aponte Cristina[1], Parasotas Irmantas[4], Kochiieru Mykola[4], Amaleviciute-Volunge Kristina[4], Pulido-Moncada Mansonia[2], Walder Florian[7], Ramos Juan Luis[5], Philippot Laurent[6], van der Heijden Marcel[7], Hallin Sara[8] and Goberna Marta[1*].

[1] *Instituto Nacional de Investigación y Tecnología Agraria y Alimentaria (INIA-CSIC), Madrid, Spain*

[2] *Aarhus University, Aarhus, Denmark*

[3] *Wageningen Enviromental Research, Wageningen University & Research, Wageningen, Netherlands*

[4] *Lietuvos Agrariniu Ir Misku Mokslu Centras (LAMMC), Akademija, Kedainiai, Lithuania*

[5] *Estación Experimental del Zaidín (EEZ-CSIC), Granada, Spain*

[6] *Institut national de recherche pour l'agriculture, l'alimentation et l'environnement (INRAe), Dijon, France*

[7] *Agroscope, Zürich, Switzerland*

[8] *Swedish University of Agricultural Sciences (SLU), Uppsala, Sweden*

** Presenting author: marta.goberna@inia.es*

Agricultural management practices aimed at minimising soil disturbance, diversifying cropping systems and increasing organic matter inputs, often referred to as conservation agriculture, promote carbon (C) sequestration in soils. Enhanced C storage can have synergies with many agroecosystem services, but may come at the cost of climate regulation services depending on the environmental context. To review the trade-offs and synergies of C sequestration in agricultural soils, we performed a global systematic literature synthesis to address: 1. What are the synergies of C sequestration practices with soil structure and soil biota?, 2. What are the associated trade-offs with respect to greenhouse gas (GHG) emissions and nutrient losses?, and 3. How does the magnitude of synergies and trade-offs vary across pedoclimatic regions and change over time since adoption of conservation agricultural practices?

We defined search terms and performed systematic literature searches in the Web of Science for articles that: 1. experimentally assay the effect of conservation agriculture, and 2. include measurements of C sequestration and at least one other response variable related to synergies or trade-offs with nutrient losses or climate regulation services. We retrieved 771 publications, 565 of which were excluded based on i) the type of article (review, opinion papers), ii) a focus on non-soil habitats, forests or organic soils, or iii) experimental designs not matching our criteria. We included 206 studies that report 502 effects of conservation practices on 215 sites located in 34 countries. Experiments averaged 9.6 years of monitoring and the majority reported effects of increasing organic matter inputs and minimising soil disturbance (89%) in temperate and continental climates (80%). Considering all management practices together confirmed that soil organic C increased, without compromising crop yields. Synergistic effects were found for soil biota, i.e. positive effects of conservation versus standard practices on soil biota biomass were more frequent than expected by chance. There were no clear effects on biodiversity. However, in terms of soil structure and physical properties equal numbers of positive and neutral effects were detected. Negative effects of C inputs were significant when considering GHG emissions and nutrient losses, and similar numbers of negative and neutral effects were found for CO_2 and N_2O emissions, and nitrogen and phosphorus losses. We examine how these effects vary across management practices, time and space, and discuss implications for mitigation strategies. Furthermore, we review the main knowledge gaps detected in the literature and the present analysis that should be covered in future research.

Keywords: agricultural management, soil biota, soil structure, greenhouse gas emissions, nutrient losses

Soil carbon sequestration is possible without trade-offs

Keel Sonja G.[1*], Bretscher Daniel[1], Leifeld Jens[1], von Ow Albert[2] and Wüst-Galley Chloé[1]

[1] *Agroscope, Climate and Agriculture Group, Zurich, Switzerland*

[2] *Agroscope, Economic Modelling and Policy Analysis Group, Tänikon, Switzerland*

** Presenting author: sonja.keel@agroscope.admin.ch*

After the 4p1000 initiative was launched, it received mixed critique in the literature. The initiative highlighted that an annual increase of 4 ‰ soil organic carbon per year in the upper 30 to 40 cm of soil, would significantly reduce atmospheric carbon dioxide concentrations. Potentials to sequester carbon were said to be strongly overestimated because limiting factors such as the availability of nutrients were ignored. Furthermore, increasing fertilization rates to enhance carbon inputs through higher biomass was criticized, as it may result in negative trade-offs such as enhanced ammonia and nitrous oxide (N_2O) emissions as well as nitrate leaching.

Using Switzerland as an example, we show that significant rates of soil carbon sequestration can be achieved without causing trade-offs for greenhouse gas emissions. We study the potential of cropland that can be allocated to biochar production instead of food production, while assuming no further increase of food and feed imports. Since plant-based food production is more efficient than animal food production, feed production on cropland soils, which currently occupies 60 % of the arable area is strongly reduced and creates free land. The resulting diets become healthier by decreasing the consumption of oil, sugar and alcohol and a moderate decrease in meat intake. These reductions are compensated by increases in the intake of starch and dairy products. Under this scenario it is possible to maintain methane (CH_4) and N_2O emissions, despite a projected increase in the Swiss population of 43 % until the year 2100 and an associated increase in food demand. In contrast, CH_4 and N_2O emissions would increase by 25 % and 14 % in the baseline scenario, which only accounts for an increasing population, but minimizes changes in diets. The resulting free land, which we suggest can be turned into agroforestry, is used to produce woody biomass. We assume a planting of short rotation coppice (fast growing trees) in rows along fields, which do not require fertilization and are regularly harvested to produce biochar. This biochar is then applied as a soil amendment on remaining cropland soils. On average a sequestration rate of 0.53 t C ha^{-1} yr^{-1} or 10 ‰ for 0-30 cm depth could be achieved for the years 2020-2100. However, without an increase in food imports, the area available for agroforestry rapidly declines towards the end of the 21st century because the land is needed for food production due to an increasing population. Yet, because of the longevity of biochar in soil, increased SOC stocks are maintained in the longer run.

In summary, we show that even in a densely populated country considerable rates of soil carbon sequestration can be achieved with benefits for the environment. The biggest challenge however, is how to reach the projected dietary changes. An opportunity might be the involvement of health organizations, because the changes described in this study are likely to have health benefits.

Keywords: greenhouse gas emissions, diet, food security, population growth, 4p1000

Evaluation of soil ecosystem services through soil quality indicators

Janků Jaroslava[1], Tóth Daniel[2], Kozák Josef[1], Borůvka Luboš[1], Maitah Mansoor[3], Poláková Jana[4]

[1]*Department of Soil Science and Soil Protection, Faculty of Agrobiology, Food and Natural Resources, Czech University of Life Sciences in Prague, the Czech Republic*

[2]*Department of Economics, Prague, University College of Business in Prague, the Czech Republic*

[3]*Department of Economics, Faculty of Economics and Management, Czech University of Life Sciences in Prague, the Czech Republic*

[4]*Department of Agroecology and Crop Production, Faculty of Agrobiology, Food and Natural Resources, Czech University of Life Sciences in Prague, the Czech Republic*

** Presenting author: janku@af.czu.cz*

The main objective of our study was to evaluate soil ecosystem services via soil quality indicators. The soil quality indicators selected for our study were the characteristics of soils that contribute most to the ecosystem services. Two methodological approaches which include the EU Urban Soil Management Strategy Project, and the Saaty Method were adopted for our study. The soil quality indicators that were monitored were divided into production, non-production, stable, and variable indicators which our expected result is the number of points depending on the quality of the soil.

The methods were tested in the Central Bohemian region, where with soil cover is heterogeneous in terms of soil quality and thus well represents almost all soil types in the Czech Republic.

The resulting score was converted to maps in ArcGIS. Our results of both approaches are comparable in both location and profile. In addition to this, the point values become the basis for the financial assessment (evaluation) of the land.

In our view, the inclusion of soil ecosystem services in its assessment, including financial ones, will lead to improved soil protection and reduced occupation of quality soils.

Keywords: soil protection, soil quality indicators, soil ecosystem services, Saaty Method

Participatory processes to involve farmers in the identification of Agricultural Soils-based' Ecosystem Services and their Bundles at regional level. Experiences in the Valencian Community (Spain)

Asins-Velis, Sabina[1*] and Molina-Donate, Mª José [1]

[1] *Centro de Investigaciones sobre Desertificación-CIDE, Consejo Superior de Investigaciones Científicas-CSIC, Valencia, Spain*

** Presenting author: sabina.asins@uv.es*

EJPSoil-SERENA Project is dealing with the involvement and engagement of end-users at each step of the Project, to understand their needs and expectations and to validate, step by step, the choices made during it. Participatory research incorporates farmers' knowledge in understanding the long-term construction of the agricultural landscape, and their interactions with the natural environment. At the same time, it favours the analysis of good agricultural practices and planning projects, to achieve the sustainable management of the soil/water territorial resources. The identification of the Agricultural Soils-based' Ecosystem Services and their Bundles can be, at first glance, a complex issue for farmers. However, following in the steps of participatory research processes and citizen science, farmers readily recognize these Bundles. Experiences in Petrer (Alicante), Carrícola (Valencia) and in the Orchard of València show the possibilities of the co-creation in developing hypotheses, defining concepts, obtaining good quality data, discussing and disseminating the results, and maintaining a long-term relation between farmers and researchers to incorporate new data and concepts. Among the Bundles that are best recognized by farmers, we would highlight those that relate several Soils-based' Ecosystem Services, such as: i) Habitat for biodiversity/Greenhouse gas and climate regulation including carbon sequestration; ii) Erosion control/Hydrological control (purification, supply, regulation); iii) Environmental pollution control (e.g. filtration, buffering or sequestration of harmful substances)/Habitat for biodiversity; iv) Environmental pollution control (e.g. filtration, buffering or sequestration of harmful substances)/Primary-biomass production. Similarly, working with them favours the understanding of the Bundles between Soil Threats, such as: i) Soil erosion (water, wind, tillage)/Nutrient imbalance (macronutrients, micronutrients, deficiency/excess); ii) Soil erosion (water, wind, tillage)/Loss of diversity; iii) Soil contamination (e.g. potentially toxic elements, organic pollutants)/Nutrient imbalance (macronutrients, micronutrients, deficiency/excess); and iv) Nutrient imbalance (macronutrients, micronutrients, deficiency/excess)/Soil organic carbon loss. The products that SERENA will develop will be validated by end-users, following a participatory process. These products, including maps and climate and land use change scenarios, will undoubtedly be important tools for designing soil-friendly agricultural policies.

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Keywords: participatory research, farmers' involvement, products validation.

Soil ecosystem service bundles at regional scale: a case study from Emilia-Romagna (NE Italy)

Costanza Calzolari[1], Romina Lorenzetti[1], Eduardo Medina-Roldan[1], Paola Tarocco[2], Fabrizio Ungaro*[1]

[1] *Italian National Research Council, Sesto Fiorentino, Italy*

[2] *Regione Emilia-Romagna Servizio Geologico Sismico e dei Suoli, Bologna, Italy*

* *Presenting author: fabrizio.ungaro@ibe.cnr.it*

Keywords: soil ecosystem services; ecosystem service bundles, indicators, Emilia-Romagna

This work presents an assessment and mapping of bundles of soil-based ecosystem services (SESs) in an intensively cultivated area of Northern Italy, the Emilia-Romagna plain (ca. 12,002 km2).

The study considered the following SESs: 1) habitat for soil organisms (BIO); 2) filtering and buffering (BUF); 3) actual carbon sequestration (CST); 4) food provision (PRO); 5) water regulation (WAR) and 6) water storage (WAS). Normalised (0-1) indicators of each ecosystem service were based on measured soil data and on data derived from locally calibrated pedotransfer functions.

Synergies and trade-offs among the considered soil ecosystem services were highlighted at general and pedolandscapes levels. SESs bundles were identified as recurring clusters in space of specific combinations of high and/or low indicator values for selected SESs indicators. The frequencies of occurrence of the different types of bundles and their spatial patterns over the study area and in the different pedolandscapes were analysed.

The analysis revealed significant differences in the occurrence of bundles typologies in the whole area as well as in the pedolandscapes, providing additional information to support sustainable land policy and planning at different governance levels.

Assessing dependencies between soil ecosystem services by copula modeling

Senga Kiessé Tristan[1], Lemercier Blandine[1*], Corson Michael S.[1], Ellili-Bargaoui Yosra[2], Afassi Jihad[1], Christian Walter[1]

[1] *INRAE, Institut Agro, SAS, F-35000 Rennes, France*

[2] *Interact, UniLaSalle, F-60000 Beauvais, France*

** Presenting author: blandine.lemercier@agrocampus-ouest.fr*

Soils are natural ecosystems that involve multiple variables related to soil properties, climate conditions or human management, all of which influence the ecosystem services (ES) that they provide. Actions or environmental conditions that can improve one ES can, inversely, degrade another ES. Dependence among soil ecosystem services (SES) must therefore be considered to reliably assess risks of improving SES, as a function of soil properties or weather conditions. In this context, the present study described relationships between pairs of regulating and provisioning SES – groundwater recharge (GW), carbon sequestration (CS) and plant biomass provision (YE) – estimated by biophysical soil and crop modeling. The analysis was based on a dataset of 64 cultivated soils located in northwestern France under a single climate observed over 30 years (1988-2018) and a single crop management of a maize and wheat rotation. To describe relationships between pairs of SES, we applied copula modeling as a statistical method that, unlike other statistical methods, can model joint distribution functions of two SES. The copula models identified enabled us to estimate probabilities of exceeding a level of one SES as a function of another SES, when considering a given soil property (lowest or highest organic carbon contents) or weather condition (driest or wettest years). For instance, when YE exceeded a threshold of 20-100 GJ/ha/yr, the probabilities of GW exceeding 200 mm/yr were 0-0.07 during the driest years but 0.78-0.89 during the wettest years. These thresholds of YE influenced the probability of exceeding a given GW threshold more during the driest years than the wettest years. For the same range of YE thresholds, the probabilities of carbon sequestration exceeding 0 kg C/ha/yr were 0.70-0.76 for the lowest soil organic carbon contents but 0.29-0.32 for the highest soil organic carbon contents. Conversely, these thresholds of YE had little influence on the probability of exceeding a given carbon sequestration threshold, regardless of soil organic carbon content. If increasing one SES strongly decreases the probability that another SES will exceed a given threshold (e.g., YE and CW), trade-offs may need to be made between them. By highlighting the degree of dependence between two SES as a function of their ranges of variation, copula models thus provide information that other statistical methods cannot and that may improve understanding or management of ES.

Keywords: soil ecosystem services, soil properties, weather conditions, dependence, copula

Increasing root carbon inputs to agricultural soils by optimized genotype selection

Heinemann Henrike [1*], Hirte Juliane[2], Seidel Felix [1] and Don Axel [1]

[1] *Thünen Institute of Climate-Smart Agriculture, Bundesallee 65, 38116 Braunschweig, Germany*

[2] *Agroscope, Reckenholzstrasse 191, 8046 Zürich, Switzerland*

** Presenting author: henrike.heinemann@thuenen.de*

The removal of carbon (C) from the atmosphere by binding C in soils can play an important role for mitigating climate change. The political pressure to reduce greenhouse gas emissions in agriculture is rising and promotes cropping systems with steady yields, but higher soil C sequestration. To enhance soil organic C stocks, higher organic C inputs to agricultural soils are necessary. Optimized genotype selection and breeding towards increased root biomass may enhance root C inputs and may therefore be a promising, easy-to-implement management option for C sequestration. The potential to increase root C inputs without compromising yield is only shown in few studies. We compiled 14 studies with experimental data in this review in order to estimate the potential of genotype selection to enhance root biomass without compromising yield. We created a database including root biomass, shoot biomass and yield of field grown winter wheat, spring wheat, silage maize, winter rapeseed and sunflower. The minority of genotypes showed a potential to increase root biomass without compromising yield compared to the average. Those who did, showed a mean of 12 % yield increase and a mean of 19 % root biomass increase compared to the average. This indicates that genotype selection may have a stronger effect on below than above ground biomass increase. Averaged over those genotypes that showed a potential to enhance root biomass, a mean root C increase of 0.11 Mg C ha^{-1} a^{-1} would be possible without yield reduction. Yield was significantly correlated to root biomass and crop type. The increased root biomass may stabilise yields as a climate adaption option under changing climatic conditions with increasing drought events during vegetation periods. The root: shoot ratios varied not only between, but also within crops. Overall, we could show that genotype selection can be a win-win option by increasing soil C while maintaining or even enhancing yield.

Keywords: root carbon inputs, carbon sequestration, climate change mitigation

Linking root biomass and traits with soil C and nutrients stocks and microbial activity down to 100 cm depth in a young Mediterranean agroforestry system

Siegwart Lorène[1]*, Jourdan Christophe[1,2], Piton Gabin[1], Van den Meersche Karel[1,2], Sugihara Soh[3], Bertrand Isabelle[1]

[1]*UMR Eco&Sols, Univ Montpellier, CIRAD, INRAE, IRD, Montpellier SupAgro, Montpellier, France*

[2]*CIRAD, UMR Eco&Sols, F-34398 Montpellier, France*

[3]*Institute of Agriculture, Tokyo University of Agriculture and Technology, 3-5-8 Saiwai-cho, Fuchu-shi, Tokyo 183-8509, Japan*

**Presenting author: lorene.siegwart@supagro.fr*

In the subsoils, roots represent a major source of organic matter. Moreover, the C inputs from rhizodeposition, root turnover (mostly perennial species) and root mortality at harvest (annual crops) have a long residence time in soil due to slow decomposition rates. However, deeper understanding of the root impact on soil C stocks and nutrient dynamics is still required, especially in deep horizons of mixed species agroecosystems.

This study aims to assess the heterogeneity of the root distribution and the root traits in two main components of an alley-cropping system, i.e. the crop and the understory vegetation strip (UVS) located under the tree rows; and to relate the root variables to soil physical, chemical and microbiological properties according to the distance from the tree and to soil depth.

The experimental alley-cropping site "DIAMS" (Mauguio, France) was planted in 2017 with *Robinia pseudoacacia* (294 trees ha^{-1}). In May 2020, we assessed the fine root biomass density, distribution, functional traits, chemical composition and some soil physical, chemical and microbiological properties in 3 soil layers (0-20, 20-50 and 50-100cm), 3 locations (the UVS under the tree rows, the wheat (Crop-1m) at 1 to 2m perpendicular to the tree line (under tree shade) and the crop (Crop-4m) at 3.4 to 4.5m from the tree (no tree shade)) and in 3 independent replicated plots.

The crop roots at 0-20 cm of depth had a biomass reduced by 3-fold near the UVS compared to far from it. UVS and crops showed similar root traits response to depth with a decrease of specific root length and stele diameter associated with an increase of root C:P ratio. The estimated annual root C inputs represented less than 0.6% of the organic C stocks and was less important under the UVS than the crop, at depth, due to C input pathways (turnover vs. mortality, respectively). Between 0 and 50 cm of depth, the soil C stocks increased with root C stocks, whereas below 50cm the relationship was negative, suggesting that root effect on soil-C might shift in subsoil. At all depths, the root stoichiometry had a tight link with extracellular enzyme N activities. According to ecoenzymatic stoichiometry, subsoil seemed more nutrient limited.

Altogether, our results suggested that increasing root biomass up to 50 cm (in our case) can foster soil C storage. In contrast, in deeper soil layers, an increase in root inputs, having high C:N ratios, could induce microbial N limitations and consequently restraint soil C storage.

Keywords: *Robinia pseudoacacia*, soil C sequestration, alley-cropping, root traits, soil enzymatic activity

Cover Crops Affecting Pool Specific SOC Sequestration in European Cropland – A Meta-Analysis

Julia Fohrafellner[1*], Sophie Zechmeister-Boltenstern[2], Katharina Keiblinger[2], Heide Spiegel[3], Rajasekaran Murugan[2], Elena Valkama[4]

[1] BIOS Science Austria, Silbergasse 30/3 1190 Vienna, Austria
[2] Institute of Soil Research (IBF), Department of Forest- and Soil Sciences, University of Environmental Sciences and Natural Resources, Vienna (BOKU), Gregor-Mendel-Straße 33 1180 Vienna, Austria
[3] Austrian Agency for Health and Food Safety (AGES), Institute for Sustainable Plant Production, Department for Soil Health and Plant Nutrition, Spargelfeldstraße 191 1220 Vienna, Austria
[4] Natural Resources Institute Finland (Luke), Bioeconomy and environment, Sustainability Science and Indicators. Tietotie 4, 31600 Jokioinen, Finland

* Presenting author: Julia.fohrafellner@boku.ac.at

Abstract

The "4 per mille" initiative proposes that by increasing the global soil organic carbon (SOC) stocks by 0.4 % per year, the global anthropogenic greenhouse gas (GHG) emissions could be offset. Especially croplands are often low in SOC and by enhancing SOC levels in these soils, GHG emission can be partly compensated. This can be achieved by adopting SOC enhancing land management practices, such as the cultivation of cover crops (CC). Up to now, no quantitative analysis of cover crop effects on SOC pool level has been done for Europe.

By conducting a meta-analysis, WP2-MIXROOT-C aims to quantitatively assess the CC effects on SOC pools throughout soil depths (0-100 cm) in European cropland soils. The pools chosen for this analysis are the microbial biomass carbon (MBC), the particulate organic matter (POM) and the mineral associated organic matter (MAOM) pool, as well as total SOC. Experimental studies conducted on a global level will be acknowledged as primary data input for the analysis, as long as the Köppen-Geiger climatic zone of the site is also present in Europe. This will allow us to incorporate more data whilst ensuring relevance for the European climate. Alongside, we will study the effects of moderators such as pedo-climatic factors (soil pH, soil texture class, percentage of clay, silt and sand, climatic zone, rainfall and temperature), other agricultural management practices (e.g., tillage, residue management, fertilization etc.) and CC characteristics and their management (species mixes vs. monoculture and legume vs. non-legume crops, shoot-to-root ratio, C/N ratio, frost resistance, seeding rate, sowing and harvesting time, termination method and time).

The meta-analysis will be conducted according to the quality criteria-set for meta-analyses in agriculture and soil sciences, which was previously developed by our group in WP7-EJP SOIL. This set will ensure that all key elements, necessary in producing a meta-analysis, will be present in our study. The overall effect sizes will provide the scientific community with valuable information about the state of knowledge on SOC pool specific sequestration rates influenced by CC and corresponding quantitative data. These results will offer guidance for future research and assist decision making processes regarding climate friendly management of agricultural soils.

Keywords: effect size; catch crop; MAOM; microbial carbon; POM; synthesis

C accumulation in the roots and sequestration in the soils of different types and agro-ecosystems in Lithuania

Monika Toleikienė[1*], Aušra Arlauskienė[2], Kęstutis Armolaitis[3], Žydrė Kadžiulienė[1]

[1] *Institute of Agriculture, Lithuanian Research Centre for Agriculture and Forestry (LAMMC), Dotnuva, Lithuania*

[2] *Joniškėlis Experimental Station, LAMMC, Joniškėlis, Lithuania*

[3] *Institute of Forestry, LAMMC, Girionys, Lithuania*

** Presenting author: monika.toleikiene@lammc.lt*

Previous studies in Lithuania show that different agro-ecosystems such as forests, grasslands, and croplands provide different Soil organic carbon (SOC) stocks in the different soil types. SOC stocks at Lithuanian national level were estimated in 754 permanent observation plots (Armolaitis et al., 2021). The SOC stocks were obtained for eight WRB Reference Soil Groups. The mean SOC concentrations in the 0–10 and 10–30 cm topsoil of most soil groups, especially fertile forest soils (Cambisols, Luvisols +Retisols) were higher for forest land and grasslands, and lower for croplands. The averaged SOC stock in topsoil varied from 56 t ha^{-1} (Arenosols) to 118 t ha^{-1} (Cambisols) in mineral forest soils and was 150 t ha^{-1} (Histosols) in organic forest soils. The total averaged SOC stock in mineral topsoil of forest land, grassland, and cropland was 80, 74, and 72 t ha^{-1}, respectively.

The important role of this SOC sequestration could be assigned to the roots of plants. However, root derived C sequestration in Lithuania is investigated less, than total SOC stocks in the soil. Lithuanian and foreign researchers state that after the insertion of the plant biomass, the roots decomposed more slowly than their aboveground parts. In Lithuania, different grassland systems were investigated for biomass output and C accumulation in the roots. According to our investigations, the composition of grasslands significantly affects the biomass of roots in the soil. Results showed that the most productive mixture was red clover with fescue, which accumulated 8763 DM kg ha^{-1}. The carbon accumulated in the roots of grassland species mixtures differed from 3299 to 4388 kg C ha^{-1}. The highest C amount was found in the roots of red clover and fescue mixture - 4388 kg C ha^{-1}, while for monoculture red clover it was – 3563 kg C ha^{-1} and for fescue – 3299 kg C ha^{-1}. Meanwhile, C accumulated in the shoots varied from 2914 to 5134 kg C ha^{-1} and mostly were taken from the system for livestock. The same tendency was observed for P and K in the roots of different mixtures. The highest lignin quantity was observed for red clover, which successfully could be used in the mixtures to prolong root decomposition and C stabilization in the soil.

All these data give important reasons to think that carbon sequestration in the roots could be elevated by using different land-uses, mixtures and management practices and more investigations needed in Lithuanian and all Europe scales. Therefore, within EJP Soil, MIXROOT-C and MaxRoot-C will provide important lacking information about SOC sequestration.

Keywords: SOC, root carbon, grasslands, forest, cropland

Potential of cover crops to sequester soil organic carbon in German croplands

Seitz Daria[1], Fischer Lisa Mareen[1,2], Dechow Rene[1], Wiesmeier Martin[2,3], and Don Axel[1]

[1] *Thünen Institute of Climate-Smart Agriculture, Braunschweig, Germany*

[2] *TUM School of Life Sciences Weihenstephan, Technical University of Munich, Freising, Germany*

[3] *Bavarian State Research Center for Agriculture, Institute for Organic Farming, Soil and Resource Management, Freising, Germany*

**Presenting author: daria.seitz@thuenen.de*

Cover crops have been suggested to maintain or even increase soil organic carbon (SOC) stocks in croplands which can contribute to soil fertility and climate change mitigation. The potential of cover crops to increase SOC stocks critically depends on how many additional cover crops can be integrated into existing crop rotations. Detailed management data are needed to quantify the SOC sequestration potential of cover crops. These are now available from the first German Agricultural Soil Inventory.

We simulated the SOC sequestration potential of cover crops using an SOC model ensemble consisting of RothC and C-TOOL. We developed a new carbon input estimation method for cover crops taking the effect of climate and sowing date on the development of the biomass into account.

We found that only one third of the cultivation windows are currently used for cultivating cover crops. Thus, the cultivation area could be tripled with additional 2 Mio ha each year which would increase total carbon input by 12% to 4.13 Mg C ha^{-1} a^{-1}. Within 50 years, this would result in 35 Tg more SOC in the topsoil of German croplands corresponding to on average 0.06 Mg C ha^{-1} a^{-1} and 2.5 Tg CO_2 equivalents per year. Our simulations predicted a negative SOC trend with business-as-usual management which cannot be stopped by maximizing cover crop cultivation. However, including cover crops remains a crucial strategy for managed cropland soils to maintain soil fertility and mitigate climate change.

Keywords: climate change mitigation, carbon modelling, carbon input estimation

Soil management effects on soil organic matter properties and carbon sequestration, SOMPACS

Weber Jerzy[1], Hewelke Edyta[2*], Leinweber Peter[3], Kuzyakov Yakov[4], Frąc Magdalena[5], Mielnik Lilla[6], Hayes Michael[7], Norton Urszula[8], Spaccini Riccardo[9], Boguzas Vaclovas[10], Jerzykiewicz Maria[11], Gregory Andy[12]

[1] Wroclaw University of Environmental and Life Sciences, Poland

[2] Warsaw University of Life Sciences (SGGW), Poland

[3] University of Rostock, Germany

[4] University of Goettingen, Germany

[5] Institute of Agrophysics, Polish Academy of Sciences, Lublin, Poland

[6] West Pomeranian University of Technology in Szczecin, Poland

[7] University of Limerick, Ireland

[8] University of Wyoming, Laramie, USA

[9] University of Naples, Italy

[10] Vytautas Magnis University, Agricultural Academy, Kaunas, Lithuania

[11] University of Wroclaw, Poland

[12] Rothamsted Research, Harpenden, UK

** Presenting author: edyta_hewelke@sggw.edu.pl*

SOMPACS is the project realized in the 1st external call of EJP SOIL program entitled "Towards Healthy, Resilient and Sustainable Agricultural Soils". The aim of the project is to identify management practices and systems enriching soils with the organic matter pools that are stable and the most resistant to microbial decomposition for various soil and climatic conditions in Europe and the USA while ensuring high yields. For this purpose, soil samples from eight long-term field experiments with different soil management and cultivation systems (conventional tillage vs. no-tillage; mineral vs. organic fertilization; management with and without catch crop; arable land vs. grassland; and cultivated vs. non-cultivated soils) will be investigated. Field experiments will include trials of increasing duration: 22-year (Lithuania); 26-year (Italy); 30-year (Poland, Ireland); 46-year (Poland); 54-year (Lithuania); 100-year (Poland) and 178-year Broadbalk experiment (UK). Experiments will also be conducted in production fields, where, in addition to the most innovative cultivation methods, additives will be applied that stimulate root growth and at the same time provide very stable C (commercial humic products, biochar, and biogas digestate). The effects of these additives on the content and properties of SOM will be investigated in plots of long-term field experiments, as well as incubation studies on the microbial decomposition of SOM and these additives. Parallel to soil sampling, plant productivity will be measured in all field experiments. Basic soil properties will be supplemented by the following investigations based on state-of-the-art approaches: SOM composition and stability by Py-GC-MS; aggregate size classes and C pools of increasing physico-chemical protection; microbiological properties (community-level physiological profiling, selected functional genes involved in C and N cycles, microbiome and mycobiome analyzes via next-generation sequencing, genetic diversity using terminal restriction fragment length polymorphism); analysis of δ13C and δ15N of the separated SOM pools; enzymatic activity; soil water retention and soil water repellency; mineral composition of clay fraction; soil structure stability. The most resistant SOM pools (humin) will be isolated by different methods and examined for chemical composition and structure, using spectrometric and spectroscopic techniques (mass spectrometry, NMR, FTIR, EPR, UV-Vis-NIR, fluorescence). The C stocks in the soil will be evaluated and the extractable cold water C will be determined to assess the potential leaching and microbial availability of C. CO_2 emissions from the soil will be measured directly under field conditions.

Keywords: soil management, carbon sequestration, soil organic matter, spectroscopic properties, soil organic matter pools

LIFE Nadapta: Soil-based indicators for the assessment of soils vulnerability and resilience in a regional adaptation strategy of agriculture to climate change.

Antón Rodrigo[1,2*], Arricibita Javier[1], Ruiz-Sagaseta Alberto[1], Enrique Alberto[1], de Soto Isabel[1], Orcaray Luis[3], Virto Iñigo[1]

[1] *Departamento Ciencias, IS-FOOD, UPNA, Pamplona, Navarra, Spain*

[2] *UR SOLS, INRA. Orleans, France*

[3] *Área de Innovación, Sección de Sistemas Sostenibles, INTIA, Villava, Spain*

** Presenting author: rodrigo.anton-sobejano@inrae.fr*

Because of the high vulnerability of agriculture, which is highly climate-dependent, farmers need crops and agricultural systems that consider the climate change effects. The IPCC defines the risk of climate-related impacts as the results of the interaction of climate-related hazards with the vulnerability and exposure of systems, and also explain how the adaptation of a system can modulate this vulnerability, and also reduce exposure to different hazards. In this context, the LIFE Nadapta project includes, among a number of strategies for improving the adaption to climate change of a region of Navarre (Spain) to climate change, an adaptation strategy intended to increase the resilience of agrosystems, especially in relation to one of the most important production factors: agricultural soils.

Considering the diversity of the region and the variety of agricultural practices spread throughout it, the work was conducted at four levels:

- First, a zoning of the territory was conducted based in biophysical characteristics (series of vegetation) and agroclimatic conditions, where 12 homogeneous zones were identified. A vulnerability study of agricultural soils was conducted at the regional level identifying critical soil characteristics in each of them.
- Second, soil vulnerability and resilience indicators were set for the different expected impacts for each area, considering a set of climate drivers identified for the region based on the study of the climate variations in the XXth century and projections of 2100. The proposed set of indicators includes those potentially modifiable by management (dynamic indicators): Soil organic C (SOC) storage, as well as water retention capacity and bulk density.

- Third, a network of up to 150 control plots was created, in groups for each zone, encompassing the diversity of both soil types and management systems. In these groups of plots, farmers using resilient strategic methodologies such as organic matter management, rotations or conservation agriculture are identified, together with conventionally managed farmers.

- Finally, the set of indicators were monitored in the network of plots, allowing for, firstly, the definition of a reference state in each zone, and, secondly, the estimation of the effect size associated with each strategic management both by zone and the overall region.

The response associated to the adoption of the three adaptive strategies tested in this region showed uneven results on the proposed soil indicators. Although uniform across the region, most of the strategies presented positive effects, in general, on SOC, where organic matter addition was the most effective practice for SOC storage while conservation agriculture seemed to show a tendency to be less effective as aridity decreases. The effectiveness of rotations seems to be strongly influenced by the type and intensity of management. The response of the physical indicators to the adoption of the strategies was more irregular, with no clear relationship between the effect of the strategies considered on the physical indicators and their effect on SOC.

Keywords: CC adaptation; regional approach, soil indicators

Arable interventions to mitigate greenhouse gas emissions

Cardenas Laura[1*], Louro Aranzazu[1], Broadley Martin[2], Chambers Jonathan[3], Dlamini Jerry[4], Gregory Andy[2], Harty Mary[5], Hood Jess[2], Kangara Grace[2], McDonell Kevin[5], Milne Alice[2], Mead Andrew[2], Lark Murray[6], Nezomba Hatirarami[7], Nalivata Patson[8], Phiri Elija[9], Radzikowska Dominika[10], Sawinska Zuzanna[10], Switek Stanislaw[10], Verbeeck Mieke[1] and Zhang Xiaoxian[2]

1 Rothamsted Research, Okehampton, UK
2 Rothamsted Research, Harpenden, UK
3 British Geological Survey, Nottingham UK
4 University of the Free State, Bloemfontein, South Africa
5 University College Dublin, Dublin, Ireland
6 University of Nottingham, Loughborough, UK
7 University of Zimbabwe, Harare, Zimbabwe
8 University of Agriculture & Natural Resources, Lilongwe, Malawi
9 University of Zambia, Lusaka, Zambia
10 Poznan University of Life Sciences, Poznań, Poland

* Presenting author: laura.cardenas@rothamsted.ac.uk

Agriculture must provide food security for all sustainably and in the face of climate change. There is concern about the effects of cropping on soils quality (losses of structural stability, soil organic carbon (SOC), biological functioning), and greenhouse gas (GHG) emissions from soil.

Soils vary globally, but there is widespread interest in how conservation agriculture (CA) might increase the sustainability of cropping from intensive temperate systems in the global north to smallholder and subsistence production in tropical and subtropical systems of the global south. In all, zero or minimum tillage (ZMT) is implemented to reduce the disruption of soil structure. The retention of organic residues, or other means to build SOC, and the diversification of cropping systems through rotations or intercropping are all components of CA, particularly in the global south.

While there is evidence that CA can increase the resilience of crop yields to climate variations and improve the structure of soils, the question of its impact on GHG budgets remains open. In particular, it is likely that different GHGs respond differently to changes in tillage practice and increase in SOC status, so a strong evidence base is needed to assess the trade-offs between components of the soils GHG budget under CA, and the net effect on global warming potential (GWP) given differences in the climate impact of different gases.

This study will make a substantive contribution to the evidence base for the impact of CA practices on GHG budgets for agricultural soils spanning temperate

European and warmer climate in sub-Saharan Africa. The project consortium brings together researchers and institutions from Europe and Africa who have been active in CA and GHG research, and who currently manage field sites where aspects of CA practice are examined in long-term experiments, mainly ZMT, use of cover crops and legumes, and incorporation of crop residues.

We will use existing experiments in the UK, Ireland, and Poland that include locally relevant ZMT and crop rotation interventions with conventional cultivation comparisons. Similarly, existing experiments in South Africa, Zambia, Zimbabwe and Malawi which compare conventional management of a maize crop with ZMT and residue retention combined with other CA interventions (e.g. intercropping) will be used.

We will test the following hypotheses:

H1: the relative importance of CO_2, CH_4 and N_2O in GHG emissions from managed soils varies between treatments, with reduced CO_2 emissions under ZMT relative to conventional cultivation, possibly due to less mineralisation and reduced gas diffusion; reduced CH_4 emission and increased N_2O under CA practices due to increased water retention and SOC content.

H2: the treatment effects outlined above result in a net reduction in soils GWP from GHG emissions from the CA treatments, due to the reduction in CO_2 from respiration and CH_4 emissions offset by increased N_2O emissions.

H3: Process-based models of C and N fluxes from soil which do not explicitly account for soil pore structure are not able to predict the impact of ZMT on GHG emissions, whereas models which incorporate characterizations of structure are able to do so.

Keywords: conservation agriculture; crop rotations, greenhouse gas emissions

The effect of tillage, manuring and mineral P-K fertilization on soil structural stability in three long-term field trials in the loess belt of Belgium

Hardy Brieuc[1*], Vanwindekens Frédéric M.[1]

[1] *Sustainability, Systems & Prospectives Department – Soil, Water and Integrated Crop Production Unit - Walloon Agricultural Research Center, Gembloux, Belgium*

* *Presenting author: b.hardy@cra.wallonie.be*

Many soils of the Belgian loess belt have a poor structural stability related to a silt-dominated texture and a low soil organic carbon content, which makes them particularly sensitive to compaction and erosion. In this work, we investigated how soil structural stability respond to contrasting tillage treatments, organic matter inputs and PK fertilization at three long-term field trials in the silt loam region of Belgium. Soil structural stability was evaluated by a new, simple test consisting in the dynamic weighting of a structured soil sample once immersed in water, referred to as the QuantiSlakeTest (QST). In total, 40 different fields were sampled and for each of them, QST curves were compared to the three tests of Le Bissonnais, targeting specific mechanisms of soil disaggregation. QST indicators calculated from curves were also related to soil properties.

The overall structural stability of soil was linearly related to the SOM status of soil, well captured by the SOC:Clay ratio. Nevertheless, for a similar C input, green manure and crop residues were more efficient in decreasing clay dispersivity whereas farmyard manure promoted SOC storage and was more efficient against slaking. QST curves had a strong discriminating power between reduced tillage and ploughing regardless of the indicator, as reduced tillage increases both total SOC content and root density in the topsoil. In contrast, long-term mineral P and K under- and over-fertilization had no significant effect on soil structural stability.

Our results confirmed, for the soils of central Belgium, the validity of the SOC:Clay ratio as a proxy to estimate the intrinsic “potential” structural stability of soil, whereas the QST mass increase recorded shortly after immersion of soil provides a quantitative measurement related to the overall soil structural stability. The QST has several advantages: it is rapid to run, doesn’t require expensive equipment or consumables and provides a high density of information on both specific mechanisms of soil disaggregation and the overall soil structural stability. As an open-access program for QST data management is currently under development, the test has a strong potential for adoption by a widespread community of end-users.

Keywords: Soil structural stability, soil management practices, tillage, organic matter, P and K fertilizers, SOC:clay ratio, QuantiSlake test

Use of hemp stem residues for soil quality

Urtė Stulpinaitė[1*], Vita Tilvikienė[1]

[1] *Lithuania Research centre for agriculture and forestry, Akademija, Kėdainiai distr., Lithuania*

** urte.stulpinaite@lammc.lt*

Increase of carbon stocks in the soil forces researchers and technology creators to look for innovative agricultural technologies all around the Europe. It is known that rotting plant residues supply bioavailable organic carbon together with essential nutrients to the soil. One of the most promising way to increase soil organic matter is growing of perennial grasses. They do not require much input, but have many benefits for the environment. Nevertheless, the use of grass biomass is decreasing with lowering level of husbandry in most countries. Therefor there is a need to look for alternatives. Nowadays the growing of hemp is increasing and as this crop has very rich root system, it is expected that they could have benefit to the soil. Hemp loosens and softens the soil and fallen foliage forms mulch that preserves substances and bacteria in the soil. After harvesting, the root system quickly disappears. If hemp is grown for the extraction of phytocanabinoids, up to two-thirds of the organic matter returns to the soil. Hemp plants reduce the population of nematodes and pathogenic fungi in the soil and can be grown without the use of pesticides, herbicides or fungicides. The introduction of hemp in crop rotation has been shown to improve soil conditions. Nevertheless, there is lo information about the degradation of hemp stems in the soil if they are left and their potential for soil quality and soil carbon content improvement. The aim of this study was to investigate the speed of hemp residues degradation under different management systems. Different amendments: ammonium nitrate (KNO_3), liquid nitrogen fertilizers (KAS) and liquid organic fertilizers have been used to accelerate the decomposition of hemp stem residues. Hemp stem residues was applicate on the top of soil and mixed with the soil. The results showed that the faster degradation was then hemp stem residues were mixed with the soil and applied with liquid nitrogen fertilizers (KAS).

Keywords: hemp, soil, residues.

Soil organic carbon and nitrate leaching loss in organic and conventional farming systems for the current and near future climate

Elena Valkama[1], Alessia Perego[2] and Marco Acutis[2]

[1]Natural Resources Institute Finland (Luke), Bioeconomy and environment, Tietotie 4, Jokioinen, Finland

[2]Department of Agricultural and Environmental Sciences - Production, Landscape, Agroenergy, University of Milan, Milan, Italy

In Finland, nitrate (N) leaching loss and soil organic carbon (SOC) decrease are current environmental threats. The aim of the study is to simulate soil C dynamic and N leaching loss for conventional (C) and organic (O) farming systems producing either crops (C) or livestock (L) in South Savo (Finland). Simulations were carried out by using the process-based model ARMOSA for both current (1999-2018) and near future climate scenarios (2020-2040, RCP 6.0: annual change + 0.8 °C, -70 mm). Daily meteorological data from Mikkeli station, and the statistical data in the region during the last 20 years served as model inputs.

Five-year crop rotations were simulated on loamy sand soil (C 3.5 %, C/N ratio 17, pH 6.2). In crop farm, rotations included cereals (with fodder pea in the organic farm), oilseed rape and grass, while in the livestock farm, the rotation consisted of two years of cereals followed by a 3-year fescue and timothy meadow (with clover in the organic farm). In the crop farm, we simulated three conventional cropping systems: mineral fertilizer with either crop residues removed (C1–R) or incorporated into soil (C1+R), mineral fertilizer + slurry, residues incorporated (C2+R); and two organic systems: green manure (O1+R) or meat and bone meal-based commercial organic fertilizer, Ecolan Agra® (O2+R). In the livestock farm, we simulated conventional and organic cropping systems: mineral fertilizer + slurry with either residues removed (LC-R) or incorporated into soil (LC+R); slurry with either residues removed (LO-R) or incorporated (LO+R).

The results showed that conventional crop production systems led to relevant SOC decline of 500-750 kg $ha^{-1}yr^{-1}$ at 0-30 cm soil depth, while organic systems showed either less SOC decline (120 kg $ha^{-1}yr^{-1}$) as in O1+R, or slight SOC increase (55 kg $ha^{-1}yr^{-1}$) as in O2+R. Under the future climatic conditions, the model estimated a faster degradation of SOC for all the cropping systems, except for O2+R that still resulted in a negligible SOC increase. Annual N leaching predicted to be about 10 kg NO_3-N ha^{-1} yr^{-1} for conventional crop farms (C1–R/+R; C2+R), while 3 kg NO_3-N ha^{-1} yr^{-1} for organic crop farm with green manure (O1+R). Under the future climate scenario, conventional cropping systems are prone to an increased N leaching loss, up to 20 kg NO_3-N ha^{-1} yr^{-1}, but organic systems do not.

The simulation of livestock farm showed a negligible loss of SOC about 25-160 kg $ha^{-1}yr^{-1}$ in LC–R, LC+R and LO–R, while a small SOC increase of 20 kg $ha^{-1}yr^{-1}$ in LO+R. Annual N leaching loss varied between 6 and 9 kg NO_3-N ha^{-1} yr^{-1} with very little differences between organic and conventional systems due to use of perennial grass in rotation and slurry as N-fertilizer. In the future climate, the model forecasted an overall increase of SOC losses for all systems, and the larger N loss in organic livestock farm, up to 15 kg ha^{-1} yr^{-1}.

In conclusion, the modelling results suggest that using green manure and crop residue incorporation as a source of organic matter allowed to sequester soil C and pose only negligible N leaching loss in organic crop production farms. In contrast, using slurry in organic livestock farms caused trade-offs between soil C sequestration and N leaching loss for the current climate, and loss of both, soil C and N, for the future climate.

Keywords: organic farming, slurry; green manure; residue incorporation; soil organic carbon, nitrate leaching, climate change

Soil carbon sequestration and trade-offs with greenhouse gas emissions and nitrogen leaching: identifying knowledge gaps

Maenhout Peter[1], Di Bene Claudia[2], Cayuela Maria Luz[3], Govednik Anton[4], Keuper Frida[5], Mavsar Sara[4], Mihelic Rok[4], O'Toole Adam[6], Schwarzmann Ana[4], Suhadolc Marjetka[4], Syp Alina[7], and Valkama Elena[8]

[1]Plant Sciences Unit, Flanders Research Institute for Agriculture, Fisheries and Food (ILVO), Merelbeke, Belgium

[2]Council for Agricultural Research and Economics, Research Center for Agriculture and Environment, Rome, Italy

[3]Department of Soil and Water Conservation and Waste Management, CEBAS-CSIC, Campus Universitario de Espinardo, Murcia, Spain

[4]Chair of Soil and Environmental Science, Department of Agronomy, University of Ljubljana, Ljubljana, Slovenia

[5]BioEcoAgro Joint Research Unit, INRAE, Barenton-Bugny, France

[6]Department of Biogeochemistry and Soil Quality, NIBIO – Norwegian Institute of Bioeconomy Research, Ås, Norway

[7]Department of Bioeconomy and Systems Analysis, Institute of Soil Science and Plant Cultivation - State Research Institute, Poland

[8]Natural Resources Institute Finland (Luke), Bioeconomy and environment, Sustainability Science and Indicators, Jokioinen, Finland

** Presenting author: peter.maenhout@ilvo.vlaanderen.be*

Carbon sequestration in agricultural soils is an important strategy to mitigate climate change. Stimulation of soil organic carbon (SOC) sequestration can be achieved via different soil management strategies. Nevertheless, such strategies may stimulate nitrous oxide (N_2O) and methane (CH_4) emissions and cause nitrogen (N) leaching losses. While these trade-offs can offset the climate change mitigation obtained via SOC sequestration, synergistic effects of certain soil management strategies may positively affect the mitigation potential. Despite the importance of these trade-offs and synergies for the selection of sustainable and climate-proof soil management strategies, knowledge on these effects remains limited.

The ∑OMMIT-project aims to investigate the trade-offs and synergies for the most relevant soil management strategies applied in European agricultural systems. A dedicated literature study was made, summarizing the results of reviews, meta-analyses, reports, and original articles. The most important soil management strategies were identified and grouped into four categories: tillage management, cropping systems, water management, and fertilization and organic matter (OM) inputs (crop residues, cover crop, livestock manure, slurry, compost, biochar, liming). Search criteria including literature and land use type, time-period, and geographic origin resulted in a unique selection of 110 references (31 reviews, 46 meta-analyses, and 33 original papers). Meta-data, extracted knowledge gaps, research recommendations and main conclusions were compiled in a knowledge gap review which provides better insights in existing trade-offs and synergies and acts as guidance to future research.

This review highlights that the increase of both SOC stock change and the microbial biomass C and N, as well as a reduction in N leaching are positively affected by conservation tillage, crop rotation, permanent cropping, more efficient water management as well as using fertilization and OM inputs

(e.g., cover crops, organic amendments, biochar, and liming). The effects on N_2O and CH_4 emission mitigation are dependent on the specific soil management strategy (e.g., water management, fertilization and OM inputs) and require more extensive research before uniform conclusions can be drawn.

In conclusion, future studies should examine the effects of soil management strategies on both SOC stocks, GHG emissions, and N leaching losses. Furthermore, a more concerted use and installation of new long-term field experiments in different pedo-climatic European regions, will be essential to fully elucidate the impact of soil management strategies at the European level. Indeed, we identified a lack of information on the impact of pedoclimatic conditions on trade-offs and synergies, especially on the long-term. Further, since soil management strategies are often combined and their interaction may affect the trade-offs and synergies, the impact of different soil management practices should be assessed simultaneously. Overall, the review provides a unique framework to aid the (re)design of dedicated field experiments and targeted measurements as well as simulations to improve our understanding of the identified knowledge gaps.

Keywords: carbon sequestration, greenhouse gas emissions, nitrate leaching, trade-offs, knowledge gaps

Short-term effects of N fertilization on soil carbon and N_2O emissions in two irrigated maize cropping systems

Álvaro-Fuentes Jorge [*], Alonso-Ayuso María [1], Lafuente Victoria [1], Bielsa Ana [1], Franco-Luesma Samuel [1,2]

[1] *Consejo Superior de Investigaciones Científicas (CSIC), Zaragoza, Spain*

[2] *Karlsruhe Institute of Technology (KIT), Garmisch-Partenkirchen, Germany*

** Presenting author: jorgeaf@eead.csic.es*

In Mediterranean areas, irrigated maize is associated with high-water consumptions and an excessive nitrogen (N) fertilizer use. The direct result of this intensive production model is the high maize yields representative of these irrigated areas. However, this productive model has also negative side effects derived from the high risk of environmental degradation, particularly N leaching and N_2O emissions. Furthermore, the usual cropping system based on maize monocropping with bare tilled fallow in-between maize growing seasons promotes soil organic carbon (SOC) losses. In this context, the intensification of these maize cropping systems with the substitution of the fallow period with a legume crop is a promising strategy which may favour not only the reduction of N fertilization rates and, in turn, the associated soil N_2O emissions, but also the increase in SOC levels. Accordingly, the main aim of this study was to evaluate the impact of N fertilization on SOC changes and soil N_2O emissions in the next two different maize systems: a maize monocropping with bare tilled fallow in between maize seasons and a pea-maize double cropping. To achieve this objective and within the framework of the UE H2020 Diverfarming project, in the two selected cropping systems (maize monocropping and pea-maize double cropping) three mineral N rates (unfertilized; medium rate; and high rate) were evaluated in a field experiment established in NE Spain during two years (2019 and 2020). The layout consisted in a split-block design with each treatment replicated three times. During the studied period, the N rate had a significant effect on soil N_2O emissions particularly immediately after the N application when, in both systems, quick and high increases of soil N_2O fluxes were observed. However, when both cropping systems were compared, the pea phase obtained greater N_2O emissions than the fallow phase but the maize after pea showed similar or even lower N_2O emissions than the maize under fallow. After two years, SOC changes differed among cropping systems and N rates. All three N rates showed SOC losses in the maize monocropping but, in contrast, increases in the pea-maize system. According to all this, the analysis of trade-offs showed differences among cropping systems and N fertilization strategies stressing the impact of these two management practices on the mitigation potential of irrigated maize systems located in Mediterranean conditions.

Keywords: Irrigated maize; SOC sequestration, Soil N_2O emissions; Trade-off analysis; N fertilization

Cover crops affect non-growing season N_2O emissions in boreal cereal cropping

Peter Dörsch[1*] and Sigrid Trier Kjær[1,2]

[1] *Norwegian University of Life Sciences, Faculty of Environmental Sciences and Natural Resource Management, Ås, Norway*

[2] *Department of Environmental Systems Science, ETH Zurich, Zürich, Switzerland*

* *Presenting author: peter.doersch@nmbu.no*

Keywords: C sequestration; off-season; GHG trade-offs

Use of cover crops under-sown to or in rotation with cereals has been recommended to increase soil carbon (C) stocks. However, producing additional biomass for C sequestration has a nitrogen (N) cost, both in form of increased N fertilizer use and by potentially increasing nitrous oxide (N_2O) emissions after mulching or incorporating cover crops. The presence of N-rich, frost-sensitive aboveground biomass can be a particular problem during wintertime, in which freeze-thaw driven emission pulses drive much of the annual N_2O emission in many temperate and boreal regions. Here we report growing season and over-winter N_2O emissions in a plot experiment in SE Norway, studying seven different cover crops (perennial and Italian ryegrass, oilseed radish, summer and winter vetch, phacelia and a 10-species herb mixture) in a barley cropping system. Cover crops where under-sown in spring or in summer, shortly before barley harvest. We found no significant effect of spring-sown cover crops (perennial and Italian rye grass, 10-species mixture) on barley yields or N_2O emissions, even though emissions tended to be lower in plots with ryegrasses during summer. Additional fertilization in fall (25 kg N ha^{-1}) to selected cover crops had no effect on off-season N_2O emissions. However, when the first night frosts occurred end of October, strongly elevated emissions were recorded from summer-sown oilseed radish, which had developed copiously throughout autumn. Elevated emissions from oil-seed radish persisted throughout early winter and were clearly higher than those from ryegrass or the mixture. Vetches and phacelia developed poorly and did not contribute significantly to N_2O emissions. N_2O emissions peaked in all treatments (including the control without cover crop) during diurnal freeze-thaw cycles in late winter. Notwithstanding, when cumulated for the entire winter, rye grasses and mixture emitted less N_2O than the control. Quantifying N_2O emission dynamics in snow-poor winters with frequent freezing-thawing cycles is challenging but plays an important role in evaluating GHG effect of cover crops. Nonetheless, the first year of our study demonstrates that cover crops should be chosen carefully as to their winter hardiness and ability to reuptake mineralized N during off-season to avoid offsetting potential carbon gains. The study continues through a second annual cycle using the same treatments to assess the effect of interannual variation in weather, notably during winter.

The ∑OMMIT index: a trade-off assessment tool to identify farming practices minimizing greenhouse gas intensity from agricultural systems

Bregaglio Simone[1*], Savian Francesco[1], Fiore Angela[2], Cayuela Maria Luz[3], Lagomarsino Alessandra[1]

[1] *Council for Agricultural Research and Economics (CREA), Research Centre for Agriculture and Environment, Bologna/Firenze, Italy*

[2] *Institute for Environmental Protection and Research (ISPRA), Rome, Italy*

[3] *Department of Soil and Water Conservation and Organic Waste Management (CEBAS-CSIC), Murcia, Spain*

** Presenting author: simoneugomaria.bregaglio@crea.gov.it*

The European Greenhouse Gas (GHG) mitigation policies need quantitative figures on the effect of management strategies on soil carbon sequestration and direct/indirect N_2O emissions, in order to identify ecologically intensive cropping systems that contribute to climate change mitigation. Evidences from scientific literature highlight that the impact of farming strategies (e.g., irrigation, fertilization, tillage) on the overall system sustainability is highly context-dependent, requiring a case-by-case evaluation to assess their interlinkages across pedo-environmental conditions. However, the current IPCC guidelines for national GHG Inventories provide default equations and emission factors for estimating carbon stock changes and N_2O emissions from agricultural soils, without explicitly considering antagonistic and synergetic interactions of farming practices across environments, and mostly disregarding the interdependence among carbon and nitrogen cycles. The ∑OMMIT project aims at filling current gaps of knowledge, thanks to the mobilization of interdisciplinary expertise and multiple research techniques including meta-analysis, long-term field experiments, and process-based simulation models. The unique datasets which will be produced by the project partners need to be harmonised and used to develop a trade-off assessment tool, capable to unravel the complex effects of soil management strategies on carbon sequestration and non-CO_2 GHG emissions. We will present the prototype of the ∑OMMIT index, the tool which will be used to perform trade-off analyses to identify best management strategies contributing to optimize the GHG intensity (emissions and removals) of the crop system, while preserving its productivity. The ∑OMMIT index is trained by an input layer constituted by multiple case scenarios, characterized by specific pedo-environmental conditions and soil management strategies. Each case scenario is associated to the value of four main trade-off components, i.e., carbon sequestration, nitrous oxide emissions, nitrate leaching and crop yield. Machine learning techniques (Variable-Importance Weighted Random Forests) are used to correlate each trade-off component with input layer variables, leading to informative modules where the relationships among soil management strategies are explicitly embedded. Expert opinion is then implemented *via* Multi Objective Decision Analysis to hierarchically aggregate these modules into a synthetic value of the ∑OMMIT index, ranging from 0 (worst trade-off) to 1 (best trade-off). The feasibility of the ∑OMMIT index to perform trade-off analysis has been tested on a dummy input layer, where correlations between management strategies, pedo-environmental conditions, and trade-off components have been superimposed. An online survey among project partners has been carried out to weight the importance of the different trade-off components on the synthetic index value. The results of this proof of concept have been released through an interactive dashboard, where users can test the effect of changing input layer variables on the overall system sustainability.

Keywords: soil carbon sequestration; crop management strategy; greenhouse gas emissions; nitrate leaching; crop yield

Harmonized inventory of soil biodiversity data sources for conservation of European agricultural ecosystem

Rajasekaran Murugan[1], Antonio Bispo[2], Vanessa Langlois[3], Maria Fantappie[4]

[1]Institute of Soil Research, University of Life Sciences and Natural Resources (BOKU), Vienna.

[2]Infosol, French National Research Institute for Agriculture, Food and Environment (INRAE), France.

[3]French National Research Institute for Agriculture, Food and Environment (INRAE), France.

[4]Council for Agricultural Research and Economics (CREA), Italy.

**Presenting author – Rajasekaran.murugan@boku.ac.at*

Soils are home to over a quarter of all living species on earth and soil organisms perform wide range of soil functions organic matter decomposition, nutrient cycling, disease suppression and crop production. Many conservation managers, farmers, policy makers, businesses and local communities cannot access the biodiversity data they need for informed decision-making on soil resource management. A handful of databases are used to monitor indicators against global soil biodiversity goals but there is no openly available consolidated list of global data sets to help stakeholders, especially in highly vulnerable agricultural ecosystems. The project MINOTAUR will aim to build an inventory of global soil biodiversity databases of potential use in monitoring soil biodiversity status, barriers and conservation responses to sustainable soil management at multiple levels. In the second step, collected data sources will be harmonized to integration of biodiversity data across spatial, temporal and taxonomic scales. Finally, the harmonized data pool will be synthesized to identify knowledge gaps in existing databases and facilitate biodiversity assessments at various scales, from local to sub-regional, culminating in a mechanism for regional scale characterization. Overall, this work will deliver an integrated harmonized soil biodiversity data for validating, monitoring, modelling, and evidence-based policy decisions.

Keywords: Soil biodiversity, data sources, harmonization, policy makers, stakeholders

Pedoclimatic contextualization of soil organic carbon content in Europe for soil health assessment

Pacini Lorenza[1,2,*], Arbelet Pierre[2], Cécillon Lauric[1] and Barré Pierre[1]

[1]*Laboratoire de Géologie, École normale supérieure, CNRS, Université PSL, IPSL, 75005 Paris, France*

[2] *Greenback SA (commercial name: Genesis), 93 rue vieille du temple, 75003 Paris, France*

* *Presenting author: lorenza.pacini@genesis.live*

Quantifying Soil Organic Carbon (SOC) is necessary for assessing soil health and its contribution to soil ecosystem services such as biomass production, flood and erosion mitigation, climate regulation, etc. Much effort is invested in monitoring SOC at the regional, national and global scale. The variability of measured SOC contents in topsoils strongly relates to different land use and management practices. However, because SOC content also depends on the pedoclimatic context, diagnosing beneficial versus harmful soil management practices is only possible if comparing SOC measures performed in similar pedoclimatic conditions. This requires a dedicated contextualisation framework that takes into account the pedoclimatic factors that influence the SOC content and allows identifying SOC thresholds that represent reference values for healthy versus unhealthy soils. Then, the health status of soils regarding the SOC criterion would be assessed more properly by comparing their SOC content with SOC reference values corresponding to their specific pedoclimatic context.

Based on the statistical analysis of the publicly-available LUCAS Topsoil dataset[1], we propose an unsupervised machine learning approach for the identification of pedoclimatic contexts of SOC in Europe. To allow for explicability of the output, we perform independent clustering of LUCAS sites based on climatic parameters on one side and on pedological parameters weakly related to soil management on the other side. Then the pedoclimatic context of a site is defined as the combination of the pedological- and climatic clusters it belongs to. The analysis of the distributions of topsoil SOC contents within each pedoclimatic context and for different land cover classes is used to assess typical versus extreme values that can be employed as references for a SOC-related diagnosis of soil health.

The proposed method results in the identification of 44 clusters of European soils associated to specific pedoclimatic contexts. We show that the SOC content distributions differ across clusters, for given land cover classes. Then we explore and discuss possible approaches for the definition of SOC threshold values and normalisation functions to allow for a better inter-comparability of SOC diagnosis of topsoils belonging to different pedoclimatic contexts. Our results demonstrate the importance of a pedoclimatic contextualisation for SOC diagnosis at large spatial scales. We suggest that the identified pedoclimatic contexts could be meaningfully used to contextualise other criteria of soil health assessment in Europe.

Keywords: Soil organic carbon; Soil health; Soil quality; Clustering

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Structural connectivity of sediment loads via surface runoff in different scales in agricultural lands of Finland

Tähtikarhu, M., Räsänen, T.A., Uusi-Kämppä, J.

Natural Resources Institute Finland, Tietotie 4, FI-31600 Jokioinen, Finland

Processes leading to soil erosion and consequent sediment transport are affected by multiple interlinked landscape characteristics which typically have high spatial variability. These factors inflict challenges on the management of sediment loads. Structural connectivity of sediment loads via surface runoff has not been previously studied in the lowland agricultural areas of Finland. Recent studies have, however, shown that the magnitude and spatial variability of erosion and sediment connectivity can be reasonably estimated with simplistic models and with low data availability. The revised universal soil loss equation (RUSLE) and sediment connectivity index (CI) are among the most widely applied models. Here, we produce the first spatially extensive erosion data (2x2 m resolution) in Finland with RUSLE and analyze structural sediment connectivity (1) within agricultural fields, (2) between agricultural fields (field-scale) and (3) between two catchments with intensive agriculture and different topographical characteristics.

Our results show that the majority of the field areas are structurally connected to adjacent open ditches or streams. The connectivity pathways were dominated by sporadically occurring flow accumulation networks, controlled by elevation differences in the model. Thus, targeting sediment disconnectivity elements (e.g. buffer strips) in the landscape is challenging without spatial data on the connectivity pathways. Within agricultural fields (2x2 m resolution), there was a statistically significant correlation (Pearson $r=0.44$-0.48, $p<0.001$) between the computed erosion loads and CI, which showed that a large share of erosion can occur in such locations which are also highly connected. Stronger relationship as well as rank correlation was found between mean erosion and mean IC on field-scale (Pearson $r=0.69$-0.81, $p<0.001$ and Spearman rank correlation $r>0.69$-0.79, $p<0.001$). Finally, we computed sediment yields (as a function of the RUSLE and IC results) with different parameterizations and show that even though the different parameterizations can lead to high uncertainties in sediment yields, ranking of the fields in terms of the sediment yields can be similar (Spearman $r>0.9$ and $p<0.001$ between the different parameterizations). Despite differences in the spatial distribution of erosion within the catchments, the above relationships were generally qualitatively similar in the two studied catchments. Overall, the results show that taking into account connectivity in efficient targeting of erosion mitigation measures may require spatial data describing relative differences in erosion and connectivity in different scales. Our study produces spatial data on the phenomena which can be used when targeting water protection measures.

Keywords: erosion; connectivity; lowlands; RUSLE; connectivity index

The LANDSUPPORT "best practices tool": identification of the trade-off between soil health and crop production.

Acutis[1] M., Botta[1] M., Tadiello[1] T., Langella[2] G., Terribile[2] F., Bancheri[3] M., Basile[3] A., Perego[1] A.

[1] Department of Agricultural and Environmental Sciences, University of Milan, Milan, Italy
[2] Department of Agricultural Sciences, University of Naples Federico II, Portici, Italy
[3] Institute for Mediterranean Agricultural and Forestry Systems, National Research Council, Portici, Italy

Keywords: Nitrate leaching, yield, soil organic carbon

The web-based "Best Practices tool" (https://dev.landsupport.eu/template.html) has been developed to be applied by public authorities, such as regional environmental agencies, to find the best solutions according to a goal (e.g., increase in soil organic carbon stock, reduction of nitrate leaching) in a region of interest (ROI). The is ROI is automatically associated with soil properties described for each horizontal layer (data available from the pedological database or LUCAS European database). The user sets up a combination of agronomic practices via web interface. The identification of optimal solution can be done in 5 climate scenarios specific for each ROI (20-year period of current, near and far future under RCP 4.5 and 8.5 IPCC scenarios).

The tool was developed in the framework of the LANDSUPPORT project (H2020-RUR-2017-2/No. 774234) and applies a what-if scenario approach at regional scale (average area of approximately 2500 km^2) in three case studies (Marchfeld – Austria, Campania Region – Italy, Zala County – Hungary). The tool is dynamically linked to the ARMOSA process-based model, which simulates at daily time step many combinations of farming systems (conservation, organic, conventional), crops, nitrogen fertilization rates, tillage solutions, crop residues management. Out of the wide set of daily ARMOSA outputs, the tool returns the mean annual value of (1) the crop yield, (2) the nitrate leaching at the bottom of the soil profile, and (3) the change of the soil organic carbon stock in the upper soil layer (0-0.4 m). The tool also gives the value of the synthetic "best practices index" (I_{BP}) that is computed as a linear combination of the three variables and the weights that the user dynamically assigns to each of the variables according to the specific goal (e.g., increase in soil organic carbon). The user then sorts the I_{BP} values in descending order to identify the most suitable combinations of practices. The mean value of I_{BP} is plotted in charts for each of the simulated combinations.

A high number of combinations (up to 2520 combinations) derived from 5 climate scenarios, 7 crops, 2 systems (conventional, organic), 3 fertilization rates (optimal amount, 15% and 30% reduction), 2 residues management (removal, retention), 3 tillage practices (ploughing, minimum tillage, sod seeding), and 2 uses of cover crops (yes, no) allowing to automatically evaluate many cropping system including those typical of regeneration agriculture. The user-friendly interface hides the high complexity of the soil and crop processes which are simulated on the fly by ARMOSA, which has many crop and soil parameters already calibrated using the dataset available in the project and in previous studies. As the close link with ARMOSA, the tool allows the close representation of actual and optimized cropping systems with the possibility of further applications at a larger scale (e.g., European), in other regional case studies, and in tailored scenarios in which the user enters her/his data of soil properties and climate.

Abstract on carbon farming

J.W.H. van der Kolk, A.B. Smit, L. Martinez Garcia and M. Hvarregaard Thorsøe

CO_2-emission is an important source of greenhouse gases and climate change. In order to reach targets set in the Paris Agreement and the European Green Deal on reduction of CO_2-emission, also farmers have to play a role. For that reason, the concept of 'carbon farming' is developed. This supports farmers to take actions that either enhance the carbon content of the soil or decrease carbon dioxide emissions, e.g. caused by oxidation of organic matter in soil or do both. This would be additional to standard soil management and lead to a more positive soil carbon balance. One could think of activities like application of manure and compost and not-ploughing grassland or enhancing the input of residues from crops to soils. In peatland regions, a higher groundwater level decreases the oxidation of peat, contributing to a lower CO_2-emission in those regions.

To stimulate and reward farmers to manage the soil in a way that carbon will be sequestered, public or private payment schemes can be used. In Road4Schemes, we first make an inventory of ongoing projects all over Europe to stimulate farmers such activities. Based on this inventory, we will make an analysis on pros and cons of each scheme to come to recommendations for a general scheme that rewards result-based activities, additionality, fairness and permanence.

Trade-off between cost and accuracy of soil carbon measurement: does the reduction of the frequency of monitoring campaigns encourage farmers to adopt carbon certification contracts?

Photinodellis Roxane[1*], Bruni Elisa[2], Bamière Laure[3], Chenu Claire[4], De Cara Stéphane[3] and Guenet Bertrand[5]

[1]*Université Paris-Saclay, AgroParisTech, INRAE, Paris-Saclay AppliedEconomics, 91120, Palaiseau, France*

[2]*Laboratoire des Sciences du Climat et de l'Environnement, LSCE/IPSL, CEA-CNRS-UVSQ, Université Paris-Saclay, Gif-surYvette, France*

[3]*Université Paris-Saclay, INRAE, Paris-Saclay AppliedEconomics, 91120, Palaiseau, France*

[4]*Ecosys, INRA-AgroParisTech, Université Paris-Saclay, Campus, AgroParisTech, Thiverval-Grignon, France*

[5]*LG-ENS (Laboratoire de Géologie) – CNRS UMR 8538 – École Normale Supérieure, PSL University – IPSL, Paris,France,*

** Presenting author: roxane.photinodellis@inrae.fr*

In order to achieve its goal of carbon neutrality by 2050, the European Union aims to develop "carbon farming". One of the goals is to maintain and increase carbon stocks in soils and biomass, thus allowing the compensation of residual GHG emissions. To encourage farmers to adopt practices that sequester carbon,the EU is relying on public and private funding and has the ambition to develop a European carbon credit certification framework.

However, the credits currently certified by frameworks from different European countries are expensive compared to the international market and limiting monitoring costs is a challenge for the development of carbon certification [Cevallos et al., 2019].

Indeed, while a low accuracy requirement can lead to undue payments and thus to a misallocation of the budget, the opposite can impact the incentive for farmers to participate in contracts. A trade-off is needed between accuracy and cost of monitoring to encourage adoption of contracts to meet mitigation goals.

While the variation in the number of samples [Mäkipää et al., 2008]and in the size of the area considered [Mooney et al., 2004] have already been studied in the context of the trade-off between monitoring costs and uncertainty, it is not, to our knowledge, the case for the temporal frequency of observations. The latter is currently about 5 years in most certification methods. Without information asymmetry, the regulator has no interest in requiring monitoring during the contract. But the risk-averse farmer may be reluctant to subscribe to a contract with a low frequency of observations. We propose here to determineunder what conditions, in terms of carbon price and uncertainty discount levels, a farmer decides to subscribe to the contract and at what frequencies he prefers to carry out observation and sampling campaigns.

To do this, we build a dynamic microeconomic model at the plot level, maximizing the expected utility of the income from the contract. There is an obligation to measure the carbon stock ex-ante and ex-post, the payments are made only after a monitoring campaign and there is a discount according to the uncertainty of the measurements. Thus, if the farmer decides to subscribe to the contract, he chooses each year the method of estimating the carbon stored. Either the farmer measures it and chooses the number of samples and pays the cost. Or he is content with a prediction based on the previous measurement campaign, which costs nothing. The number of samples taken as well as the time elapsed since the last monitoring campaign has an impact on the uncertainty of stored carbon predictions.

We apply this economic model to experimental data from Ultuna (Finland) and to simulations of a multi-model of carbon stock evolution [Bruni et al, In prep] calibrated on the Ultuna data. We run simulations with the economic model for several carbon price, discount, and risk aversion levels and several practices.

Our results are still in progress.

Keywords: carbon certification contract design, soil carbon sequestration, measurement cost, monitoring accuracy, monitoring frequency

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A Marginal Abatement Cost Curve for Greenhouse gases attenuation by additional carbon storage in French agricultural land

[*]Bamière Laure[1], Bellassen Vaentin[2]., Angers Denis[3], Cardinael Rémi[4,5,6], Ceschia Eric[7], Chenu Claire[8], Constantin Julie[9], Delame Nathalie[1], Graux Anne-Isabelle[10], Houot Sabine[8], Klumpp Katja[11], Launay Camille[8, 9,12], Letort Elodie[13], Martin Raphael[11], Meziere Delphine[14], Mosnier Claire[15], Réchauchère Olivier[16, 17], Schiavo Michele[16,18], Thérond Olivier[19] and Pellerin Sylvain[20].

[1]Université Paris-Saclay, INRAE, AgroParisTech, PSAE, F-78850, Thiverval- Grignon, France

[2]CESAER UMR1041, INRAE, Institut Agro, Université Bourgogne Franche-Comté, F-21000, Dijon, France

[3]Agriculture and Agri-Food Canada, Québec City, Canada.

[4]AIDA, Univ Montpellier, CIRAD, Montpellier, France

[5]CIRAD, UPR AIDA, Harare, Zimbabwe;

[6]Department of Plant Production Sciences and Technologies, University of Zimbabwe, Harare, Zimbabwe

[7]INRA, USC 1439 CESBIO, Toulouse, France

[8]Université Paris-Saclay, INRAE, AgroParisTech, UMR Ecosys, F-78850, Thiverval-Grignon, France

[9]Université de Toulouse, INRAE, UMR AGIR, F-31320, Castanet-Tolosan, France
[10]INRAE, Institut Agro, UMR PEGASE, F-35590, Saint-Gilles, France
[11]Université Clermont Auvergne, INRAE, VetAgroSup, UMR Ecosystème Prairial, F-63000, Clermont-Ferrand, France

[12]GRDF, F-75009, Paris, France

[13]INRAE, UMR 1302 SMART, Rennes, France

[14]Université Montpellier, CIHEAM-IAMM, CIRAD, INRAE, Institut Agro, UMR ABSYS Montpellier, France

[15]Université Clermont Auvergne, *INRAE*, VetAgroSup, UMR Herbivore, F-63122, Saint-Genès-Champanelle, France

[16]Direction de l'Expertise, de la Prospective et des Etudes, INRAE, Paris

[17]Université Paris-Saclay, INRAE, AgroParisTech, UMR Agronomie, F-78850, Thiverval-Grignon, France

[18]Institute for Sustainable Development and International Relations (Iddri), 41 rue du Four, 75007 Paris, France
[19]Université de Lorraine, INRAE, UMR LAE, Colmar, France

[20]INRAE, Bordeaux Sciences Agro, UMR ISPA, Villenave d'Ornon, France

[2] *Organisation Name, Town, Country*

** Presenting author: laure.bamiere@inrae.fr*

Following the Paris agreement at COP21, the European Union (EU) set a carbon neutrality objective by 2050, and so did France. The French agricultural sector can contribute as a carbon sink through carbon storage in biomass and soil, in addition to reducing GHG emissions. The objective of this study is to quantitatively assess the additional storage potential and cost of a set of eight carbon-storing practices. The impacts of these practices on soil organic carbon storage and crop production are assessed at a very fine spatial scale, using crop and grassland models. The associated area base, GHG budget, and implementation costs are assessed and aggregated at the region level. The economic model BANCO

uses this information to derive the marginal abatement cost curve for France and identify the combination of carbon storing practices that minimizes the total cost of achieving a given national net GHG mitigation target. We find that a substantial amount of carbon, 36 to 53,5 $MtCO_2e\ yr^{-1}$, can be stored in soil and biomass for reasonable carbon prices of 55 and 250 € tCO_2e^{-1}, respectively (corresponding to current and 2030 French carbon value for climate action), mainly by developing agroforestry and hedges, generalising cover crops, and introducing or extending temporary grasslands in crop sequences. This finding questions the 3-5 times lower target retained for the agricultural carbon sink by the French climate neutrality strategy. Overall, this would decrease French GHG emissions by 8 to 11,7% respectively.

Keywords: soil organic carbon sequestration, greenhouse gas, abatement cost, agriculture, France

What role for the agri-environment in the era of carbon farming schemes?

Polakova Jana

Czech University of Life Sciences in Prague, Czech Republic

** Presenting author: jpolakova@af.czu.cz*

Today farmers make valiant efforts to work on the balance of market and society as they negotiate the drivers of technology, climate change, diet and population alongside pressures to natural resources. Market and society are not in conflict, according to Ostrom (2009) when they come to the significant challenge as to developing 'common kinds of heterogeneity that have independent effects and operate through different causal mechanisms'.

This paper sets out to pose a few questions underpinning the role of the agri-environment in the era of carbon farming schemes. The agri-environment (AE) is a strategy that operates precisely on the balance between market and society. AE takes into account the transactional perspective (Falconer 2000). This means that AE applies causal mechanism so as to incentivize farmers. The AE incentive is toward achieving the implementation of climate-friendly measures such as the safeguarding of soil carbon assets.

Carbon farming scheme is a term that prompts us to question the nature and the definition of a "scheme". In other words, what is the role for the AE scheme in the era of carbon funding schemes? The investigation is about the definition of a "scheme" to qualify as a causal mechanism worthy of the denomination "scheme". In this paper we set out three complementary definitions of the term "scheme": a) AE scheme associated to the carbon sequestration b) a scheme defined according to the usage of "quality schemes" in the area of food quality; and c) a scheme defined by the Commission report with regard to carbon farming.

Inasmuch as farmers increasingly align around private standards with regard to monitoring and verification associated to carbon farming, the agri-environment is a public measure representing the distribution of stakeholders' immense shared knowledge (Barnes et al. 2011; Nowicki et al. 2009), as shown in Fig. 1. The AE results emerge via farmers' complex interactions at different dimensions in tandem with supporting rural development policy organisations (Poláková et al. 2011 and 2013).

The conference paper outlines advantages and disadvantages with regard to AE schemes, in particular with regard to monitoring and verification, in comparison with carbon farming.

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Keywords: agri-environment; scheme; carbon farming; private standards; policy tools

Note to panel coordinators:

If you are unable to travel to Palermo but can attend online, and you still want to submit an abstract for a breakout session, you may do so, but please let us know in the form that you will only be attending online. – May you kindly be informed I apply for the online presentation.

Danish Farmers’ perceptions of carbon farming practices – opportunities and barriers

Graversgaard Morten[1*],

[1] *Department of Agroecology, Aarhus University, 8830 Tjele, Denmark*

** Presenting author: morten.graversgaard@agro.au.dk*

Carbon farming practices play a key role for soil fertility and climate adaptation, while also having potential to contribute towards climate mitigation. However, successful implementation depends on understanding farmers’ perceptions of management practices and aligning policies with these behavioural insights. Here we analyse Danish farmers’ views of carbon farming practices using a representative national survey. The results show that Danish farmers have limited knowledge of SOC content and limited awareness of SOC management practices. The SOC practices perceived to be most effective were grass in rotation, manure application, use of cover crops, residue management and to some degree, permanent grassland. Rewetting of organic soils, biochar and agroforestry are the management practices with least knowledge of effectiveness. We demonstrate that age and farm size constitute barriers and opportunities in developing effective polices for SOC management. We show that younger farmers (with larger farms) are more critical about the current SOC content than older farmers (smaller farms). However, younger farmers are more interested in and optimistic towards the potential effectiveness of SOC management practices. Our findings indicate that age and farm size demographics are important to include in the design of policies for upscaling the adoption of SOC management practices. The study also shows the importance of demonstrating myriad benefits to implementing SOC management practices as part of knowledge dissemination. There is a need for tailoring knowledge of practices and implementation strategies tailored to the farm context.

Keywords: Climate change; carbon farming; knowledge management; policy implementation; farmer demographics

Energy cover crops for anaerobic digestion should increase soil organic carbon storage

Florent Levavasseur[1,], Patrice Kouakou[2], Julie Constantin[3], Romain Cresson[2], Fabien Ferchaud[4], Romain Girault[5], Vincent Jean-Baptiste[6], Hélène Lagrange[7], Sylvain Marsac[7], Sylvain Pellerin[8], Sabine Houot[1]*

[1] *INRAE, AgroParisTech, Université Paris-Saclay, UMR ECOSYS, 78850 Thiverval-Grignon, France*

[2] *INRAE Transfert, Centre INRAE de Narbonne, Avenue des Etangs 11100 Narbonne*

[3] *Université de Toulouse, INRAE, UMR AGIR, F-31320, Castanet-Tolosan, France*

[4] *BioEcoAgro Joint Research Unit, INRAE, Université de Liège, Université de Lille, Université de Picardie Jules Verne, 02000 Barenton-Bugny, France*

[5] *INRAE, UR OPAALE, F-35000, Rennes, France*

[6] *GRDF, 6 rue Condorcet, 75009 Paris*

[7] *Arvalis-Institut du végétal, F-31450, Baziège, France*

[8] *INRAE, Bordeaux Sciences Agro, UMR ISPA, Villenave d'Ornon, France*

** Presenting author: florent.levavasseur@inrae.fr*

Energy cover crops for anaerobic digestion (AD) are inserted between two main crops. They replaced either bare soil or non-harvested cover crops. They thus do not compete with food production and allow the production of renewable energy (biogas) as well as of digestate, used as an organic fertilizer. Because of the changes in both quantity and quality of C returned to soil, the impact of energy cover crops on soil organic carbon (SOC) stocks is questioned. Our objective was thus to study the difference in SOC stocks induced by the introduction of energy cover crops for AD coupled with the application of the resulting amount of digestate. We used the AD model Sys-Metha combined with the soil C model AMG to simulate SOC stocks for 13 case studies with energy cover crop in France. The main results indicated that energy cover crops (with digestate returned to soil) led to higher SOC storage in comparison to non-harvested cover crops or bare soil (from 0.01 to 0.12 t C ha^{-1} year^{-1} during 30 years). The higher biomass production of energy cover crops (from 6.7 to 11.1 t DM ha^{-1}) in comparison to non-harvested cover crop (2 t DM ha^{-1}) or bare soil was the driver of SOC storage, leading to higher humified C input (belowground input and digestate) despite the high C losses in AD. The uncertainties in model calibration did not modify these results. However, in the case of equal biomass production between energy cover crops and non-harvested cover crops (not representative of actual field practices), SOC stocks would be lower with energy cover crops. Finally, a multicriteria assessment should be performed to consider other effects than SOC storage, especially the impacts of the intensification required to increase the biomass production of energy cover crop.

Keywords: cover crop; anaerobic digestion, SOC, modelling

Effect of long-term sewage sludge amendment on plastic distributions in soils

Heinze Wiebke Mareile[1], Steinmetz Zacharias[2] and Cornelis, Geert[1,*]

[1]*Swedish University of Agricultural Sciences, Uppsala, Sweden*

[2] *iES Landau, Institute for Environmental Sciences, Group of Environmental and Soil Chemistry, University of Koblenz–Landau, Landau, Germany*

** Presenting author: geert.cornelis@slu.se*

Fertilizing soils with organic amendments such as wastewater treatment sludge is being prioritized by countries seeking to become bio-based societies. Moreover, recycling external organic matter rather than burning it contributes to carbon sequestration in soils. However, many organic amendments contain microplastics that thus contaminate the soils. While the number of studies demonstrating microplastic presence in agricultural soil under different management systems is increasing, there is still a considerable knowledge gap on the potential mobility of microplastics. Laboratory-based process studies indicate transport of microplastics. However, field investigations of microplastic distribution in the soil profile are still lacking which makes it challenging to understand their long-term fate and local impact. The environmental impact of organic amendments is thus not fully understood. The objective of this study was to investigate the abundance and spatial distribution of microplastics in soil profiles from a long-term field experiment, including field plots exposed to 25 years of bi-annual sewage sludge application in contrast to field plots without fertilization. To this end, soil cores of 90 cm depth were taken and segmented into 10 cm thick layers, except the plough layer (0-20 cm). Polyethylene (PE), polystyrene (PS) and polypropylene (PP) microplastics below 2 mm size were then analysed using pyrolysis gas chromatography mass spectrometry after density separation and subsequent organic solvent extraction with 1,2,4-TCB and p-xylene. Microplastic abundance and differences between treatments were polymer-specific with PE being more abundant when sewage sludge was applied to the soil. In contrast, PS and PP were less strongly related to sewage sludge applications and detected in occasional single instances in both treatments. The detection of PE, PS and PP in control plots indicates that the area may be exposed to other more diffuse input sources, albeit at low levels. Notably, all microplastics were at least partly detected below the plough layer (0-20 cm). PE was detected in significant levels down to approximately 40-50 cm in the soil profile, which is likely attributed to transport processes within the soil profile. On the one hand, this emphasizes the need to consider deeper soil layers for accurate mass estimates and monitoring purposes; on the other hand, our results indicate that depending on the soil properties, soils may act as a temporary sink for microplastics arriving in soils following addition of organic amendments.

Keywords: external organic matter; risk assessment; carbon sequestration

Bridging the gap between research and practice: the importance of biochar quality and pyrolysis yield for soil carbon sequestration

Rodrigues Leonor*, Keel Sonja [1] and Leifeld Jens [1]

[1] *Agroscope, Climate and agriculture research group, 8046 Zürich, Switzerland*

** Presenting author: Leonormaria.gondimrodrigues@agroscope.admin.ch*

Biochar is a carbon rich, relatively stable product produced from biomass, by anaerobic or oxygen-limited combustion known as pyrolysis. Storing biochar in soil has been suggested as a potentially effective long-term option to sequester CO2. Under the rising international interest in the application of biochar to soils as a negative emission technology, there is an urgent need for a robust but simple tool to estimate its carbon sequestration potential. The H/Corg molar ratio has been widely recognized as a proxy to describe stability, in science and in practice. Empirical data deriving from different scientific field and incubation studies of biochar are being used to calculate the fraction of biochar carbon remaining in soil after 100 years (Fperm) as a function of the molar ratio H/Corg. In experiments, biochars of varying quality are applied. These sometimes do not represent well the properties of biochars typically used in practice. For the latter, often qualities adhering to the guidelines of the European Biochar Certificate (EBC) apply. We suggest how to bridge this gap between research and practice and show how biochar quality and pyrolysis yield influence the calculated Fperm for biochar based carbon sequestration. For our analysis, we only include those studies where the biochars are in accordance with the EBC criteria in terms of Corg content and H/Corg ratio. As a result, we propose a new parameter to describe pyrolysis efficiency in relation to stability of biochar and suggest an alternative model for estimating the carbon sequestration potential of biochar.

Keywords: biochar; carbon sequestration, model

Influence of biochar on nitrous oxide emission from vermicompost.

[1]Hood-Nowotny R., [1]Schütz F., A.,[2]Heiling [3]Grand M.,[2] Resch C., and [2]Dercon G.

[1] *Institute of Soil Research, Department of Forest and Soil Sciences, University of Natural Resources and Life Sciences, Vienna, Austria*
[2] *Soil and Water Management and Crop Nutrition Laboratory, Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture, Seibersdorf, Austria*
[3] *Grand Farms. Absdorf Austria.*

Vermicomposting is the process of using worms to transform organic waste into a nutrient-rich fertilizer. The end product is called vermicast, which is used as fertiliser or as a soil activator. There are many advantages of vermicomposting, such as the improvement of soil aeration, enrichment of the soil with beneficial micro-organisms, increased water holding capacity, leading to improved root growth and structure, these positive effects are all well documented. However, there are some studies that suggest worms produce potent greenhouse gases (GHG), in particular nitrous oxide, although biochar (BC) addition to the soil-worm systems studied reduced the emissions. Biochar is pyrolysed biomass, specifically produced to be added to soil as a soil conditioner-carbon sequestration measure. It has been recognised that vermicomposting could play a significant role in the circular economy, particularly tackling food waste recycling in peri-urban areas, whilst creating green business opportunities. To confidently advocate these novel systems, knowledge of the pollution swapping risks must be assessed. Therefore a study was proposed to determine the influence of adding biochar to the vermicomposting process in order to reduce GHG emissions. The incubation experiment was a collaboration of a local industrial worm farmer (VERMIGRAND, Naturprodukte GmbH Absdorf) and the Institute of Soil Research, University of Natural Resources and Life Sciences (BOKU), Tulln and the Soil and Water Management and Crop Nutrition Laboratory of the Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture, Seibersdorf.

The aim of the research is to quantify the GHG emissions from the entire worm composting process and to assess the impact of the addition of BC to the vermicompost particularly its impact on nitrous oxide (N_2O) and carbon dioxide (CO_2) emissions, in addition to determining the influence of the timing of the BC addition, whether there was an effect if biochar was added before or after the initial hot composting process.

In this study two stages of composting and different types of vermicompost were be compared: In the first stage GHG's were be measured from regular feedstock hot composted normally (Comp) and feedstock pre-treated with 5% (v/v) BC added prior to hot composting (BC-Comp). Following hot composting an additional treatment where BC was added after the initial hot composting (Comp+BC) was included. Equal quantities of worms were added to the replicated treatments and the GHG's measured regularly throughout the compost maturation process.

The following measurements were conducted: compost temperature, pH, and salinity. In addition to N_2O and CO_2 concentrations measured using off-axis Integrated Cavity Output Spectroscopy (OA-ICOS) in continuous flow mode. Concurrently compost properties of total soluble nitrogen, soluble organic nitrogen, soluble inorganic nitrogen, total soluble carbon, soluble organic carbon and soluble inorganic carbon were be measured using a combination of standard colourmetric methods and elemental analysis.

Biochar as heavy metals immobilization agent

Barcauskaite Karolina[1*], Olga Anne[2] , Mockeviciene Ieva[1] , Siaudinis Gintaras [1] , Repsiene Regina[1] and Danute Karciauskiene [1]

[1] *Lithuanian Research Centre for Agriculture and Forestry, Kėdainiai District, Lithuania*

[2] *Klaipeda University, Klaipeda, Lithuania*

** Presenting author: karolina.barcauskaite@lammc.lt*

Biochar can be produced from a wide range of organic wastes via pyrolysis, where due to its versatility it has been widely applied in many different research areas, i.e., for carbon sequestration in soils as physicochemical soil amendments and to improve soil productivity. Biochar like lime and fly ash increases soil pH and hence can act as an immobilizing agent for heavy metals. This study aimed to investigate biochar produced from different organic by-products effects on heavy metals immobilization into the soil. Three types of biowaste, such as corn stalks, degistates from sewage sludge biogas, and rapeseed residues of biodiesel production, were used for biochar preparation via pyrolysis and used as soil amendments. Vegetation experiment with two plants (mustard and buckwheat) were instaled to determine biochar effect as an immobilization agent. It was evaluated heavy metals accumulation trends in roots and plant shoots, in the soil after harvest and in drainage water as well. Obtained results demonstrate that biochar is a prospective agent for heavy metals immobilization and could decrease its availability to plants. Organic amendments incorporation increased soil pH and reduced heavy metals availability to plants. Biochar additive increased bond to organic matter nickel and copper content. Biochar application on soil decreased bond to carbonates and bond to manganese and iron oxides content of copper. The hugest changes were observed with zinc. In the soil without, organic amendments around 80 percent of zinc were easily bioavailable to plants. While after organic amendments application residuals fraction increased and only around 20 percent of the total determined amount of zinc was found as a bioavailable fraction. The results will be presented during EJP Soil Science days breakout session are obtained by implementing the Interreg South Baltic Programme 2014-2020 project "Baltic Phytoremediation (BAPR)". This project show case solutions on phytoremediation and energy production from grown crops to clean polluted soil, and host a network to exchange cross-border knowledge through best practices/standards.

Keywords: biochar; heavy metals; phytoremediation; immobilization;

Repeated applications of external organic matters potentially enhance soil carbon storage and soil fertility with potential adverse effects

Houot Sabine[1*], Michaud Aurélia[2], Resseguier Camille, Montenach Denis and Levavasseur Florent [1]

[1] *INRAE, ECOSYS, Université Paris-Saclay, AgroParisTech, 78850 Thiverval-Grignon, France*

[2] *INRAE, SAS, Institut Agro, 35000 Rennes, France*

3 INRAE, UEAV, 68000 Colmar, France

** Presenting author: sabine.houot@inrae.fr*

Repeated application of organic amendments can enhance carbon sequestration in soils. These organic amendments are mainly issued from exogenous organic matters (EOM) (not directly produced from the soil where application occurs), coming from organic wastes or by-products related to other activities and often treated before application for different purposes (sanitation, stabilisation of organic matter,…). Their application in agriculture has been largely encouraged since it makes possible to recycle the nutrients they contain as substitute to mineral fertilizers and also potentially increase carbon storage in soils and improve associated soil properties. If agricultural and industrial wastes are largely recycled in agriculture, the recycling of urban wastes is strongly encouraged after biological treatments (composting or anaerobic digestion). These recycling participate to circular economy, however such practice needs to be proved to have no adverse impacts on soil, crop and water qualities. It is thus important to balance benefits and risks associated to their repeated application.

A network of long-term field experiments (SOERE-PRO) have been created among French research institutes, to quantify, explain and be able to predict the consequences of repeated fertilization with OW on soil and water qualities and on crop production and quality. The SOERE-PRO included different pedoclimatic conditions including temperate and tropical conditions, various OW including animal manures and slurries, sewage sludge composted or not, biowaste composts and digestates… with some experiments as old as 1998.

The presentation will explore how long-term experiments are useful tools to quantify the effects of repeated applications of EOM on soil C stocks, define indicators making possible to predict their efficiency, quantify the side effects they may have on soil ecosystem services but also potentially on soil contamination. By making possible the assessment of multiple impacts and their interactions, such experiments should be useful tools to help decision makers at providing new regulations or best management practices.

This abstract has been prepared for the “Carbon sequestration and amendments” session. But this session is not available on the web page.

Keywords: external organic matter, long-term field experiment, C storage, contaminant, nitrogen

Abstract EJP Soil Science Days 2022

Session: #4: Soil Biodiversity and Ecosystem Service

Hanegraaf M.C., Waren-Raffa, D., Van den Berg, W., Di Lonardo, S & R. Martin

Modelling the impact of the soil microbiome on carbon sequestration in the AGROECOseqC-project

Soil fauna and microbial communities drive key ecosystem functions such as carbon sequestration and nitrogen mineralisation. The soil microbiome itself is shaped by land-use and soil management, e.g. plant diversity. Detailed knowledge about the relationships involved would provide options for baseline accounting and/or soil management. However, current models for assessing carbon sequestration are poorly equipped to represent the soil biota composition, functional diversity and activity. We hypothesize that the effect of plant diversity on carbon sequestration, playing a key role on shaping soil microbiome, may be differentiated from its effect as a mere source of carbon. To test the hypothesis, a modelling exercise will be carried out using the ROTHC-model and data from EU long-term experiments (LTE). Data collection in the LTEs will include all relevant aspects of the soil microbiome, i.e. particularly regarding its composition and activity. The ROTHC-model includes a BIO pool that represents carbon stored in the microbial biomass. Not only have pool size and turnover rate of the BIO pool been poorly validated, but the concept falls short in taking soil biodiversity into account. Furthermore, the model may be extended to include C from plant roots. Based on the outcomes of a multivariate analysis focusing on carbon use efficiency (CUE), the inclusion of the effect of the soil biome may be improved. Several possible adaptations of the RothC model will be tested with data from selected LTEs and evaluation made relative to time series of measured SOC from selected LTEs reserved for validation. Then conclusions may be drawn for a policy-relevant indicator, e.g. regarding the impact of the soil microbiome on carbon sequestration. This approach for model development will be discussed.

Do we need an ISO standard on the valuation of ecosystem services provided by soils?

Antonio Bispo, INRAE, InfoSol, F-45075 Orléans, Cedex 02, France

Isabelle Cousin, INRAE, UR Sols, F-45075 Orléans, Cedex 02, France

Gregory Obiang Ndong, INRAE, UR Sols, F-45075 Orléans, Cedex 02, France

Thomas Eglin, ADEME, DBER, F-49000 Angers, France

Cecile Grand, ADEME, DVTD, F-49000 Angers, France

Pascal Pandard, INERIS, F-60550 Verneuil en Halatte, France

Christian Mougin, UMR ECOSYS, Platform Biochem-Env, INRAE, AgroParisTech, Université Paris-Saclay, 78026, Versailles, France

Elsa Limasset E.Limasset@brgm.fr, BRGM

Jorg Rombke, ECT Oekotoxikologie GmbH

Caroline Lhuillery caroline.lhuillery@afnor.org,

Michel Brossard, michel.brossard@ird.fr, France

Soils host an enormous biodiversity, both in terms of abundance, number of species and functions of organisms. These organisms and their interactions are fundamental to many soil processes and ecological functions, as organic matter decomposition, nutrient and water cycling, soil structure formation, pest regulation, filtration and biotransformation of contaminants. All those processes and functions can be related to ecosystem services that are of direct benefit to humans, such as food production, climate regulation or provision of clean water.

Ecosystem services are quite easily understandable and communicable: the way Nature provides you a service. Very quickly policy makers and even citizens have asked for valuations of ecosystem services provided by land (not only soil). As a consequence several world, EU, national or local experiments have been conducted leading to a great number of publications, the most famous one being the Millennium Ecosystem Assessment. All those valuations have more or less proposed their own definitions and methodologies leading to a wide diversity of results. For more than 10 years several approaches and frameworks were developed by research units around the world to assess soil functions and the related ecosystem services. As a consequence various minimum datasets of parameters were proposed for those assessments including at least soil biological, physical and chemical parameters, but also integrating land use, land management or climate information. Now it appears there is a need to gather all those experiences to provide a consensual methodology to evaluators.

Methods and models developed by scientists for investigating and deciphering processes in soils need to be translated into practical and transparent procedures. International standardization is a way to achieve such objective, as the aim is to share knowledge and reach agreement on a document (e.g., standard, guideline, technical report) that can be used worldwide. Having an international common way to assess soil functions and related ecosystem services is crucial to further compare valuations made in different countries, soil types and land uses (from degraded or contaminated land to agricultural or natural land) for management or remediation purposes.

ISO/TC 190 has developed from the 1980's more than 180 standards dealing with soil description and soil analysis. Until the 1990's most of the standards were dedicated to the characterization of soil quality regarding fertility in relation to food production. Subsequently, the main emphasis shifted to the analysis of soil contaminants (e.g., trace elements, organic molecules) and their respective impact on soil living organisms (e.g., microorganisms, soil invertebrates, plants). More recently the issues of climate change and ecosystem services were raised. Last year during the plenary meeting ISO/TC 190 asked a group to decide about the need of standardization in the field of ecosystem services. We want to take the opportunity EJPS SOIL Annual Science Days to discuss this question with a broad range of research communities, coming from ecology, pedology, climatology, economics, agronomy…: do you think we can reach an agreement on definitions, indicators, models… to develop standards and by the way will you join us?

Tuning the soil microbiome to support sustainable crop systems

Hernandez-Soriano Maria[1*], Warren Fred J[2], Wingen Luzie U[1], Urbina Ifigenia[1], Acedo Alberto[1], Griffiths Simon[1], and Miller Tony[1]

[1] *John Innes Centre, Norwich, UK*

[2] *Quadram, Norwich, UK*

[3] *Biome Makers Inc., Valladolid, Spain*

** Presenting author: maria.hernandez-soriano@jic.ac.uk*

Soils provide 99.9% of the food consumed by humanity. Wheat is the most widely grown crop in agricultural system and is the staple crop for 35% of the world population, providing 20% of daily protein and food calories. To meet the sustainable development goal of 'food security' it is necessary to maintain healthy soils and to restore degraded agricultural land. Effective strategies require identifying, and targeting, the parameters that define a healthy soil but also the effectors. One of the WISH-ROOTS project goals addresses a main markers of soil health: the capacity to provide essential nutrients to plants and soil organisms while maintaining a balance, focusing on nitrogen cycling.

Application of nitrogen (N) fertilisers to agricultural soils supports half of the world's food production. However, approximately 50% of this N worldwide is transformed by soil microbes (through nitrification/denitrification) and lost to the environment by leaching/gaseous emissions. Biological nitrification inhibitors (BNIs) exuded from the roots of certain varieties of plants can reduce loss of N-fertilizer. Particularly, some historic landraces of bread wheat (*Triticum aestivum L.*) have shown evidence of BNI activity in their root exudates. Introducing this agronomic trait into modern cultivars could improve the efficiency of use of N-fertilizer by crops while reducing N loses to the environment.

Performing 16S sequencing analysis for rhizosphere soil from a modern wheat variety (Paragon) and an ancient landrace with BNI capacity has revealed a significant segregation in microbiome composition in the rhizosphere with significant differences in the abundances of several bacterial communities, particularly for guilds involved in the transformation of N in soil. The prediction of the functions of these communities using PICRUSt2 and shotgun sequencing has confirmed differences for several functions related to N transformation between Paragon and Persia.

Microbiome diversity in rhizosphere soil and associated functionality can be used for quantitative trait loci (QTL) mapping of agronomic traits such as control of soil nitrification. We have sequenced (16S and ITS) rhizosphere soil from 88 recombinant inbred lines of bread wheat derived from parentals with contrasting capacity to control nitrification in the rhizosphere. We have identified genomic regions in the wheat genome significantly linked to the abundance of specific nitrifying communities (*Nitrospiraceae*, *Nitrosomonadaceae* and *Nitrosococcaceae)* and associated ecological functions: aerobic ammonia oxidation and nitrification (PICRUSt2).

We are currently using wheat gene expression databases to identify potential target genes in the wheat genome which are expressed at high levels in root tissue and may influence soil microbial communities. This will be used to develop breeding targets for wheat breeders to incorporate BNI activity into modern bread wheat varieties. This strategy can provide advantageous varieties for farmers that support a more sustainable use of land improving soil microbial biodiversity and N cycling while ensuring wheat production for food security.

Keywords: rhizosphere, soil microbiome, nitrogen, wheat

Microorganisms as biological indicators of soil quality under different tillage systems in *Retisol*

Vilkiene Monika[1*], Mockeviciene Ieva[1] and Karcauskiene Danute[1]

[1] *Vezaiciai Branch, Institute of Agriculture, Lithuanian Research Centre for Agriculture and Forestry, Vezaiciai, 96216, Lithuania;*

** Presenting author: monika.vilkiene@lammc.lt*

Soil microorganism diversity have a close relation with soil function, and the changes in the composition of soil microbial population can directly affect it. To meet increasing human food demands, scientists and farmers face new challenges that result from significant ongoing climate changes which includes mild winters, prolonged vegetation period, extreme temperatures, and intense rain in the Northern part of Europe. Sustainable soil management and biodiversity conservation may be the key actions for the soil health maintenance. The aim of this study was to identify bacterial community composition and to determine the main soil chemical and physical properties formed by the different tillage systems. The experiment was set up in the year 2013 and had a split-plot design where the whole-plot treatments were laid out in a randomized design with three replicates. The whole-plot treatments consisted of three tillage methods – deep ploughing (22–25 cm) (DP), ploughless tillage (7–10 cm) (PT) and ploughless tillage (7–10 cm) with additional deep loosening (up to 40 cm), which was applied every 4 years (PTS). The split-plot treatments involved four types of additional organic fertilizers: stubble (S), chopped straw + N_{10} (ChS), chopped grass (1^{st} cut) + N_{10} (G) and farmyard manure 40 tha^{-1}(M). Soil samples were taken from the two layers of the soil profile, the upper 0–10 cm, and the lower 10–20 cm. Composition and diversity of soil bacterial communities were assessed by the sequencing of 16S rRNA genes. Results revealed that acidification process was determined in all analysed soils except in the soil with shallow ploughless tillage and additional loosening, however, this method significantly increased soil density and humidity but adversely affected aeration and general porosity of the soil. The highest biodiversity was found in the soil with shallow ploughless tillage and enriched with farmyard manure. *Actinobacteria* and *Proteobacteria* were the dominant bacterial species across all treatments. Their total abundance varied between 26% and 36% in the different analysed agroecosystems. In the conditions of western Lithuanian climate, the process of mineralization in *Dystric Bathygleyic Glossic Retisol* takes place all year round but becomes the most intensive in autumn. Neither the application of different organic fertilizers, nor tillage methods have any significant effect on the rate of mineralization of the substrate samples. Shallow ploughless tillage is the most suitable tillage technology, as it creates favourable conditions for the accumulation of organic carbon in the soil. Additional loosening promotes the loss of organic carbon in soil and increases the number of unsaturated compounds, which leads to soil degradation. These experimental results showed that great opportunities exist to change deep ploughing with alternative more environmentally friendly techniques, but further research is encouraged to determine the soil fungal and mesofauna biodiversity.

Keywords: bacterial communities; biodiversity; 16S rRNA sequencing; *Dystric Glossic Retisol*.

Scanning soil biodiversity in long term Agroforestry system in temperate climate: results from central Italy

Anita Maienza[1*], Stefano Ghignone[2] and Erica Lumini [2]

[1] *National Research Council (CNR): Institute for Bio Economy (IBE), Florence, Italy*

[2] *National Research Council (CNR): Institute for Sustainable Plant Protection (IPSP), SS Turin, Italy*

** Presenting author: anita.maienza@cnr.it*

Soils have recently become part of the global carbon agenda for climate change mitigation and adaptation through the launch of high-level initiatives. Last year, FAO launched the RECSOIL program with the intention of increasing attention to management practices that increase soil organic carbon (SOC) and can partially mitigate carbon emissions. Recarbonisation of soil by current SOC stocks maintenance and fostering SOC sequestration, has positive effects on soil structure, water retention and nutrient supply and is critical for supporting ecosystem services and agricultural productivity (FAO). In this context, agroforestry, one of the most ancient agricultural practices of the Mediterranean culture and partly lost due to agricultural intensification, has recently been reintroduced for its positive effects on the SOC sequestration (FAO and ITP 2021).

In fact, agroforestry systems positively improve the resources of the agroecosystem by providing numerous advantages as reported in experiments performed, in recent years, on tropical areas. By contrast, long-term agroforestry (LTA) studies in temperate climate are still lacking. Temperate LTA studies focusing on the soil biota communities and relative roles of the ecological drivers of organic carbon dynamics are extremely interesting and deserve to be analyzed.

This survey aims to provide monitoring tools and to highlight specific "biological traits" and / or ecological relationships for the assessment of soil quality and to define appropriate biodiversity indicators useful for providing functional information relating to ecosystem services.

During spring and autumn 2021, we analyzed some components of soil biota: mesofauna and microbial fungal communities. Particular attention was given to collembola and possible relationships with fungi, as these can significantly influence the soil carbon cycle and the related trophic network.

The study was conducted inside an area of " Tenuta di Paganico", an extensive farm devoted to organic agro-zootechnical productions in central Italy based on silvopasture practices of the local Maremmana cattle breed. The methodology was developed along a gradient based on land use (Mediterranean forestry, Silvopastoral and Grassland) and on the intensity of grazing as a function of the maximum distance that animals usually reach from the main feeding stations (high density pastures with lower distance from the station feeder and low-density pasture at greater distance).

The first results showed a substantial trend in how some silvopastoral practices can better preserve soil biodiversity, with a high level of abundance of mesofauna and fungal biodiversity, as well as soil biological quality and ecological stability, if managed in a way rational.

If forest pasture is not properly managed and livestock is persistently on the ground, biodiversity levels drop dramatically and the benefits of silvopastoral practice are not realized.

Further analyses will be necessary to 1) deepen understand and highlight the complex interactions between biological communities and physicochemical variables, all of which contribute to the overall quality of soils; 2) explore if interactions can be reliable enough to be applied for soil quality monitoring and management.

Keywords long-term agroforestry (LTA), mesofauna, Fungi, soil monitoring

Effect of Plant Probiotics and Biochar Application on Rhizosphere Biodiversity and Maize Growth in the Field

Bevivino A[1]*, Fiore A[1], Hett J[2], Caldara M[3], Cangioli L[4], Maestri E[3], Aprea G[1], Costanzo M[1], Gullì M[3], Graziano S[3], Mengoni A[4], Pihlanto A[6], Neuhoff D[2] and Marmiroli N[3]

[1] *ENEA, Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Department of Sustainability, 00123 Rome, Italy*
[2] *Department of Agroecology & Organic Farming, Rheinische Friedrich-Wilhelms-Universität Bonn, 53121 Bonn, Germany*
[3] *SITEIA.PARMA, Interdepartmental Centre for Food Safety, Technologies and Innovation for Agri-food - Department of Chemistry, Life Sciences and Environmental Sustainability, 43124 Parma, Italy Dept.*
[4] *Department of Biology University of Florence, 50121, Florence, Italy*
[5] *Centro Colture Sperimentali, CCS-Aosta S.r.l., 11020 Quart, Italy*
[6] *Natural Resources Institute Finland (Luke), FI31600 Jokioinen, Helsinki, Finland*

** Presenting author: annamaria.bevivino@enea.it*

Keywords: microbial consortia; biochar; maize rhizosphere; soil microbiome

Many efforts in the recent years are being made in developing new inoculants microbial consortia not only for growing crops sustainably but also for preserving soil health; in this context, the question of whether natural soil microbiomes are negatively or positively affected by adding foreign microorganisms needs to be addressed. The main objective of the present work is to exploit the potential of three microbial consortia, developed within the frame of the Horizon 2020 SIMBA, for sustainable crop production of maize and to assess the impact of their application in field on indigenous rhizosphere microbial diversity. Microbial consortia were applied alone or in association with Arbuscular Mycorrhizal Fungi (AMF) and biochar in open field under conventional and organic management and compared with commercial microbial products. The diversity and composition of bacterial communities in maize rhizosphere soil was investigated at different maize growth stages and with different fertilization levels via partial 16S rRNA gene amplicon sequencing. The application of SIMBA'microbial consortia had clear effects on biomass growth, yield and N content of maize, especially at lower fertilization levels while did not significantly affect species diversity and richness of native rhizospheric microbial communities. A significant change in rhizospheric microbiota diversity was found following application of commercial Micosat F1, AMF and biochar as well as increased fertilization level. Overall, our results suggested that SIMBA microbial consortia may be effectively exploited as biofertilizer in sustainable maize cultivation without altering the biodiversity or the resident microbiota, thus removing risks of long-term impacts on natural soil biodiversity.

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Designing sustainable agrosystems to promote plant-soil synchrony

S. Fontaine

Understanding how natural ecosystems may reach equivalent levels of productivity to high-input annual crops whilst providing key regulating services such as carbon storage is critical for both theoretical and applied biology. Using the latest advances in biogeochemistry and ecology, I propose that the capacity of natural ecosystems to be sustainably productive largely results from a coordination between multiple plant- and soil-related processes, synchronizing the supply of soluble nutrients by soil biota to fluctuating plant nutrient demand. This synchrony limits deficiencies and excesses that usually penalize both biomass production and the environmental performance of agrosystems. I outline four systems of plant-soil synchrony, and discuss their importance in regulating nutrient and carbon cycles depending on the environmental context. Finally, I discuss the implications of this framework for the design of sustainable agrosystems.