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Soils Newsletter

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Contents

To Our Readers

Fig. 1: The FAO and IAEA jointly launched the Atoms4Food initiative

Happy New Year and Season's Greetings. It is with much humility and joy that I write to you as the Head of the Soil and Water Management and Crop Nutrition (SWMCN) Section of the Joint FAO/IAEA Centre of Nuclear Techniques in Food and Agriculture.

Firstly, I would like to acknowledge and appreciate my predecessor Lee Heng, under her leadership, the SWMCN section effectively expanded its work globally, while effectively contributing to the mission of addressing Food Security and Climate Change.

My name may be familiar to many readers, however, for those few who do not know me, I will briefly introduce myself and explain what is my vision for the SWMCN section.

My name is Mohammad Zaman. I have been part of the SWMCN team since 2013

As Section Head, I know that the SWMCN team and its lab should be seen as a hub of research activities and scientific exploration to help our Member States in achieving their food security goals through combating climate change, conservation of soil and water, and improving the livelihoods of the under-resourced farmers.

Several events took place in the past six months. In July, Joseph Adu-Gyamfi presided over the Final Research Coordination Meeting on 'Integrated Isotopic Approaches to monitor Sources of Agro Contaminants, in Vienna, while in the same month he also took part in the Regional Training Course on Assessing and Mitigating Agro-Contaminants to Improve Water Quality and Soil Productivity in Catchments Using Integrated Isotopic Approaches, in Da Lat, Vietnam. In September, Hami Said Ahmed attended the Regional Training Course on the development of digital platforms for agricultural water management through the combination of advanced nuclear techniques and remote sensing technology, in Cairo, Egypt. In October, Gerd Dercon represented the Agency at the CGIAR,which hosted a two-day international gathering for 'Pooling Collective Intelligence' at the University of Montpelier.

There were many developments at the Laboratory with the following research topics: Water deficit and potassium affect carbon isotope composition in cassava bulk leaf material and extracted carbohydrates; The determination of fate and environmental impact of sulfamethoxazole in agricultural soils; Applying isotopic techniques to assess the impact of plastic debris in tropical agroforestry systems; Restoring Farmland from Radioactive Impact: AI-Guided Potassium Profiling; Soil moisture monitoring, a tool for sustainable irrigation development; Soil particle size distribution using the integral suspension pressure method (ISP) and gamma-ray spectrometry techniques for soil texture mapping; Predicting Carbon-13 (δ13C) signatures in cassava leaves using Mid-Infrared Spectroscopy (MIRS); 15N Tracing Technique to Measure N2O and N2 and Identify Their Sources; Assessing Soil Carbon Sequestration Using Isotopic and Related Techniques; Towards more effective soil remediation decision-making in response to large-scale nuclear emergencies; Advanced soil moisture forecasting using Cosmic Ray Neutron Sensor and Artificial Intelligence (AI).

On 18 October 2023, the IAEA and FAO jointly launched the Atoms4Food Initiative. The Atoms4Food initiative seeks to provide Member States with ground-breaking solutions tailored to their specific needs and circumstances, by harnessing the advantages of nuclear techniques along with other advanced technologies, to enhance their innovation capacity so as to boost food and nutrition security, while keeping sustainable natural resource management. To optimise our services to Member States under the framework of the Atoms4Food Initiative, SWMCN initiated identifying cross-cutting opportunities with the appropriate private and public sectors for institutional collaborations.

As we actively work on helping countries in line with the Atoms4Food initiative, a Panel Discussion at the COP28 in Dubai, UAE took place titled "Climate Smart Agriculture Solutions to Combat Salinity and Climate" on 3 December 2023. The discussion raised awareness on climate change impacts on soils and crop production, as well as climate-smart agricultural solutions and the importance of collaborative approaches to scale them up. Following these discussions two practical arrangements were signed with the International Center for Biosaline Agriculture (ICBA) and Anglo American Woodsmith Ltd. Both partnerships will boost the work of the Joint FAO/IAEA Centre in its soil and water management and crop nutrition activities.

In this busy transitional period, the SWMCN team remains steadfast to do its utmost to deliver solutions to mitigate climate change to our Member States. We welcome Ho-Seung Lee on board to help us take care of some of the tasks we have. Many may remember him as a Programme Management Officer from the IAEA Division for Asia and the Pacific. We look forward to his contributions to the work of the SWMCN Team.

I personally hope to build on the strong foundation, doing the day-to-day work, but also having a long-term vision for food security and climate change mitigation and adaptation. I aspire to be a leader who is trustworthy, sincere, and approachable.

Mohammad Zaman
Head
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Staff News

Mariana Vezzone (Brazil) joined the SWMCN Laboratory in September 2023 as a cost-free expert (funded by the Brazilian Foundation for Science and Technology) to work on microplastic biodegradation under CRP D15021. She is a postdoc in applications of nuclear physics in the field of environmental sciences at the Physics Institute of the Federal Fluminense University, Brazil. Her main research focus in Brazil is on soil and water conservation issues, applying nuclear, stable isotope, and related techniques to assess the impact of environmental stressors in tropical agroforestry systems.

Magdeline Camille Vlasimsky (USA) joined the SWMCN Laboratory as an Associate Greenhouse Gas (GHG) Emissions Officer, funded by the US government. Magdeline will be working on the development of GHG measurement procedures using laser isotope analysis and Mid-Infrared Spectroscopy (MIRS) models for predicting soil and plant parameters (including 13C). She graduated with a Bachelor's degree in Chemistry from Colorado College in 2019 and an International Master's degree in Biogeochemistry of Soils and Global Change from Ghent University, Universität für Bodenkultur (Wien), and Georg-August-Universität (Göttingen) in 2022. She has robust exposure to the soil and water management sector, working on model farm projects in Uganda and the USA, and in laboratories at several wineries, a sustainable fisheries institute, and a zoological garden. For the last two years, she has worked with the Global Soil Partnership at FAO headquarters in Rome, Italy, first on soil pollution as part of the soil threats team and then with the Spectroscopy Initiative of GLOSOLAN.

Barira Shoukat Hafiza (Pakistan) joined the SWMCN Laboratory in July 2023 as a PhD Consultant. She is a PhD student at the University of Vienna, Austria, studying Microbiology and Ecosystem Science, especially mitigation strategies of nitrous oxide (N_2O), a potent greenhouse gas. Barira will be working under the CRP D1.50.20 project on "Developing Climate Smart Agricultural practices for carbon sequestration and mitigation of greenhouse gases" by URENCO. This opportunity to work with specialists in soil ecology and environmental biology will enable her to improve her experimental skills as well as data analysis techniques.

Sobia Bibi (Pakistan) joined the SWMCN laboratory in July 2023 as a PhD consultant. She completed her master studies, major in Soil Science, from University of Agriculture Peshawar (UAP), Pakistan. She received two gold medals for her excellent academic achievements in BSc (Hons) and MSc (Hons). Ms Sobia is enrolled in the University of Vienna, Department of Microbiology and Ecosystem Science Division Terrestrial Ecosystem for pursuing her PhD study under Research group led by Prof Wolfgang Wanek. She will carry out research work in SWMCN lab in Seibersdorf supervised by Dr Gerd Dercon and Dr Mohammad Zaman in close collaboration with the University of Vienna under the CRP D1.50.20. The aim of her PhD study is to develop climate smart agricultural practices using nuclear and related techniques to mitigate the emissions of greenhouse gases from agriculture and to sequester carbon in soil to make soil more resilient to the negative impacts of climate change. This opportunity will not only enhance her knowledge to better understand these critical environmental issues, but also enable her to develop experimental skills, technical expertise, and data analysis capabilities.

Hassan Ahmad (Pakistan) joined the SWMCN Laboratory as an intern in July 2023 for one year. Hassan is a master's student at the PMAS Arid Agriculture University in Rawalpindi, Pakistan. He has been studying soil science, focusing especially on carbon sequestration and greenhouse gas (GHG) emissions. He will be working under CRP D1.50.20, aiming to learn about how to assess carbon sequestration and mitigating the emissions of GHGs, including CO_2, N_2O, and CH_4, from agriculture. This internship opportunity will enhance his knowledge and technical skills about GHG emissions, mitigation, and carbon sequestration using isotopic and related techniques.

Sanaraiz Khan (Pakistan) joined the SWMCNL as an intern in July 2023. Sanaraiz pursued a degree in Computer System Engineering at the University of Engineering and Technology, Peshawar, Pakistan, and is a tech enthusiast. He understands the principles of Cosmic Ray Neutron Sensor (CRNS) technology to assess soil moisture for efficient irrigation scaling and Gamma Ray Spectroscopy (GRS) technology to estimate soil physical and chemical properties. He will be working under the CRP D1.50.20 project to dig deep into the Cosmic Ray Neutron Sensor (CRNS) and Gamma Ray Spectroscopy (GRS) technology. With his knowledge of artificial intelligence and computer engineering he will also try to develop models for predicting short-term changes (days) in soil moisture. The opportunity to collaborate specialists will facilitate the expansion of Sanaraiz's analytical, professional, technical, and research skills.

Brenda Trust (Uganda) joined the SWMCN Laboratory in August 2023 as a Marie Sklodowska-Curie Fellowship Programme (MSCFP) intern. With the support of an IAEA-MSCFP scholarship, she graduated in April 2023 from the IHE Delft Institute for Water Education in the Netherlands with a Master of Science and Engineering specialisation in Hydrology and Water Resources. At the SWMCNL she will be working on the use of Gamma Ray Spectrometry for soil texture and property mapping at landscape level under the ongoing CRP D12014. The opportunity to work with specialists in this field will enable her to improve her skills in experimental design, field sampling and data analysis.

Sarata Darboe (The Gambia) joined the SWMCN Laboratory in October 2023 for a year as a Marie Sklodowska Curie Fellowship Programme (MSCFP) intern. She is a graduate of the Erasmus Mundus Master program in Water Science and Engineering with a specialisation in Groundwater and Global Change - Impacts and Adaptation, under the IAEA-MSCFP scholarship. Her degree is a joint degree held in three European universities (IHE Delft, Netherlands; Instituto Superior Tecnico Universidade de Lisboa, Portugal; and Technische Universitat Dresden, Germany). At the SWMCNL she is working on the use of nuclear and isotope techniques to enhance water use efficiency of cropping systems. With this opportunity to work with experts on stable isotope and mid-infrared spectroscopy analysis on soil and plant samples, she aims to expand her expertise in field experiments, data analysis, and data interpretation.

Chunhua Jiang (China) joined the SWMCNL in December 2023 as an intern. Chunhua is a master's student from the State Key Laboratory of Estuarine and Coastal Research of East China Normal University, researching microplastic pollution in estuarian waters and plastic pollution on riverbanks. She focuses primarily on monitoring techniques and strategies, and she brings 8 years of ocean-related research experience to the Lab. Chunhua will learn and work on the development of nuclear technologies and stable isotopes for assessing the fate and decomposition of plastic in soils. This internship opportunity will enable her to receive training in the use of carbon-13 techniques for microplastic persistence in agricultural soils.

Feature Articles

Sewage Sludge Usage in Agriculture: Are we introducing Microplastics in Food Chain?

Mohammad Zaman[1] and Saif Uddin[2]

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Waste Water Treatment Plants (WWTPs) worldwide yield substantial sewage sludge. The European Union designates municipal solid waste as non-hazardous; however, the considerable amounts of sewage sludge produced by Waste Water Treatment Plants (WWTPs) pose diverse environmental challenges. Sludge must, therefore, be effectively managed before it is discarded to avoid these environmental challenges. Concerted efforts towards waste reduction align with United Nations Sustainable Development Goals 11 and 12, and The United Nations Human Settlements Programme (UN-Habitat) collaborates globally to promote environmentally sound waste management. The "Waste-Wise Cities" initiative urges a comprehensive approach encompassing rethinking, reducing, recycling, refusing, and reusing waste.

Diverse strategies for sustainable waste management exist internationally. Spain, Ireland, Norway, and the USA primarily utilize over 50% of sludge as fertilizers, reflecting their commitment to sustainability. Estonia, Hungary, Cyprus, Luxembourg, and Slovakia prioritize composting with diverse organic waste utilization approaches. In contrast, 100% of sludge in Malta and Bosnia and Herzegovina goes to landfills, 52% of Romania's sludge and 22% of sludge in the USA finds its way to landfills. 16% to 100% of sludge in Switzerland, the Netherlands, Belgium, Germany, Austria, Greece and the USA is incinerated for disposal. The improper management and dumping of sludge have severe economic and environmental consequences

Current sludge disposal methods, such as sanitary landfilling and incineration, prove economically impractical. Global annual estimates reveal the production of 128 – 255.5 kg of wet sludge per capita, with dry sludge estimated at 25.5 kg per person per year [2,3]. Managing large sludge quantities intensifies greenhouse gas emissions and significantly augments wastewater operation costs. Approximately 20 – 60% of WWTP operating costs are allocated to final sludge disposal. Identifying more sustainable land-based alternatives is, therefore, economically desirable.

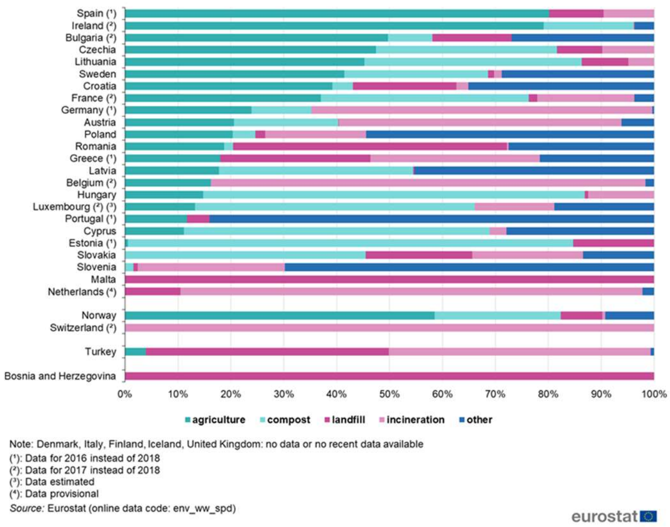

Fig. 1. Sludge utilization in various European Countries.

Regarding environmental damage, wastewater treatment plants (WWTPs) emerge as substantial conduits for MPs due to microbeads in detergents, cosmetic and personal care products, and synthetic clothing fibers. A recent examination of microplastics (MPs) in wastewater, amidst rapid population growth and escalating municipal solid waste production, revealed staggering annual discharges of 1.47 × 1015 MPs from treated effluent and 3.85 × 1016 MPs from untreated effluent globally [1]. The focus on MPs in sludge, however, remains limited. Bushehr WWTP exhibited an average MP inventory of 1.6 – 2.5 MP L-1 in wastewater, contrasting sharply with 5263 – 6877 MP kg-1 in sludge. In Kuwait's Sulabiya, Kabd, and Umm Al-Haiman WWTPs, sludge recorded the highest concentration at 72 and 103 particles in 10g, while influent ranged between 119 ± 2 – 230 ± 4 MPs L-1. These findings underscore the pivotal role of WWTPs in the dispersion of MPs, emphasizing the critical need for comprehensive management strategies.

Various pathways introduce microplastics (MPs) into agricultural soils, including the degradation of plastic linings in greenhouses and some agricultural fields, the application of sewage sludge-derived compost and fertilizers, irrigation with treated or untreated wastewater, and atmospheric deposition. Crop root growth reportedly hinders downward vertical MP migration, leading to topsoil accumulation. With the prevalent practice of land-applying dry sludge, a substantial MP quantity is expected in soils. Conservative estimates indicate MP inputs to European agricultural soils range from 0.63 – 4.30 tons y-1, and in the United States, 0.44 – 3.00 tons y-1. Depending on the WWTP type, up to 99% of MPs may be retained in sludge. Reports suggest MPs can persist in soils for up to 15 years [4]. The current understanding of MPs in sludge necessitates standardized protocols due to significant modifications in physical and chemical structures during drying and composting.

Ecological concerns regarding microplastics (MPs) arise from their potential to leach chemicals and serve as carriers for metals, organic contaminants, and microbes. The substantial surface-to-volume ratio of MPs enhances their capacity to adsorb hydrophobic chemical pollutants. During prolonged exposure to wastewater and sludge, MPs degrade, releasing chemical additives like phthalates, Bisphenol A (BPA), and polybrominated diphenyl ethers commonly used to enhance plastic properties. The degradation rate of MPs in sludge is anticipated to exceed that in marine environments. Municipal sludge is well-documented for containing microplastics, mainly when used as fertilizer for agricultural purposes, positively impacting soil fertility. Synthetic fibers are detected in sludge-treated soils, with experimental data indicating vertical MP migration in various soil profiles post-sewage sludge application. A recent study highlights the uncontrolled contamination of adjacent land due to sludge application, with 44% of the MP load on sludge-applied ground found on nearby untreated land, suggesting spill-over effects reaching depths of 60-90 cm in the soil profile.

Another investigation reveals a substantial presence of microplastics (MPs) persisting in soils treated with sludge, even after 34 years. Studies explore the impact of virgin/photo-aged biodegradable mulching films on arsenic (As) transport and accumulation in agricultural soils. A comprehensive review addresses primary sources of MPs in agricultural soils, encompassing direct and indirect effects on soil fauna, interactions with pollutants, and environmental aging. The FAO-IAEA center and the Kuwait Institute for Scientific Research are conducting research using radiolabeled microplastics, explicitly examining the translocation of MPs and potentially nanoplastics into the food chain.

Using sewage sludge in agricultural applications prompts concerns beyond microplastics (MPs). Sludge, rich in metals, organic contaminants, pharmaceuticals, and nutrients, poses potential diffusion and osmotic uptake risks for crops, warranting their inclusion in assessments. The joint FAO-IAEA Centre launched a Coordinated Research project (D15021) to evaluate the fate and environmental impact of plastics in soil and crops. Preliminary results indicate rapid microplastic migration in the soil column, with no observed translocation into crops. Ongoing experiments aim to provide a comprehensive dataset, ensuring conclusive insights into the hypothesis of microplastic assimilation into crops.

The variation in waste management strategies and the serious environmental consequences of improper wastewater treatment emphasizes the necessity for context-specific, sustainable waste management solutions to mitigate the impacts.

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Amazon expedition of Justus Liebig University Giessen/Germany

Christoph Mueller[1] and Mohammad Zaman

[1]*Justus-Liebig University, Giessen, Germany*

An international, interdisciplinary team of researchers led by Prof. Dr. Christoph Müller, Institute of Plant Ecology of the Justus Liebig University Giessen, Germany, has undertaken an expedition to the Brazilian rainforest from 26.8 - 24.9.2023, which has been prepared for years, to investigate important future questions of global climate change.

The starting point of the four-week expedition was Manaus. From there, the international research team visited various study sites along the Amazon to Santarém. This involved traveling over 700 km on the Amazon. (Figure 1).

The research was carried out in close cooperation with the Brazilian government and the EMBRAPA Agricultural Research Institute in Manaus. The International Atomic Energy Agency (IAEA) in Vienna has been closely involved in the planning for years and has provided scientific support for the research projects through the Joint FAO/IAEA Centre.

Expedition goals

The research trip had two essential goals: One is to research the so-called Terra preta soils, which have special carbon storage properties, and the other is to develop scientific- forensic procedures for combating logging - the latter in line with the current Brazilian government under President Lula, which has made combating illegal logging and preserving the rainforest one of its core missions.

First research focus: Terra preta de Indio

Importance and characteristics of the Brazilian rainforest

Tropical forests, especially those of the Brazilian rainforest in Amazonia, are elementary for mankind under various aspects.

They play a key role in determining the global climate and weather patterns and are a major contributor to biodiversity.

The soil of the rainforest is generally nutrient-poor; it has no significant humus formation. The soil thus differs fundamentally from soils in temperate climates, which exhibit a more or less strong humus formation.

Special properties of the Terra preta soil

Terra Preta soils have an a ca. 600% greater potential to mitigate C emissions compared to common rainforest soil, and are therefore of global scientific interest in the context of climate change1 . The soil has been formed - man-made - by long-term input of charcoal and food waste, manure and compost on cultivated fields (Fig. 2). This is indicated by clay shards and a high P content, which can be explained by decomposition of fish bones (Fig. 3). Current research suggests that the oldest Terra preta sites date from more than 6,000 years ago.

Due to the high charcoal content, the soil stores an extraordinary amount of C, which is difficult for microorganisms to degrade. However, previous studies by JLU on greenhouse gas (GHG) emissions of the Brazilian Terra preta soils show that investigations under laboratory conditions do not yield valid results. Therefore, it is necessary to do the specific investigations in the field.

In addition to the studies on GHG fluxes (CO_2 , CH_4 , N_2O), soil samples were examined to analyze the structure of the soil as well as C storage and microbial activity. Terra preta soils are also characterized by a long-term fertility. This results from the specific properties of charcoal. Therefore, Terra preta soils are a central research subject for global agriculture for the development of resource-conserving and climate-sensitive cultivation methods.

"The research has close links with the research focus in Giessen, to investigate the consequences of climate change on native ecosystems. On the research site near Giessen, Germany, we have been conducting biochar experiments since 2011, in which plant charcoal made from Miscanthus was applied together with pig slurry. Nuclear techniques are used to quantify the C storage potentials. Initial results confirm the hypothesis that appropriately treated soils store more C (Fig. 4). However, further targeted research is needed to answer questions about the capacity for long-term C storage. For this purpose, stable isotope analysis methods are used. The Institute of Plant Ecology at JLU has outstanding, globally recognized expertise in this field and cooperates closely with the Joint FAO/IAEA Centre and numerous scientific institutes around the world such as the EMBRAPA Institute. The IAEA, is the global authority for providing isotopic standards. It is urgent to take the necessary steps to develop appropriate standards (including N-N152 O) to ensure the necessary comparability of test results.

Second research focus: Illegal logging

The second research focus dealt with the question of how illegal logging can be combated more effectively with scientific support. The often illegal and organized logging is also largely responsible for the clear-cutting of large areas of rainforest, increasing the risk of the so-called tipping point of Amazon rainforest death - with fatal consequences for the global climate 2, 3 .

Up to now, there has been a lack of knowledge about how incriminated tropical timber can be detected (e.g. in timber warehouses in Europe). For this purpose, it is necessary to prove in a reliable and legally secure manner that this timber was illegally harvested at a specific location.

The isotope analyses developed at JLU will be used to investigate whether the analysis methods developed for soils can also be transferred and used for trees (wood). During the expedition, standardized wood samples were taken and documented accordingly (Fig. 6). The long-term goal is to provide the relevant international investigating authorities with corresponding data for targeted follow-up investigations and to create a tree register with the aid of isotope analysis in order to enable the assignment of wood to be checked to the respective felling site.

Follow-up research will be carried out in Giessen and in collaboration with the FAO/IAEA Centre, including a Brazilian PhD student from Manaus.

Conclusion

We have noticed a willingness among all partners (EMBRAPA, INPA, University of Manaus, Federal Police Manaus) to reach out to each other, even across disciplines and departments, in the interest of climate change mitigation and combating ongoing rainforest deforestation, to meet global challenges.

This research will be continued in particular within the framework of the IAEA's "Collaborative Centre" currently under construction, the: "Liebig Centre for Agroecology and Climate Impact Research".

Research team

The ten-member research team, led by Prof. Dr. Christoph Müller, included a scientist and a student from his Institute of Plant Ecology, four scientists or students from Brazil, a scientist from India, and a charcoal maker and a criminalist from Germany.

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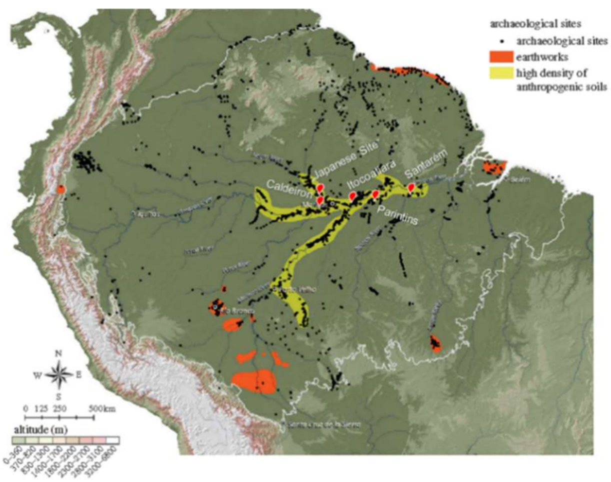

Fig. 5. Biochar investigations on an experimental field of the Institute of Plant Ecology (Justus Liebig University of Giessen).

Fig. 1,2. The study area with marked terra preta deposits (anthropogenic soils) and the selected study sites (top) (modified from Clement et al. 2015) in the Amazon rainforest (bottom). (© Christoph Müller)

Fig. 3. Agroforestry systems in the Amazon on Terra preta (© Everton Rabelo Cordeiro)

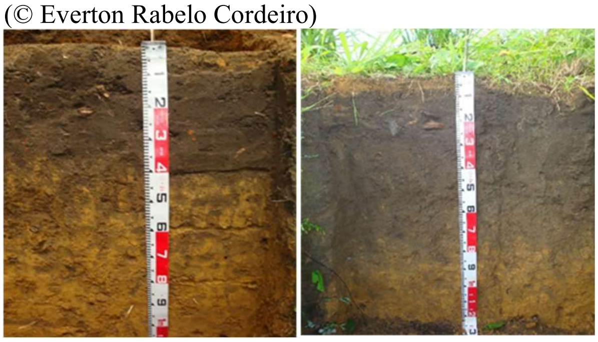

Fig. 4. Soil profiles of Terra preta (© Gilvan Coimbra Martins)

Fig. 6. A typical kiln as it was probably operated for many centuries in the Siegerländer Hauberg and in a very similar way also in the Amazon (© Institut für Pflanzenökologie)

Fig. 7ab. Sampling of a wood core

Announcements

Looking for more participants for the WEPAL proficiency test

Proficiency Tests are an important tool for external quality control and provide confidence in the analytical performance of laboratories. The University of Wageningen, the Netherlands, organizes Proficiency Tests on ^{15}N and ^{13}C isotopic abundance in plant materials, the participation fee for one round per year for selected participants is covered by the IAEA. The Wageningen Evaluating Programs for Analytical Laboratories (WEPAL, http://www.wepal.nl) is accredited for the organization of Inter-laboratory Studies by the Dutch Accreditation Council.

The SWMCN Laboratory is currently looking for more stable isotope laboratories, who want to participate in one round of this yearly Proficiency Test free of charge.

The applications are treated according to the principle "first come, first served", laboratories from developing countries are encouraged to apply.

Please send your application with a brief description of your stable isotope laboratory to Mr Christian Resch, ch.resch@iaea.org.

Technical Cooperation Projects

Country/Region	TC Project	Description	Technical Officer(s)
Afghanistan	AFG5008	Strengthening Climate Smart Agricultural Practices for Wheat, Fruits and Vegetable Crops	M. Zaman
Algeria	ALG5031	Using Nuclear Techniques to Characterize the Potentials of Soils and Vegetation for the Rehabilitation of Regions Affected by Desertification	M. Zaman
Angola	ANG5018	Enhancing the Productivity of Cereal Crops in the Country through Climate Smart Agricultural Practices	M. Zaman
Azerbaijan	AZB5003	Determining of Radioactive Substances in the Environment with a Focus on Water and Soil	M. Zaman
Azerbaijan	AZB5004	Strengthening Best Soil, Nutrient, and Water Agricultural Practices for Cotton Production	M. Zaman
Bangladesh	BGD5036	Enhancing Crop Production under Changing Climatic Conditions through Resilient Crop Varieties and Sustainable Land Use Management Using Nuclear Techniques	H. Said Ahmed
Belize	BZE5012	Use of Nuclear and Isotopic Techniques for Optimizing Soil-Water-Nutrient Management in Rainfed Agriculture Systems	J. Adu-Gyamfi
Bosnia and Herzegovina	BOH5004	Building Capacity for Soil Erosion Assessment Using Nuclear Techniques to Implement Sustainable Land Management Measures	M. Zaman
Bolivia	BOL0009	Strengthening National Capacities for the Development of Nuclear Technology Applications in Bolivia	M. Zaman
Bolivia	BOL5024	Strengthened National Capacities for the Identification of the Origin and Transport of Pesticides Compounds in Agricultural Watersheds	J. Adu-Gyamfi
Botswana	BOT5024	Improving Selected Legumes and Cereals against Biotic and Abiotic Stresses for Enhanced Food Production and Security	J. Adu-Gyamfi and PBG
Bulgaria	BUL5018	Improving Crop Water Productivity and Nutritional Quality of Orchards	J. Adu-Gyamfi
Burkina Faso	BKF5024	Improving Food Crops through Mutation Breeding and Best Soil and Nutrient Management to Ensure Food Security	J. Adu-Gyamfi and PBG
Burundi	BDI5005	Enhancing Productivity of Staple Crops Using Nuclear-derived Technologies	M. Zaman and PBG
Cambodia	KAM5008	Introducing a Digital Soil Information System and Remote Sensing for Sustainable Land Use Management	H. Said Ahmed
Central African Republic	CAF5014	Strengthening Capacity for Enhancing Cassava Production and Quality through Best Soil Nutrient Management Practices	M. Zaman
Chad	CHD5012	Improving Soil and Water Management Systems Using Nuclear Techniques	H. Said Ahmed
Chile	CHI0023	Building Capacity for Nuclear Science and Technology Applications	NAPC, NAFA. H. Said Ahmed
Colombia	COL5026	Enhancing Crop Productivity of Creole Potato Using Nuclear and Related Techniques	M. Zaman and PBG
Congo Rep. of	PRC5003	Protecting Water and Fertility in Agricultural Soils	J. Adu-Gyamfi
Costa Rica	COS5035	Building Capacity for the Development of Climate-Smart Agriculture in Rice Farming	M. Zaman
Costa Rica	COS7006	Strengthening National Capacities to Identify Sources of Contamination that Affect Highly Vulnerable Aquifers Using Isotopic and Conventional Techniques	J. Adu-Gyamfi and IH
Cuba	CUB5024	Strengthening National Capacities for the Adaptation or Mitigation of the Negative Impacts of Climate Change and the Sustainable Management of Land and Water, Through the Integrated Use of Nuclear Techniques	M. Zaman
Egypt	EGY5027	Strengthening Capacities for Combating Soil Erosion and Restoring Soil Fertility to Support Sustainable Soil and Water Management Practices and Rehabilitation of Degraded Soils for Enhanced Production and Food Security	M. Zaman
Gabon	GAB5004	Improving Soil Fertility Management for Enhanced Maize, Soybean and Groundnut Production	J. Adu-Gyamfi
Ghana	GHA5039	Mainstreaming Nuclear Based Climate Smart Agriculture Technologies into Sustainable Production	H. Said and PBG

Country/Region	TC Project	Description	Technical Officer(s)
Haiti	HAI5008	Strengthening National Capacities for Enhanced Agricultural Crop Productivity	M. Zaman
Haiti	HAI5010	Stengthening National Capacities for Enhanced Agricultural Crop Productivity	M. Zaman
Honduras	HON5011	Implementation of Soil, Water and Nutrient Management for Sustainable Coffee Production in Honduras using Nuclear Technologies	M. Zaman
Interregional project	INT5156	Building Capacity and Generating Evidence for Climate Change Impacts on Soil, Sediments and Water Resources in Mountainous Regions	G. Dercon
Interregional project	INT5159	Atoms4Cllimate Adaptation and Mitigation: Non-Power Technologies for the Terrestrial Landscape	NAFA, NAPC, G. Dercon
Iran	IRA5015	Enhancing Capacity of National Producers to Achieve Higher Levels of Self-Sufficiency in Key Staple Crops	H. Said Ahmed, FEP and PBG
Iraq	IRQ5022	Developing Climate-Smart Irrigation and Nutrient Management Practices to Maximize Water Productivity and Nutrient Use Efficiency at Farm Scale Level Using Nuclear Techniques and Advanced Technology	M. Zaman
Lao PDR	LAO5006	Enhancing Crop Production with Climate Smart Agricultural Practices and Improved Crop Varieties	M. Zaman and PBG
Lesotho	LES5012	Improving Productivity of Potato and Sorghum through Mutation Breeding and Best Soil, Nutrient and Water Management Practices	M. Zaman and PBG
Madagascar	MAG5026	Enhancing Rice and Maize Productivity through the Use of Improved Lines and Agricultural Practices to Ensure Food Security and Increase Rural Livelihoods	J. Adu-Gyamfi and PBG
Malaysia	MAL5033	Strengthening national capacity in food and animal feed for food safety and security	M. Zaman and FSC
Mali	MLI5031	Improving Rice Productivity through Mutation Breeding and Better Soil, Nutrient and Water Management Practices	M. Zaman and PBG
Namibia	NAM5020	Enhancing Staple Crop Yields, Quality, and Drought Tolerance through Broadening Genetic Variation and Better Soil and Water Management Technologies	J. Adu-Gyamfi and PBG
Namibia	NAM5022	Enhancing Crop Production in Fragile Agrosystems	H. Said Ahmed, Fatma Sarsu
Nicaragua	NIC2002	Strengthening of National Capacities in Energy Planning and Geothermal Resource Assessments through the Application of Isotopic Analytical Methods	M. Zaman
Nigeria	NIR5042	Developing Climate Smart Agricultural Practices and Soil Fertility for Increased Crop Productivity and Contributing to Food Security	M. Zaman
Pakistan	PAK5053	Strengthening and Enhancing National Capabilities for the Development of Climate Smart Crops, Improvement in Animal Productivity and Management of Soil, Water, and Nutrient Resources Using Nuclear and Related Techniques	H. Said Ahmed with PBG and SIT
Palestine (T.T.U.T.J.)	PAL5011	Enhancing Food Security via Nuclear Based Approaches	M. Zaman
Panama	PAN1002	Strengthening the Operation of the Panama Canal through Erosion and Sediment Transport Analysis using Nucleonic Control System Applications, Radiotracers and FRN and CSSI methodologies	M. Zaman
Panama	PAN5028	Improving the Quality of Organic Cocoa Production by Monitoring Heavy Metal Concentration in Soils and Evaluating Crop Water Use Efficiency	J. Adu-Gyamfi
Panama	PAN5029	Strengthening National Capacities to Combat Land Degradation and Improve Soil Productivity Through the Use of Isotope Techniques	M. Zaman
Peru	PER5035	Improving Pasture Production Through Best Soil Nutrient Management to Promote Sustainable Livestock Production in the Highland Region	M. Zaman
Peru	PER5037	Enhancing Sugarcane Production Through Improved Climate Smart Agricultural Practices	M. Zaman
Qatar	QAT5008	Developing Best Soil, Nutrient, Water and Plant Practices for Increased Production of Forages under Saline Conditions and Vegetables under Glasshouse Using Nuclear and Related Techniques	M. Zaman
Regional project Africa	RAF0056	Enhancing Nuclear Science and Technology Capacity Building through Technical Cooperation Among Developing Countries	H. Said Ahmed
Regional project Africa	RAF5081	Enhancing Productivity and Climate Resilience in Cassava-Based Systems through Improved Nutrient, Water and Soil Management (AFRA)	M. Zaman and G. Dercon

Country/Region	TC Project	Description	Technical Officer(s)
Regional project Africa	RAF5086	Promoting Sustainable Agriculture under Changing Climatic Conditions Using Nuclear Technology (AFRA) 2022-2023	H. Said Ahmed
Regional project Africa	RAF5090	Supporting Climate Change Adaptation for Communities Through Integrated Soil–Cropping–Livestock Production Systems (AFRA)	M. Zaman and APH
Regional project Africa	RAF5092	Enhancing Agricultural Productivity for Improved Food Security in Africa (AFRA)	M. Zaman
Regional project Asia	RAS5091	Assessing and Mitigating Agro-Contaminants to Improve Water Quality and Soil Productivity in Catchments Using Integrated Isotopic Approaches	J. Adu-Gyamfi
Regional project Asia	RAS5093	Strengthening Climate Smart Rice Production towards Sustainability and Regional Food Security through Nuclear and Modern Techniques	M. Zaman
Regional project Asia	RAS5094	Promoting Sustainable Agricultural and Food Productivity in the Association of Southeast Asian Nations Region	M. Zaman with PBG and FEP
Regional project Asia and Pacific	RAS5099	Developing Climate Smart Crop Production including Improvement and Enhancement of Crop Productivity, Soil and Irrigation Management, and Food Safety Using Nuclear Techniques (ARASIA)	M. Zaman with PBG and FEP
Regional project Europe	RER5028	Improving Efficiency in Water and Soil Management	H. Said Ahmed
Regional project Latin America	RLA5084	Developing Human Resources and Building Capacity of Member States in the Application of Nuclear Technology to Agriculture	J. Adu-Gyamfi, PBG and FEP
Regional Project Latin America	RLA5089	Evaluating the Impact of Heavy Metals and Other Pollutants on Soils Contaminated by Anthropogenic Activities and Natural Origin (ARCAL CLXXVII)	J. Adu-Gyamfi
Regional Project Latin America	RLA5090	Improving Agriculture Productivity through Better Agricultural Practices and Improved Varieties (ARCAL CXCII)	M. Zaman
Rwanda	RWA5001	Improving Cassava Resilience to Drought and Waterlogging Stress through Mutation Breeding and Nutrient, Soil and Water Management Techniques	M. Zaman and PBG
Saudi Arabia	SAU5004	Strengthening National Capacities for the Assessment of Groundwater Contamination with Radionuclides and their Environmental Effects on Soil and Agriculture Production	M. Zaman, S. Kumar
Saint Vincent & the Grenadines	SVT0001	Building National Capacity in Nuclear Technology Applications	J. Adu-Gyamfi, NAHU and NAPC
Senegal	SEN5041	Strengthening Climate Smart Agricultural Practices Using Nuclear and Isotopic Techniques on Salt Affected Soils	M. Zaman
Seychelles	SEY5013	Developing and Promoting Best Nutrient and Water Management Practices to Enhance Food Security and Environmental Sustainability	M. Zaman
Sierra Leone	SIL5021	Improving Productivity of Rice and Cassava to Contribute to Food Security	M. Zaman and PBG
Slovenia	SLO5005	Strengthening Agricultural Land Use and Management to Reduce Emerging Contaminants and Improve Water Quality	J. Adu-Gyamfi
Sri Lanka	SRL5051	Introducing Climate Smart Agricultural Practices to Mitigate Greenhouse Gas Emissions	M. Zaman
Sudan	SUD5041	Enhancing Productivity and Quality of High Value Crops through Improved Varieties and Best Soil, Nutrient and Water Management Practices	M. Zaman and PBG
Thailand	THA5057	Enhancing Capabilities for the Application of Isotopic Techniques for Enhanced Water Resource Management	H. Said Ahmed
Togo	TOG5004	Improving the Productivity of Crops and Agricultural Practices through Radiation Induced Mutation Techniques	M. Zaman
Togo	TOG5006	Improving the Productivity of Soybean (Glycine max L) Using Nuclear Techniques	M. Zaman
Viet Nam	VIE5026	Building Capacity for Mitigating Greenhouse Gas Emissions and Combating Climate Change through Climate Smart Agricultural Practices	M. Zaman
Zimbabwe	ZIM5026	Improving Soil Quality for Optimizing Selected Cereal and Legume Productivity in Smallholder Farms	J. Adu-Gyamfi

Forthcoming Events

FAO/IAEA Events

Second Research Coordination Meeting of CRP D15022 on Isotopic Techniques to Assess the Fate of Antimicrobials and Implications for Antimicrobial Resistance in Agricultural Systems, 11-14 March 2024, Vienna, Austria.

Technical Officer J. Adu-Gyamfi

Regional Workshop on Soil-Water Management Practices to Reduce Agro-contaminants and Improve Water Quality under TC project RAS5091 (Assessing and Mitigating Agro-Contaminants to Improve Water Quality and Soil Productivity in Catchments Using Integrated Isotopic Approaches), 18-22 March 2024 Bahadurgarh, India.

Technical Officer: J. Adu-Gyamfi

Third Research Coordination Meeting of CRPD12014 on Enhancing Agricultural Resilience and Water Security Using Cosmic-Ray Neutron Technology, 4-8 March 2024, Vienna, Austria

Technical Officer: H. Said Ahmed

Second Research Coordination Meeting of CRPD15020 on Developing Climate Smart Agricultural Practices for Mitigation of Greenhouse Gases, 7-11 Oct 2024, Vienna, Austria.

Technical Officer: M. Zaman

Fourth Research Coordination Meeting of CRPD15019 on Monitoring and Predicting Radionuclide Uptake and Dynamics for Optimizing Remediation of Radioactive Contamination in Agriculture, 15-19 July 2024, Vienna, Austria

Technical Officer: G. Dercon

Past Events

FAO/IAEA Events

'Pooling Collective Intelligence' Meeting in Montpellier, a two-day international gathering hosted by CGIAR and the University of Montpellier, 2-3 October 2023, Montpellier, France

Technical Officer: G. Dercon

From 2-3 October 2023, Mr. Gerd Dercon represented the IAEA at a crucial meeting hosted by CGIAR and the University of Montpellier in France. The primary objective of this meeting was to lay the foundation for an upcoming event scheduled for March 2024. This event aims to assemble a range of international panels, committees, UN conventions, scientists, and policymakers to establish a collaborative platform for effectively bridging science and policy in the field of food security. This effort seeks to establish a lasting dynamic of cooperation known as "The Montpellier Process." The goal of the 2024 event is to pool collective intelligence and deliver an integrated, compelling message to various stakeholders, including policymakers, investors, civil society, and the scientific community. This message will resonate in critical global arenas such as COPs and G20, contributing to a tangible impact and shaping the post-2030 Agenda.

During the working session in October, participants collaborated to shape the agenda for the 2024 event and foster a shared sense of ownership for this initiative. On the first day of the meeting, following welcoming addresses by the President of the University of Montpellier and the Executive Managing Director of CGIAR, the organizer, Mr. P. Carron, delivered an introductory presentation outlining the ambition and objectives of the Montpellier Process. Discussions then explored the significance of collaborative Science Policy Interphases (SPI), highlighting achievements, challenges, and forward-looking pathways for collaboration across SPIs. The day culminated in the official launch of the Montpellier Process.

The second day of the meeting was dedicated to delineating the objectives for the 2024 event, discussing ambitions, and formulating the necessary strategies to attain these goals. Participants pinpointed priority areas and delved into the intricate aspects of event organization. These activities included defining the key stakeholders who should participate, crafting content, allocating resources, and ensuring the event's long-term sustainability. Moreover, the meeting facilitated discussions surrounding commitments and the subsequent steps.

In conclusion, it is vital for the IAEA to remain actively engaged in this process, facilitating the connection between science and policy in the domain of food security and nurturing a long-term collaboration. The participation of panels like IPCC, HLPE-FSN, and IPBES, along with various UN organizations and the Club of Rome, underscores the importance of the Montpellier Process. Through our involvement, the IAEA has the opportunity to underscore the critical role of nuclear science in finding solutions to enhance food security and safety.

The meeting in Montpellier brought together:

- International Panels, Committees, and UN Conventions, including the High-Level Panel of Experts on Food Security and Nutrition (HLPEFSN),One Health High-Level Expert Panel (OHHLEP), Intergovernmental Panel on Climate Change (IPCC), Committee on World Food Security (CFS/CSA), Convention on Biological Diversity (UNCBD), Convention to Combat Desertification (UNCCD), and The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES),
- UN Agencies (FAO, IAEA, UNESCO), and
- Related public and non-profit international organizations like the Club of Rome, European Commission, International Science Council, and OECD

Regional Training Course on Integrated Isotopic Approaches to Monitor Sources of Agro Contaminants in the Environment under TC project RAS5091 (Assessing and Mitigating Agro-Contaminants to Improve Water Quality and Soil Productivity in Catchments Using Integrated Isotopic Approaches), 24-28 July 2023 Da Lat, Vietnam

Technical Officer: J Adu-Gyamfi

The regional technical cooperation (TC) Project RAS5091 “Assessing and Mitigating Agro-Contaminants to Improve Water Quality and Soil Productivity in Catchments Using Integrated Isotopic Approaches” has the overall objective to improve agricultural catchment, water, and soil management practices in the Asia–Pacific region by enhancing the capacity of countries to assess and mitigate agricultural contaminants. Twenty-five project counterparts from 14 Asia-Pacific member states participated in the meeting hosted by the Nuclear Research Institute, Da Lat, Viet Nam. The course consists of presentations, hands-on-training, case studies and discussions on experimental design, sampling strategy and sample preparation on the use of multi-stable isotope tracers to monitor the sources and contribution of agro-contaminants to water and soil quality.

Final Research Coordination Meeting of the CRP D15018 ‘Integrated Isotopic Approaches to Monitor Sources of Agro Contaminants’, 3-6 July 2023, Vienna, Austria, hybdrid.

Technical Officer: J. Adu-Gyamf

The final research coordination meeting of the the CRP D15018 was held (hybrid) in Vienna, Austria. This CRP aims to develop to develop protocols and methodologies for using multiple stable isotope tracers to monitor soil, water and nutrient pollutants from agriculture, establish proof-of-concept for an integrated suite of analytical stable isotope tools. Fourteen contract holders presented their outputs/achievements related to the specific objectives of the project. The need to apply the scientific *toolbox* developed during the CRP to investigate the sources and fate of agro-pollutants in transboundary rivers (Mekong, Danube etc) was realised. The project trained 15 graduate Students (MSc and PhD) in various disciplines related to water quality. [Photo to be provided]

Regional Training Course on Advanced Data Analysis of Isotopic Approaches to Assessment and Tracing of Agro-Contaminants in Catchments, under TC project RAS5091 (Assessing and Mitigating Agro-Contaminants to Improve Water Quality and Soil Productivity in Catchments Using Integrated Isotopic Approaches) 23-27 October 2023, Beijing, China,

Technical Officer: J Adu-Gyamfi

Seventeen participants from eleven Asia-Pacific Member States participated in the training course on advanced data analysis of isotopic approaches to assessment and tracing of agro-Contaminants in catchments, held at the Institute of Environment and Sustainable Development in Agriculture (IEDA), Chinese Academy of Agricultural Sciences (CAAS) Beijing, China. The training course consisted of lectures and working sessions on principles of the use of isotopes and fallout radionuclides (FRNs) as soil and sediment tracers, sediment fingerprinting, mixing models (e.g. MixSIAR, FingerPro) and advanced statistical techniques for selecting optimum sediment tracers. The participants visited the IAEA ALMERA Laboratory, Analytical Testing Center, Environmental Stable Isotope Laboratory, and the Shunyi Comprehensive Experimental Fields of the IEDA-CAAS.

Participating in the World Food Forum (WFF) 16-18 October 2023 (Rome, Italy)

Technical Officer: H. Said

During the World Food Forum, held at the headquarters of the Food and Agriculture Organization of the United Nations (FAO) in Rome, Italy and with the different sub-programmes of the joint FAO/IAEA Center, the Soil and Water Management & Crop Nutrition (SWMCN) sub-programme showcased tangible examples and demonstrations of how nuclear and related techniques hold the potential to provide innovative solutions for global food security challenges.

On Monday, 16 October, the booth was open from 9:00 to 18:00, successfully engaging a diverse range of attendees, including country representatives, delegates, members of academia, and FAO staff. The booth even received visits from the Director General, Chief Scientist, and Chief Economist of the FAO.

On Wednesday, 18 October, the booth was moved to the main atrium, achieving significant engagement, including visits by the Director General and DDGs of NA and TC of the IAEA. In addition, the Joint FAO/IAEA Initiative Atoms4Food was launched by the DGs of the two UN Agencies.

Photo 1,2.Exhibition booth of the SWMCN Subprogramme and the other four subprogrammes of the Joint FAO/IAEA Center during the World Food Forum, held at the headquarters of the Food and Agriculture Organization of the United Nations (FAO) in Rome, Italy, from 16 to 18 October 2023. (Photo credit: D. Feng & D. Calma/IAEA, 2023)

Regional training course on the development of digital platforms for agricultural water management through the combination of advanced nuclear techniques and remote sensing technology under RAF5086 'Promoting Sustainable Agriculture under Changing Climatic Conditions Using Nuclear Technology (AFRA)', 11-22 September 2023 (Cairo, Egypt)

Technical Officer: H. Said

Under the regional project RAF5086 titled 'Promoting Sustainable Agriculture under Changing Climatic Conditions Using Nuclear Technology (AFRA),' twenty participants from nineteen African Member States took part in a regional training course held in Cairo, Egypt. The course focused on developing digital platforms for agricultural water management by utilizing advanced nuclear techniques and remote sensing technology.

During the training, participants attended lectures on employing the Cosmic-ray Neutron sensor (CRNS) and learned how to integrate its data with earth observation satellite imagery. This integration enables the enhancement of agricultural water management by facilitating the measurement and prediction of crucial agricultural factors like crop-specific water requirements, soil evapotranspiration, rainfall, and temperature.

Coordinated Research Projects

Project Number	Ongoing CRPs	Project Officer
D12014	Enhancing Agricultural Resilience and Water Security Using Cosmic-Ray Neutron Technology	H. Said Ahmed
D15018	Multiple Isotope Fingerprints to Identify Sources and Transport of Agro-Contaminants	J. Adu-Gyamfi
D15019	Remediation of Radioactive Contaminated Agricultural Land	G. Dercon
D15020	Developing Climate-Smart Agricultural Practices for Mitigation of Greenhouse Gases	M. Zaman
D15021	Assessing the Fate, and Environmental Impact of Plastics in Soil and Crop Ecosystems Using Isotopic Techniques	J. Adu-Gyamfi
D15022	Isotopic Techniques to Assess the Fate of Antimicrobials and Implications for Antimicrobial Resistance in Agricultural Systems	J. Adu-Gyamfi

Enhancing Agricultural Resilience and Water Security using Cosmic-Ray Neutron Sensor (D12014)

Technical Officer: H. Said Ahmed

This CRP (2019 to 2024) aims to test the efficacy of cosmic ray neutron sensors (CRNS) and gamma ray sensors (GRS) for agricultural and environmental protection purposes, especially in irrigation scheduling and managing extreme weather events. CRNS offers real-time, large-scale soil moisture data crucial for land and water management. The CRP's objectives include: (1) Advancing CRNS capabilities for Best Management Practices (BMP) in irrigated and rainfed agriculture; (2) Integrating CRNS, GRS, remote sensing, and hydrological modelling to enhance agricultural water management and resilience; and (3) Developing approaches using CRNS and GRS for long-term soil moisture monitoring in agroecosystems. Approved in March 2019, this initiative involves eleven partners across various countries.

The initial Research Coordination Meeting in August 2019 set the groundwork by reviewing existing research on CRNS and GRS utilization for soil moisture assessment, developing detailed work plans and establishing collaboration between partners. By late 2019 and early 2020, CRNS installations and soil moisture measurements began at selected study sites. However, challenges arose due to COVID-19-related travel restrictions, disrupting fieldwork and delaying sensor installations at some sites.

Despite these hurdles, the project achieved significant milestones. Initial results were disseminated through publications and presentations at international conferences. Some setbacks due to travel limitations were mitigated by continued measurements and installations at new sites in late 2020. Subsequently, the project produced three research papers in scientific journals and presented two oral presentations at a COSMOS Workshop.

The Second Research Coordination Meeting in June 2021 marked progress in drafting methodological guidelines. Lockdowns and remote work periods were utilized effectively for writing publications and preparing inputs for the CRNS guidelines for agricultural water management, scheduled for publication in 2024.

Mid-term evaluation in the previous year highlighted achievements such as developing CRNS data processing tools, testing new soil moisture monitoring techniques, and creating added-value soil moisture products for agriculture. These achievements were consolidated through additional publications in international scientific journals and the formulation of CRNS guidelines for agricultural water management.

Notably, the project successfully tested a novel CRNS device eliminating the need for Helium-3 or boron trifluoride, with results accepted for publication. Furthermore, a ground-breaking study connecting CRNS with soil erosion research was published, exploring the relationship between soil water content and soil redistribution processes using advanced nuclear techniques.

The project's final Research Coordination Meeting is scheduled for spring 2024 (4-8 March 2024).

Multiple Isotope Fingerprints to Identify Sources and Transport of Agro-Contaminants (D15018)

Technical Officer: J. Adu-Gyamfi

This five-year CRP (2018-2022) aims to develop protocols and methodologies for using multiple stable isotope tracers to monitor soil, water and nutrient pollutants from agriculture, establish proof-of-concept for an integrated suite of analytical stable isotope tools, and create guidelines to adapt the new toolkit to a variety of agricultural management situations. Nuclear techniques are used to achieve the objectives including a combined stable isotope ($\delta^{18}O$' $\delta^{2}H$, $\delta^{13}C$, $\delta^{15}N$,' $\delta^{13}C$-DIC, $\delta^{15}N$-NO_3 $\delta^{18}O$-NO_3 $\delta^{18}Op$, $\delta^{34}S$) techniques and compound specific isotope (CSSI)-based monitoring approach for evaluating in-situ degradation, transport, transformation, and fate of pesticides.

Fourteen contract holders presented their outputs/achievements related to the three specific objectives of the project namely to (1) develop, evaluate, and standardize an integrative isotope approach for identifying and apportioning sources of contaminants in agro-ecosystems, (2) apply the combined approach to different agro-ecosystems to control contaminants during the final RCM held (hybrid) from 9–12 October 2023. The CRP achieved all the three specific objectives. Major outputs from the CRP are:

(1) Two Publications in Springer (1)"Tracing the Sources and Fate of Contaminants in Agroecosystems: Applications of Multi Stable Isotopes (https://doi.org/10.1007/978-3-031-472665-7) and (2) Oxygen Isotopes of Inorganic Phosphate in Environmental Samples: Purification and Analysis'(https://link.springer.com/book/10.1007/978-3-030-97497-8) that will serve as a toolbox that provides guidelines and decision trees planned for March 2023.

(2) A special issue on Agro-contaminants sources, transformation, and transport in agroecosystems (2021) was published in Agriculture, Ecosystems & Environment Journal (Elsevier) https://www.sciencedirect.com/journal/agriculture-ecosystems-and-environment/special-issue/101RHMH9Z15.

(3) Simplified protocols for sampling, sample preparation and analysis of pesticides using the compound-specific isotope analysis CSIA ($\delta^{13}C$) was developed (https://doi.org/10.1016/j.mex.2022.101880); https://doi.org/10.1002/vzj2.20275; https://doi.org/10.1021/acs.est.9b04606) and were successfully tested in the field in India and Germany.

(4) A collaboration between IAEA and the Joint Danube survey in Europe to apply stable isotopes to monitor nitrate from tributaries to the mainstem of the transboundary Danube River was successfully achieved and published (https://www.nature.com/articles/s41598-022-06224-5.pdf). A similar collaboration with the Mekong River Commission (MRC) on isotopic water quality monitoring along the Mekong transboundary river that flows through China, Myanmar, Thailand, Laos, Cambodia, and Viet Nam is established.

(5) $\delta^{34}S(SO_4)$ and $\delta^{18}O(SO_4)$ for partitioning different sources of pollutants from household waste and from mining areas in the catchment tested at the Nambeelup Brook catchment in Western Australia.

(6) A Combined use of ($\delta^{18}O$ and $\delta^{2}H$) and FRN-based sedimentary geochronology was used to assess the contribution of sediment source apportion to pollution [UK, Tanzania, China, and Chile].

(7) A success story from Viet Nam "Nuclear Techniques and Improved Resource Management Help Reduce Pollution in Viet Nam's Nhue River (https://www.iaea.org/newscenter/news/nuclear-techniques-and-improved-resource-management-help-reduce-pollution-in-viet-nams-nhue-river) and 2 journal articles were published.

(8) A Special issue "Contaminant tracing and impacts on environment: multi-isotope approaches", a publication in Environmental Research to culminate the end of the CRP is planned for April 2024.

A total of 101 articles (60 Journal articles, 31 Conference papers, 6 books, 2 Patents) were published and 15 graduate students (MSc and PhD) in various disciplines related to water quality were trained during the project period. Funding frameworks and exploring the scope for extra-budgetary funds to continue the use of isotopes to monitor water quality was discussed and agreed. The final review of the CRP is scheduled for February 2024.

Remediation of Radioactive Contaminated Agricultural Land (D15019)

Technical Officer:G. Dercon

The innovative monitoring and prediction techniques proposed in this Coordinated Research Project (CRP) aim to enhance societal readiness and capability to optimize the remediation of agricultural areas affected by large-scale nuclear accidents. This project involves the development, testing, and validation of new field, laboratory, and machine learning tools. These tools are designed to predict and monitor the transfer of radionuclides in crops and their dynamics at the landscape level, specifically focusing on under-explored environments and main crop categories affected by such incidents.

The research methodology encompasses laboratory, greenhouse, and field-based studies using stable caesium and strontium isotopes, combined with integrated time and space-dependent modeling and machine learning. These approaches aim to predict the uptake and movement of radiocaesium and radiostrontium in crops following large-scale nuclear accidents that impact food and agriculture.

To guide remediation efforts at a landscape level, operational research is being employed, involving the selection, optimization, and prioritization of remediation techniques. Protocols are being developed for innovative spatio-temporal decision support systems for agricultural land remediation, integrating machine learning, operations research, and Geographic Information System (GIS) techniques.

The primary goal is to improve societal readiness and capability to optimize the remediation of agricultural areas affected by large-scale nuclear accidents through innovative monitoring, decision-making, and prediction techniques. Specific objectives include understanding environmental influences on radionuclide transfer in food chains, especially in under-explored agro-ecological environments like arid, tropical, and monsoonal climates. Furthermore, the project aims to customize remedial options for these environments and to develop decision support systems tailored to optimizing remediation efforts following nuclear accidents.

This CRP involves participation from eleven countries, including research contract holders, technical contract holders, and agreement holders, following the recommendations from a consultants' meeting at the IAEA in February 2019.

Progress meetings have been held, refining and aligning national research projects with the CRP's objectives and work plan. Notably, advancements in laboratory experiments improving the remediation of radioactive contamination in farmland have been made. The team aims to develop new isotope techniques and to utilize advanced mathematical approaches to better predict soil properties and optimize remediation strategies.

Significant mid-term progress was reviewed and showcased at international symposiums in 2022 and 2023. Currently, ongoing PhD studies and successful presentations contribute to the advancement of knowledge in optimizing remediation of radioactive contamination in food and agriculture.

The final Research Coordination Meeting is scheduled for July 2024.

Developing Climate Smart Agricultural practices for carbon sequestration and mitigation of greenhouse gases (D15020)

Technical Officer: M. Zaman

Climate Change due to continued increased anthropogenic emission of greenhouse gases (GHGs) is a global threat to food security. Direct and indirect GHG emissions from agriculture, forestry and other land-uses changes contribute approximately 25% of the global anthropogenic GHG emissions. Data by the Intergovernmental Panel on Climate Change (IPCC) clearly show that anthropogenic emissions of the three major GHGs including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) have increased significantly since the industrial revolution and as a result, the Earth's average surface air temperature has increased about 1.2°C. This warming of the Earth has led to extreme weather events such as frequent heat waves, droughts, floods, and uneven distribution of rainfall, rising sea levels and melting of glaciers. The GHGs with the largest global warming potential are N_2O and CH_4, which predominantly originate from agriculture. The objectives of this CRP are to develop and validate climate-smart agricultural (CSA) practices, based on isotopic and related techniques, to increase soil carbon (C) sequestration, mitigate GHG emissions and limit gaseous losses of ammonia (NH_3) and dinitrogen (N_2) from agricultural ecosystems, with the aim to enhance agricultural productivity and sustainability. Results from field trials provided significant insights on factors influencing emissions of GHGs, NH_3 volatilisation, C sequestration and crop productivity. The Technical University of Madrid developed and validated a novel field method to measure NH_3 volatilisation at field scale (one hectare). They also developed a robust method of C budgeting tool for estimating C footprint of cropping systems and shared this knowledge via on-line training with CRP participants. Field results from Brazil reported that mixed planting of legumes with pasture increased pasture and livestock productivity, improved animal feed quality, reduced emission of NH_3 and N_2O (37% reduction) and increased C sequestration (10 Mg C ha^{-1} in 0 to 30 cm). Bangladesh for the first time identified microbial process of N_2O

production using ^{15}N tracing technique and CSA for increased rice production with lower environmental footprints. Field studies from China provided important insights on the effects of applying biochar, urease, and nitrification inhibitors on NH_3 emissions from a rice paddy field and these results were published in a refereed scientific journal. In a field study, Ethiopian scientists reported that the combined use of compost and mineral fertilisers at smallholder farms increased soil fertility, nitrogen use efficiency, and maize yields and reduced GHG emissions compared to chemical fertiliser application. In another field study, researchers in Ethiopia reported that agroforestry practices and on-site charcoal production enhanced soil fertility and soil C sequestration. Researchers in Viet Nam developed CSA practices which led to reduced emissions of GHGs and NH_3 volatilisation as well as increased C sequestration.

Assessing the Fate, and Environmental Impact of Plastics in Soil and Crop Ecosystems Using Isotopic Techniques (D15021)

Technical Officer: J. Adu-Gyamfi

This five-year CRP (2023-2028) has the overall objectives to (1) develop guidance for improving the understanding of the fate and impacts of plastics and microplastics in agricultural soils based on nuclear and related techniques, and (2) establish network and coordinating inter-laboratory studies of analytical techniques to support CRP network member states in developing common strategies to effectively mitigate the plastic pollution of agricultural soils and crops. The specific objectives are to (1) develop, evaluate, and standardize integrative isotopic and standard approaches for identifying and elucidating the fate of plastics and microplastics in agricultural soils, (2) apply the isotopic approaches, in combination with existing methodologies, for assessing the fate and impact of plastics and microplastics in agricultural soils under different environmental conditions, and (3) provide knowledge and guidance for informed decisions that help minimize the possible negative impacts of plastics and microplastics on soil health and ecosystem services.

The CRP was approved in September 2022. It involves ten partners: seven research contract holders (Brazil, China, Ghana, Kuwait, Malaysia, Morocco, and Vietnam, two technical contracts (all from Germany) and one agreement holder (Norway). The first research coordination meeting (RCM) was held from 3 to 6 March 2023 in Vienna (hybrid) with the virtual participation and presentations from FAO (Italy), the Austrian Agency for Health and Food Safety (AGES) and the IAEA Marine Environment Laboratories (Monaco). A SoilPlastic Apps (https://www.minagris.eu/index.php/resources/soilplastic-app) developed by MINAGRIS (https://www.minagris.eu/) that help scientists understand how much plastic ends up in soils was presented. Four working groups (WGs) were established during the meeting namely:

- WG1: Develop (a) soil sampling protocols for field experiments (b) methods for sample preparation of microplastic from soil for isotope ration analysis, and (c) spectral library of plastics with different ages and history.
- WG2: Isolate polylactic (PLA) degrading bacteria and fungi from soils and conduct incubation of non-labelled plastics in soils.
- WG3: Monitor the translocation of radio-labelled coated plastics through the soil profile and to crops.
- WG4: Develop/harmonize methods for monitoring (including sampling methods) current plastics in agricultural soils.

Working Group leaders were identified, and all contract holders were assigned to each working group with deadlines. The workplans of individual countries were integrated into the overall workplan of the CRP. The second RCM is scheduled for Q3 2024.

Isotopic Techniques to Assess the Fate of Antimicrobials and Implications for Antimicrobial Resistance in Agricultural Systems (D15022)

Technical Officer: J. Adu-Gyamfi

This five-year CRP (2021-2026) has the overall objective to develop guidance for improving the understanding of the fate, dynamics and persistence of AM and AMR in agricultural systems based on nuclear and related techniques and support MS to develop common strategies to mitigate the spread of AM in agricultural systems. The specific objectives are (1) to develop, evaluate and standardize integrative isotopic and conventional approaches for tracing the sources and persistence of AM and AMR in agricultural systems, (2) to apply a combination of approaches of isotopic and bioanalytical/molecular biological methods to different agricultural systems for assessing the fate and dynamics of AM and implications for AMR, and (3) to provide knowledge and guidance for informed decisions that help mitigate the spread of AM and AMR in agricultural systems. Nine member states are participating in this CRP including four research contract holders from Brazil, China, South Africa, and Viet Nam, three agreement holders from China, Norway, and USA, and two technical contract holders from Germany and Australia.

The first research coordination meeting (RCM) was held virtually on 11–13 May 2022. The purpose of the meeting was to discuss workplans and activities with meeting participants and to develop an overall workplan to realize the project objectives. Eleven participants including the nine-research contract, agreement, and technical contract holders, one participant from FAO and one observer from Germany (Technical University of Munich). For effective implementation of the workplans, four working groups (WGs) were established. These are (1) WG1 on synthesis of sulfamethoxazole (SMX) labelled compound that will be used in the glasshouse and field experiments, (2) WG2 to develop sampling and analytical (SMX) protocols to be distributed to the partners, (3) WG3 to develop glasshouse and field experimental designs, and (4) WG4 to develop sampling and analytical protocols related to microbiology/microbial resistance genes. The coordinators of all the 4 WGs made their presentations to elucidate their implementation plans. There were discussions with the participant from FAO on possibilities for collaboration on FAO's Strategy and initiative in AMR. A submission "Novel isotopic Fingerprinting to Assess and Mitigate the Persistence and Transport of Antibiotics and Implications on Antimicrobial Resistance" was published in Nuclear Technology Review 2022. To date, extraction protocols for (1) SMX in soil and plant (lettuce) samples and, (2) DNA extraction and analysis from soil and water samples has been developed and sent to all participants who will also receive synthesized SMX labelled-13C compound for field trials in July 2023. The CRP is funded mainly through extrabudgetary funding of US$150 000/year by the Food and Agriculture Organization (FAO). The second RCM will be held in Vienna, Austria, 11-14 March 2024.

NAMIBIA SUCCESS STORY GOES TO COP28

Technical Officers: J Adu-Gyamfi and L Heng

Together with the Department of Nuclear Sciences and Applications (NA), the Technical Cooperation (TC) Department will present a case study on Soil and Water Management in Namibia entitled "Ensuring Healthy Crops in a Changing Climate." Soil and water resources are under increasing stress because of climate change. Due to a variety of extreme weather events – from heat waves, droughts and floods to seawater intrusion caused by rising ocean levels – freshwater resources are becoming less available. However, given the ever-increasing demand for water, efficient water use is key to ensuring sustainable water availability, particularly for agricultural activities. Extreme weather events can reduce the amount of moisture in soil, but they can also lead to salinity and soil erosion, which are serious concerns for agricultural production. According to the Food and Agriculture Organization of the United Nations (FAO), it takes up to one thousand years for just 2 to 3 centimeters of topsoil to form. Climate-smart agriculture helps ensure healthy crops and healthy agrifood systems.

The IAEA and the FAO have been working with Namibia to increase water use efficiency in the northern part of the country since 2020. Approximately 92 per cent of Namibia is considered to be very arid, arid or semi-arid. Most small farmers in Namibia depend upon rainfall for their crops, but due to climate change Namibia now experiences unpredictable rainfall and severe droughts, which are causing serious food shortages. By building national capacity to apply nuclear techniques and to use a cosmic ray neutron sensor, the IAEA and the FAO have been able to help farmers to assess the moisture levels in their fields and to determine the amount of water necessary for healthy crops. Based upon these real-time measurements, drip irrigation systems were installed. These systems save water by delivering exactly the right amount of water directly to the roots of plants. Farmers participating in the project have increased their crop yields by up to 70 per cent for crops like maize, tomatoes, and peppers while at the same time reducing their water use by 80 per cent. To address soil fertility degradation in Namibia, isotopic techniques were also used to identify cowpea varieties for their ability to add nitrogen to the soil. By rotating cowpea with other crops like sorghum, the need for expensive fertilizers in participating fields in Namibia has decreased, with a savings in fertilizer expenses of at least 30 per cent.

Fig. 1 and 2. Grey to Green: (a) Farmers's field devastated by drought, (b) integration of legumes in cereal-based cropping system and small scale drip irrigation has improved soil fertility and boost farmers' yields in Kanvango East district in Namibia.(Photo credit: Athon W., 2023)

IAEA and the Joint Danube survey to monitor agro-contaminants to the mainstem transboundary Danube River in Europe

Technical Officer: J. Adu-Gyamfi

The Danube is Europe`s second longest river, stretching from Germany to the Black Sea. Water quality in the Danube River Basin is regularly monitored every six years by the national authorities of all riparian countries to evaluate contaminant sources and to reduce the pollution loads to the Danube River and the Black Sea. Four Joint Danube Surveys (JDSs) have been previously conducted in 2001(JDS1), 2007 (JDS2), 2013 (JDS3) and 2019 (JDS4) at 51 sampling sites in 13 countries across the entire Danube River Basin. In summer 2019 the SWMCN Section and laboratory participated in cooperation with the IAEA Isotope Hydrology laboratory in the Joint Danube Surveys 4 (JDS4). The survey was organized by the International Commission for the Protection of the Danube River (ICPDR). Its main purpose is to gather specific water quality data, which are not covered in standard monitoring campaigns, across the entire length of the Danube River and its major tributaries. The ICPDR harmonizes water monitoring practices across the Danube countries, following the EU Water Framework Directive (WFD) committing member states to achieving good water quality. The water sampling is implemented by the national authorities, but water analyses are performed through cooperation with external institutions to cover a wide range of parameters. The isotopic water quality monitoring of nitrate sources and mixing in the Danube watershed was published in Nature Scientific Report 2022 (https://www.nature.com/articles/s41598-022-06224-5)

The next survey, JDS5, will take place in 2025. The SWMCN plans to participate in the sampling campaign by providing sampling material and perform analysis of the stable isotope compositions of sulfates $\delta(^{34}S)_{SO4}$, $\delta(^{18}O)_{SO4}$, phosphates $\delta(^{18}O)_{PO4}$ and carbon $\delta(^{13}C_{POM\ or\ DIC})$ in addition to nitrates $\delta(^{15}N)_{NO3}$, $\delta(^{18}O)_{NO3}$, water $\delta(^{2}H)_{H2O}$, $\delta(^{18}O)_{H2O}$, and advanced hydrochemical analysis. The SWNCN through a coordinated research project (CRP) in partnership with national and international research institutes, have developed and evaluated a set of analytical techniques, i.e., the *toolbox (published in Springer https://doi.org/10.1007/978-3-031-47265-7)* that integrates multiple isotope tracers that provide information on the origins and pathways of multiple pollutants through agroecosystems, thereby providing more accurate guidance on mitigations will be applied during JDS5

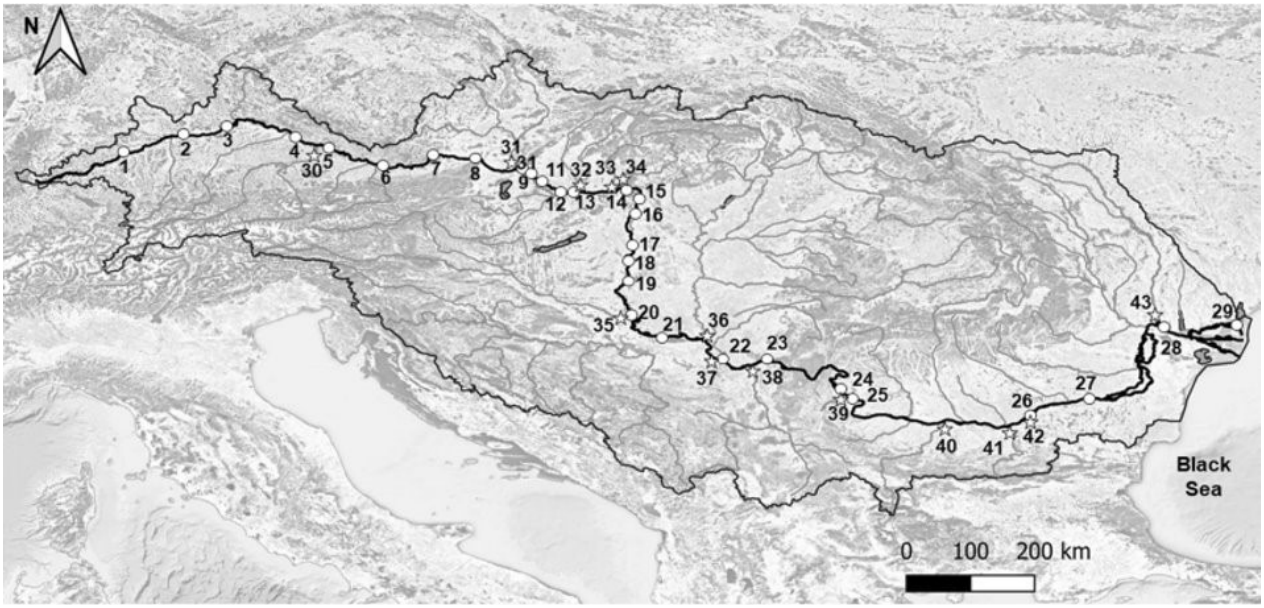

Fig.1. The 51 sampling sites along the Danube Sampling sites (Germany - Austria - Czech Republic - Slovakia - Hungary - Slovenia - Croatia - Bosnia and Herzegovina - Serbia - Montenegro - Romania - Bulgaria - Moldova – Ukraine).

Developments at the Soil and Water Management and Crop Nutrition Laboratory

Water deficit and potassium affect carbon isotope composition in cassava bulk leaf material and extracted carbohydrates

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Fig. 1. Cassava plants growing in the SWMCN greenhouse under the different treatments. (Photo credit: Van Laere, J., 2021.)

In October 2023, an article was published in Frontiers in Plant Science in which the effects of drought and potassium application on the carbon isotope signature of cassava leaves were assessed.

Cassava (Manihot esculenta Crantz) is an important root crop which, despite its drought tolerance, suffers considerable yield losses under water deficit. One strategy to increase crop yields under water deficit is improving the crop's transpiration efficiency, which could be achieved by variety selection and potassium application. We assessed carbon isotope composition in bulk leaf material and extracted carbohydrates (soluble sugar, starch, and cellulose) of selected leaves one month after inducing water deficit to estimate transpiration efficiency and storage root biomass under varying conditions in a greenhouse experiment. A local and improved variety was grown in sand, supplied with nutrient solution with two potassium levels (1.44 vs. 0.04 mM K^+), and it was subjected to water deficit five months after planting.

Potassium application and selection of the improved variety both increased transpiration efficiency of the roots with 58% and 85% respectively. Only in the improved variety were 13C ratios affected by potassium application (up to - 1.8‰ in δ13C of soluble sugar) and water deficit (up to + 0.6‰ in δ13C of starch and soluble sugar). These data revealed a shift in substrate away from transitory starch for cellulose synthesis in young leaves of the improved variety under potassium deficit. Bulk δ13C of leaves that had fully developed prior to water deficit were the best proxies for storage root biomass (r = - 0.62, r = - 0.70) and transpiration efficiency (r = - 0.68, r = - 0.58) for the local and improved variety respectively, making laborious extractions redundant. Results obtained from the youngest fully developed leaf, commonly used as a diagnostic leaf, were complicated by remobilized assimilates in the improved variety, making them less suitable for carbon isotope analysis. This study highlights the potential of carbon isotope composition to assess transpiration efficiency and yield, depending on the chosen sampling strategy as well as to unravel carbon allocation processes.

The full paper can be found here: https://doi.org/10.3389/fpls.2023.1222558

Data and R scripts to come to the results can be found here: https://zenodo.org/records/7929991

The determination of fate and environmental impact of sulfamethoxazole in agricultural soils

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Antimicrobial resistance (AMR) presents a pressing global issue. It is characterized by the ability of microorganisms – including bacteria, fungi, and viruses – to resist the effects of antibiotic compounds. Despite the various measures implemented in recent decades to combat this problem, global trends in AMR continue to show no signs of abating. The use of antibiotics in agriculture contributes significantly to the development of AMR in humans, e.g., through the storage of animal manure and by using manure solids, effluents, and sludge from sewage treatment plants as fertilizers (Binh et al., 2008; and Krzeminski et al., 2020).

While extensive research has been conducted to understand AMR in the context of human and animal health, its impact on soil and water ecosystems remains relatively unexplored.

The impact of antibiotics on soil microorganisms has received relatively little attention, and the results of existing studies are sometimes contradictory. For example, some antibiotics have been observed to inhibit the activity of soil microorganisms in a concentration-dependent manner whereas others do not. Sulfonamides such as sulfamethoxazole (SMX), a commonly found antibiotic in considerable soil concentrations, particularly raise questions about their persistence, fate, and environmental effects in soils. The limited knowledge on this topic arises from the fact that most previous research on SMX degradation primarily occurred in controlled water treatment environments rather than soil-based settings.

To explore the fate and environmental impact of the antibiotic sulfamethoxazole (SMX) in agricultural soils, the SWMCN Laboratory initiated two experiments, both of which used stable isotope technology aimed at determining the (1) rate of SMX mineralization in soil at different concentrations and application of mineral nitrogen (N) and phosphorus (P) fertilizers on SMX decomposition; and (2) role of bacteria in SMX mineralization.

In the first experiment samples of two soil types: (i) Chernozem soil from Seibersdorf and (ii) Cambisol soil from Grabenegg, both in Lower Austria were used. ^{13}C-labelled SMX (10 mg.kg^{-1}), N (500 kg N.ha^{-1}), and P (250 kg P.ha^{-1}) were applied. The 100 mL incubation jars, containing 20g of each soil with different treatments and a corresponding control treatment (soil only), were prepared with three replicates. The soil moisture was kept constant at 50%, the incubation temperature was 22°C. Emitted CO_2 and CH_4 fluxes and their C-isotopic signatures were analyzed using a Laser Cavity Ring Down Spectroscopy (CRDS, Picarro 2201-i). Preliminary findings from the first experiment suggested a significant influence of N and P fertilizers on the δ^{13}C-CO_2. The high influence of P is an important finding, as there is hardly any literature on the influence of P on SMX mineralization available. Phosphorus fertilizers play a significant role in changing the taxonomic composition and biological activity of microorganisms' community in soil, especially in the utilization of antibiotic compounds.

To determine the role of bacteria in the mineralization of SMX, the abundance of total cultured bacteria was assessed using the agar plate method. Samples of Chernozem soil incubated for 3 months with SMX and the N and P fertilizers were cultivated on Gause 1 mineral agar (7 days, 28°C). The total amount of bacteria in the control sample (CFU.g^{-1}) was 7.4 x 10^6, in the SMX treatment was 3.9 x 10^6, in soil incubated with SMX and nitrogen fertilizer 2.8 x 10^8, and in soil incubated with SMX and phosphorus fertilizer: 1.3 x 10^8. For the 65 strains isolated for further AMR test, the dominant group of cultivated bacteria was Actinomycetota (Fig.1).

The second experiment was an evaluation of the degradation rate of SMX at different concentrations. The same two types of soil were prepared for analysis. The doses of ^{13}C-labelled SMX were 100 mg.kg^{-1}, 10 mg.kg^{-1}, 1 mg.kg^{-1}, 0.1 mg.kg^{-1}, and 0.01 mg.kg^{-1}. The incubation jars with soils and applications were prepared with two replicates, leading to 24 incubation jars in total. The measurements of emitted CO_2 and CH_4 fluxes and their C-isotopic signatures were also carried out using the SWMCNL based Laser Cavity Ring Down Spectroscopy (CRDS) analyser (Picarro 2201-i). The initial data show that even the smallest concentration of SMX (0.01 mg.kg^{-1}) has an impact on the δ^{13}C-CO_2.

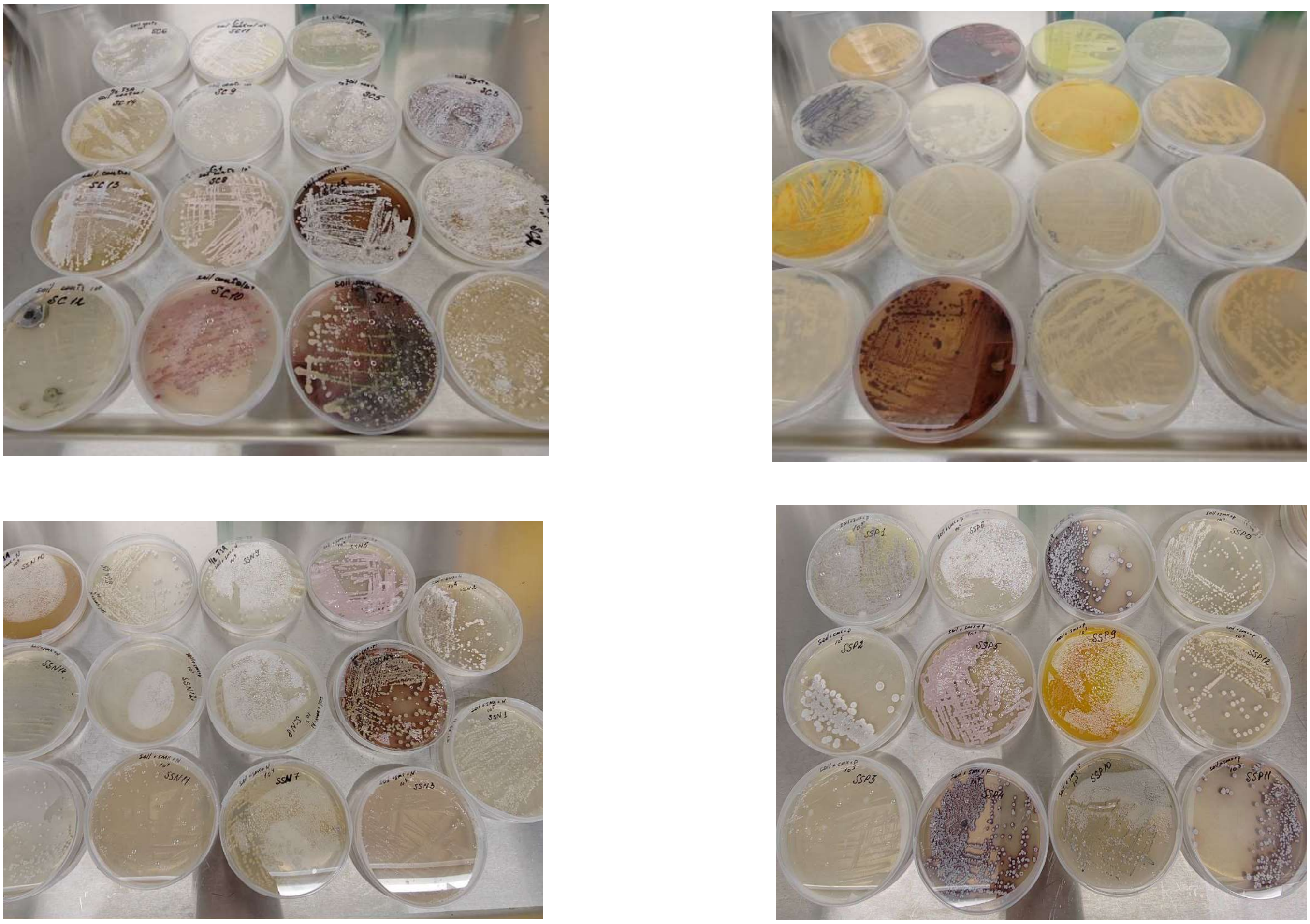

Fig. 1. The collection of bacterial strains isolated from a control sample without treatments (upper left); from soil incubated with SMX (upper right); from soil incubated with SMX and nitrogen fertilizer (lower left); from soil incubated with SMX and phosphorus fertilizer (lower right).

These ongoing experiments aim to provide insights into the fate and environmental impact of sulfamethoxazole (SMX) in agricultural soils. Understanding the behavior of antibiotics in soil and their effects on microbial communities is crucial for addressing the growing concern of antibiotic resistance. By shedding light on the mechanisms of antibiotic degradation in soil, this research contributes to the development of strategies for mitigating the global threat of antimicrobial resistance, ultimately safeguarding human health and environmental sustainability.

This research is being carried out under CRP D15022 on *Isotopic Techniques to Assess the Fate of Antimicrobials and Implications for Antimicrobial Resistance in Agricultural Systems*.

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Applying isotopic techniques to assess the impact of plastic debris in tropical agroforestry systems

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Besides the negative impact of industrial/domestic plastic debris in marine habitats, plastic materials also show a great concern in agroforest ecosystems (FAO, 2021). Soil erosion processes and the consequent loss of water quality from unsustainable agricultural activities significantly increase the microplastic contamination in soil, freshwater catchments and associated coastal-marine ecosystems. Common agricultural practices such as discarding plastic mulch, water pipes and plastic greenhouse covers have raised concerns due to their impact on the environment. In addition, microplastics are used for coating seeds and fertilizer pills (in controlled-release fertilizers), as well as for plant protection. Currently, agricultural lands are becoming the most plastic-contaminated places outside of landfills and urban spaces. The lack of sustainable land conservation practices allows microplastic-contaminated soils to be removed from watersheds, carried to rivers, and deposited in water reservoirs, lakes, lagoons, and coastal and oceanic habitats.

Currently, most of the studies on the negative impact of microplastics on agricultural lands are conducted in temperate countries. Given that climate and the physical, chemical, and mineralogical properties of the soil impact the turnover and dynamics of plastics in the soil, carrying out studies in tropical soils is also crucial to understand the influence of these parameters on the dynamics, fate and impact of debris plastics in food production for the global population. As soils serve as a source of plastics for aquatic ecosystems, it is important to investigate potential markers that can distinguish sources and track the fate of these polymers. Stable isotope analysis (Figure 1) and Compound-specific stable isotope (CSSI) analysis combined with Mid-infrared spectroscopy (MIRS) and Micro-Fourier transform infrared spectroscopy (µFTIR) techniques can provide valuable information about the chemical composition of polymers, the degree of degradation, and the characterization of the ultimate products of plastic decomposition. These techniques can be essential for gaining an objective understanding of the properties of plastic and its impact on the environment.

The Soil and Water Management and Crop Nutrition Laboratory (SWMCNL) in Seibersdorf, Austria conducted an experiment which aims to assess biodegradation of different types of microplastics in typical soils of tropical climates (Ferralsol) and temperate climates (Chernozems), evaluating turnover and degradation products, as well as investigating how soil properties influence these parameters. Additionally, isotopic analysis of specific compounds such as phospholipid-derived fatty acids (PLFA) will allow differentiating microbial groups accountable for the biodegradation of these plastics and the examination of correlations between soil properties and microbial activity. This information will be important for understanding the degradation mechanisms of microplastics in various contexts and establishing efficient soil management and remediation strategies. Furthermore, the results of this project will provide relevant data for establishing public policies and effective plastic waste management.

These experiments were conducted under CRP D15021 on Assessing the Fate and Environmental Impact of Plastics in Soil and Crop Ecosystems Using Isotopic Techniques.

Photo 1. Measuring $\delta^{13}CO_2$ from soil microplastic biodegradation experiments.

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Restoring Farmland from Radioactive Impact: AI-Guided Potassium Profiling

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Launched in 2019, the IAEA Coordinated Research Project, "Monitoring and Predicting Radionuclide Uptake and Dynamics for Optimizing Remediation of Radioactive Contamination in Agriculture" (CRPD15019), has spurred a wide array of research initiatives. Specifically, the function of exchangeable potassium (K_{ex}) has been extensively examined for its competition with radiocaesium in soil-plant transfer, aiding in the reduction of this key fallout radionuclide's absorption by crops. Therefore, the ability to characterize accurately, rapidly, repeatedly and at sample or landscape scale exchangeable potassium (K_{ex}) in soil is critical.

Conventional techniques for evaluating K_{ex} in soil, despite their thoroughness, are both expensive and time-consuming, making them impractical for widespread nuclear remediation projects. However, Albinet et al. (2022), contributors to this CRP, have demonstrated that deep learning algorithms can efficiently harness existing extensive soil spectral libraries. This innovative method not only accelerates the characterization of K_{ex} but also makes it more cost-effective and scalable.

In early 2023, KU Leuven and Curtin universities launched a joint PhD project to explore the integration of AI, soil spectroscopy, and remote sensing in Kex characterization at both local and global scales. This research, which seeks to bridge soil science and deep learning, focuses on three key questions:

- The feasibility of using Mid-Infrared spectroscopy (MIRS) and deep learning with large soil spectral libraries to accurately predict K_{ex} for local-scale remediation.
- Assessing Near-Infrared spectroscopy's (NIRS) potential for high-throughput K_{ex} prediction, considering its lower cost and portability compared to MIRS.
- Exploring global-scale K_{ex} prediction using remote sensing data and geographical soil-forming factors in advanced modeling approaches.

Within this framework, we have been laying the groundwork for several months, focusing on pivotal and interdisciplinary questions like transfer learning and spectrometers cross-instrument calibration. Concurrently, a controlled experiment is being conducted on soil samples with varied mineral compositions. These samples have been systematically enriched with increasing levels of potassium at KU Leuven. Infrared spectroscopy scanning took place at Soil and Water Management and Crop Nutrition Section in Seibersdorf last December 2023 to observe the response of infrared spectroscopy to these changes.

Soil moisture monitoring, a tool for sustainable irrigation development

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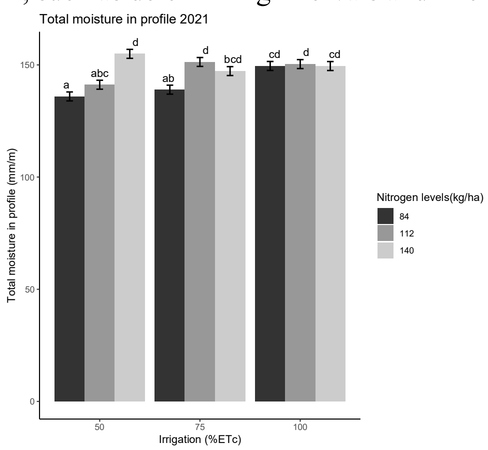
Reduced rainfall has been identified as a highly probable consequence of climate change in certain regions of Zambia (Hamududu & Ngoma, 2020). This is particularly concerning for small-holder farmers who rely heavily on rainfall and are the primary producers of the country's staple foods, such as maize. The resulting decrease in production significantly impacts national food security. Recognizing the potential of irrigated agriculture to improve food security and sustain production levels, the Zambian Agricultural Research Institute (ZARI) has been actively engaged in research since 2021. Their focus is on enhancing irrigation and soil fertility management under conditions of reduced water availability.

To address these challenges, a research trial was initiated at the ZARI research station in 2021. This trial aims to identify the optimal and sustainable water and nitrogen application for achieving maximum maize production in irrigated crop systems (Vol. 44 No. 2 Jan 2022). Access tubes were installed in each subplot to monitor soil moisture to a depth of 1 m before and after irrigation on a weekly basis.

Over recent years, various aspects of this study have been reported in this newsletter, including the role of soil moisture monitoring in designing effective irrigation management, such as determining intervals and intensities. This newsletter issue delves further into the interplay between nitrogen fertilizer and water application concerning stored water in the root zone (up to 1 m).

In the 2021 season, the results indicate that significantly more water was retained on average throughout the growing season in treatments with higher nitrogen levels, especially under reduced irrigation water applications (50% and 75% ETc) (Figure 1, season 2021). A similar trend was observed in the 2022 season, albeit only for 50% ETc (Figure 1, season 2022). The increased stover yield may have contributed to reduced evaporation, minimizing losses. As nitrogen application levels rise, the ability to store soil water in the profile appears to increase. However, further analyses of soil moisture depth and root systems are needed to determine whether excess water in deficit-irrigated treatments is obtained from lower depths or if (and how much) water is lost in optimally irrigated treatments.

This project has been supported through the ICTP/IAEA Sandwich Training Educational Programme (STEP) ICTP - ICTP/IAEA Sandwich Training Educational Programme.



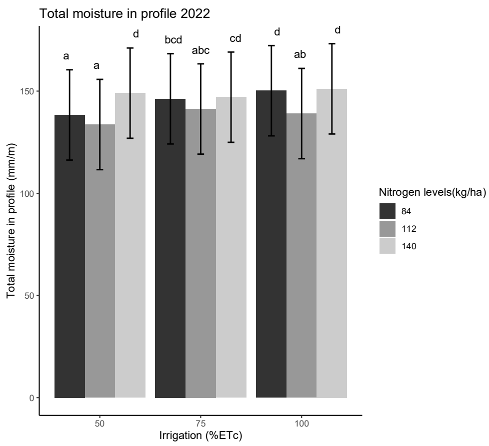


Fig. 1. Average soil moisture storage in 2021 and 2022 cropping seasons.

Soil particle size distribution using the integral suspension pressure method (ISP) and gamma-ray spectrometry techniques for soil texture mapping

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Soil texture is a fundamental aspect of soil and water management, particularly in the context of climate change. It influences water availability, nutrient dynamics, erosion control, carbon sequestration, and overall soil health. Monitoring soil texture is critical for sustainable agriculture and effective adaptation to the challenges posed by climate change.
However, soil texture monitoring is labour-intensive, and the SWMCNL therefore started to look at upcoming methods for estimating and mapping soil texture.
The first method is the use of the integral suspension pressure method (ISP) to derive the particle size distribution after chemical and physical dispersion. It is recording continuously the change of suspension pressure as well as the temperature at an interval of 10 seconds. For this purpose, a PARIO® system was used, allowing automated operation, which calculates the particle size distribution by Stokes' law, with the range of particle sizes spanning from 63 µm to 1 µm, finally making it easy to obtain a complete particle size distribution curve. Soil samples from Hydrological Open-Air Laboratory (HOAL) in Petzenkirchen (Lower Austria) are being analysed for soil particle' distribution using this system. Pre-treatment of soil samples is done by removing organic matter, soluble salts and determining the dry weight of the samples. This is followed by chemical and physical dispersion and then soil textural classification. Measurement of the samples is still ongoing (Fig. 1).
These data will then be used in 2024 for testing a second method for soil texture determination, i.e. Gamma-Ray Sensor (GRS) technology, which measures the spatial activity concentration (Bq.kg^{-1}) of ^{40}K (potassium), ^{238}U (uranium), and ^{232}Th (thorium). The radionuclide activity measured by GRS will be correlated with soil texture data obtained by the first method.

Photo 1 (above). Particle size distribution analysis with the integral suspension pressure method (ISP).

Photo 2 (next page): Spectral analysis of cassava samples using MIRS for C-13 prediction.

Predicting Carbon-13 ($\delta^{13}C$) signatures in cassava leaves using Mid-Infrared Spectroscopy (MIRS)

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In close partnership with the Royal Holloway University of London and the Alliance Bioversity International – CIAT, the SWMCN Laboratory is actively pursuing research and development using stable carbon isotope techniques to enhance the resistance of cassava—a crucial staple crop in many regions—to the effects of climate change.

Understanding how plants react to limited water and insufficient nutrients is essential for devising effective agricultural strategies in response to climate change. Previous work conducted by the SWMCNL on cassava has revealed that analysing the carbon-13 ($\delta^{13}C$) signatures in different parts of the plant provides valuable insights into water usage efficiency and transpiration efficiency (Van Laere et al., 2023). A change (increase) in $\delta^{13}C$ signature has been identified as an indicator of water stress in cassava plants (Van Laere *et al.*, 2023), also demonstrating distinct variations based on the cassava variety. This information can assist agricultural scientists in efficiently managing water in cassava farming systems, thereby enhancing food security among Member States.

While Isotope Ratio Mass Spectrometry (IRMS) is a highly accurate technology for measuring $\delta^{13}C$ signatures, its cost and limited accessibility pose challenges for many. Consequently, the SWMCN Laboratory team aims to explore more accessible and cost-effective alternatives. Based on their findings, they plan to develop methodologies that can be widely adopted in various countries.

The SWMCNL intends to use Mid-Infrared Spectroscopy (MIRS) to estimate Carbon-13 ($\delta^{13}C$) signatures (Figure 1). This estimation will rely on the correlation between MIR spectral features and reference ^{13}C data of cassava plants obtained through Isotope Ratio Mass Spectrometry (IRMS). To conduct this study, a sample set comprising 265 leaf samples from different cassava varieties, along with associated data collected by the Royal Holloway University of London, will be utilized. These cassava varieties were cultivated at the Alliance research station in Cali, Colombia.

The prediction of $\delta^{13}C$ signatures in primarily leaf material via MIR spectra represents an indirect estimation, utilizing IRMS measurements as the dataset for model calibration and validation. Although Near-Infrared Spectroscopy (NIRS) has shown acceptable accuracy in modeling ^{13}C content in plant material (Kleinebecker et al., 2009), research on using MIRS for this purpose is limited. MIRS demands smaller sample sizes and has demonstrated higher accuracy compared to NIRS for estimating similar indirect parameters in soil but has not been extensively explored for plant material (Soriano-Disla et al., 2014). The accuracy of the predictions will hinge on the quality and representativeness of the calibration dataset, the precision of the MIR instrument, and the strength of the correlation between MIR spectra and $\delta^{13}C$ signatures.

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^{15}N Tracing Technique to Measure N_2O and N_2 and Identify Their Sources

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The global population is projected to reach 9 billion by mid-century, presenting food security challenges, particularly in developing nations. Agriculture, a significant economic contributor in these regions, raises concerns about feeding a larger population due to limited land, water, and financial resources (Brauman *et al.,* 2013). Meeting the rising food demand requires a 70% increase in agricultural production using existing resources, leading to higher greenhouse gas (GHG) emissions, notably nitrous oxide (N_2O), which significantly affects the environment and contributes to global warming. N_2O, with a half-life of 120 years and a global warming potential 300 times greater than CO_2, is a major concern due to its long-lasting impact (IPCC, 2021). Its atmospheric concentration has risen by over 20% since the pre-industrial era, highlighting the need to estimate global N_2O emissions and understand influential factors for mitigation efforts. Microbial processes release N_2O into the atmosphere, influenced by various biological and environmental factors such as soil conditions and substrate availability (Xu *et al.,* 2017). However, quantifying N_2O and N_2 emissions remains challenging, with uncertainties noted in agricultural soil emissions, necessitating further study.

The IPCC (2021) emphasizes uncertainties in N_2O release, especially in agricultural soil, due to complex simultaneous processes. Although nitrification and denitrification processes concurrently produce N_2O in soil, further detailed studies are crucial for detailed insights into N_2O production. Measuring N_2, the denitrification end-product, poses challenges with conventional methods. Quantifying both N_2O and N_2 gases is difficult, requiring specialized techniques. Isotopic techniques, like enriching NO_3^- and tracking labeled denitrification products with ^{15}N isotope techniques, provide insights into N_2O sources and support emission reduction strategies.

To tackle these challenges, a new PhD study under CRP D15020 titled "Developing Climate-Smart Agricultural Practices for Mitigation of Greenhouse Gases" (funded by URENCO, and in collaboration with the University of Vienna) aims to better understand nitrogen losses through N_2O and N_2 in agricultural systems, and the impact of biochar application on these losses. Additionally, this study aims to enhance isotope techniques for identifying the sources of N_2O and N_2 in agricultural systems (Figure 1).

The proposed PhD study offers a comprehensive approach to mitigate N_2O emissions, increase carbon sequestration, and improve crop productivity by providing cost-effective and robust climate-smart agricultural technology. It will enable more effective advising of Member States on the best agricultural practices to mitigate climate change from agriculture while ensuring food security.

Photo 1: Starting the first incubation experiment for developing the research methodology to better understand nitrogen losses through N_2O in Austrian soil, coming from Chernozems at Seibersdorf (Austria).

Assessing Soil Carbon Sequestration Using Isotopic and Related Techniques

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In complement with the previously mentioned PhD study conducted by Barira Hafiza, a second PhD study, under the same CRP D15020 titled "Developing Climate-Smart Agricultural Practices for Mitigation of Greenhouse Gases" (funded by URENCO, and in collaboration with the University of Vienna) has started to address how carbon sequestration in agricultural land can be improved and thus contribute to the development of climate-smart agricultural practices for better food security.

The project has started with an incubation experiment investigating the effects of N fertilizer, related nitrogen process inhibitors and biochar application on greenhouse gas emissions. The experiment will provide valuable insights into the specific mechanisms influencing the release of carbon dioxide (besidesnitrous oxide and methane) in soil under controlled conditions (Temperature and soil moisture, Figures 1 and 2). By utilizing isotopic labeling techniques, the aim is to trace the origin and fate of these gases, contributing to a more comprehensive understanding of the sources and sinks of greenhouse gases in agricultural systems.

In 2024, implementation of a field experiment is planned. In this study biochar will be made with plant biomass containing ^{13}C, which will then be applied to the soil, allowing for tracing of the ^{13}C through the soil. This approach will provide information for quantifying carbon sequestration and emissions more accurately under on-farm conditions.

Photo 3. Gas sampling with syringe and transferring to exetainer.

Photo 4. Putting parafilm on incubation jars to conserve moisture.

Towards more effective soil remediation decision-making in response to large-scale nuclear emergencies

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Although nuclear energy can be categorised as a safe and low-carbon energy source, two major accidents (Chornobyl, 1986 and Fukushima, 2011) demonstrated the large-scale impact it may have on people and the environment. While immediate response plans to nuclear accidents are well established, the complex and resource-intensive recovery phase needs more adequate (inter)national guidance and tools (OECD and NEA, 2022). Recovery is especially important for agricultural areas, where food production needs to return to normalcy. Within the PhD project, in collaborating with partners under CRP D1.50.19 (*Remediation of Radioactive Contaminated Agricultural Land*), we contributed to the development of tools within a spatial decision support system (sDSS) to improve the post-accident decision-making process about where, how, and when to remediate agricultural land. A proof of concept for an sDSS was created called OREFA (Optimizing Remediation Efforts Affecting Food and Agriculture). The sDSS was tested on 2 sites, a hypothetical contamination in the Maarkebeek, Belgium and the Niida catchment in Japan.

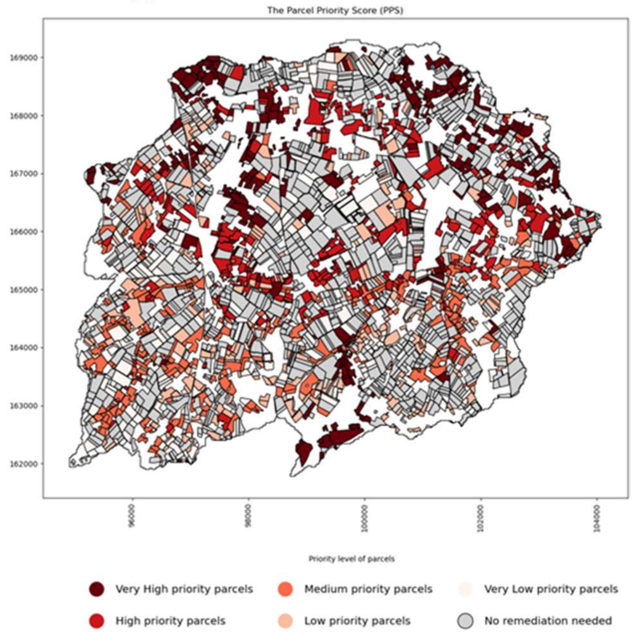

Fig. 1. The parcel priority score (PPS) for agricultural parcels in need for remediation, displayed in 20% quantiles. The lower the PPS, the more urgent the remediation is.

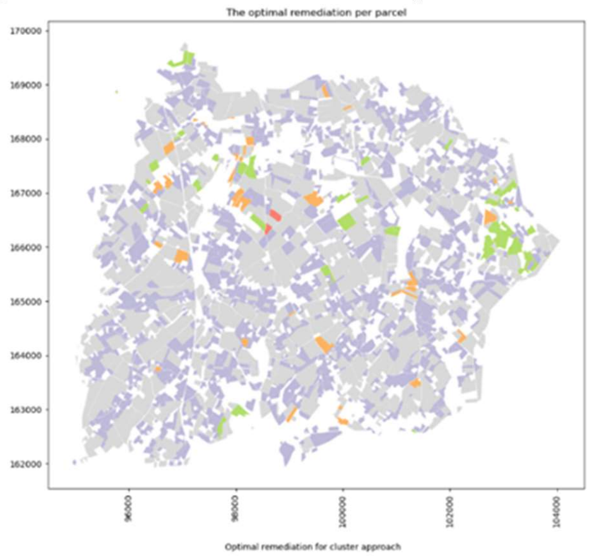

Fig. 2. Proposed remediation plan based on the optimal remedial action for each parcel.

At the basis of the sDSS is a multi-criteria decision-aiding methodology (MCDA). This was used to support soil remediation on a regional scale through optimal site selection (Figure 1). The model considers 7 criteria: Cs-137 activity in food products, Importance of food in the local diet, Distance to the urban infrastructure, Distance to nature reserves, Distance to surface water, Population density, and Erodibility of the parcel.

The SDSS will provide a priority score for each agricultural parcel. With this priority score, decision-makers are informed and can decide on an action plan for tackling the remediation needs of the contaminated area. In addition, on a local scale, the sDSS supports selecting the optimal remedial technology for a specific site (Figure 2). Using the following qualitative and quantitative criteria (Feasibility, Incremental dose, Local Impact, Cost of application, Environmental impact, Reduction efficiency), remedial techniques can be compared on a per-parcel basis to find the optimal technique for each parcel. The MCDA methodology can be seen as a decision framework geared towards more inclusive and collaborative decision-making compared to others like cost-benefit (Munda, 2019). The MCDA framework allows for the inclusion of difficult-to-monetize criteria and collaboration with stakeholders in the decision-making process. However, a literature review identified four difficulties in the implementation of MCDA in the context of soil remediation: (i) A lack of inclusion of social criteria; (ii) A lack of early stakeholder engagement; (iii) A mismatch between weighting and aggregation methodologies; and (iv) A need for uncertainty analysis. To improve the implementation of MCDM, we introduced linguistic scorings as fuzzy numbers for weights and qualitative criteria. By introducing fuzzy numbers in the MCDA, the impact of increasing uncertainty on these fuzzy scorings was studied (Figure 3). It became clear that increasing uncertainty creates less straightforward priorities in the selection process between remedial techniques. We refer you to Abrams et al. (2022a) for more insights.

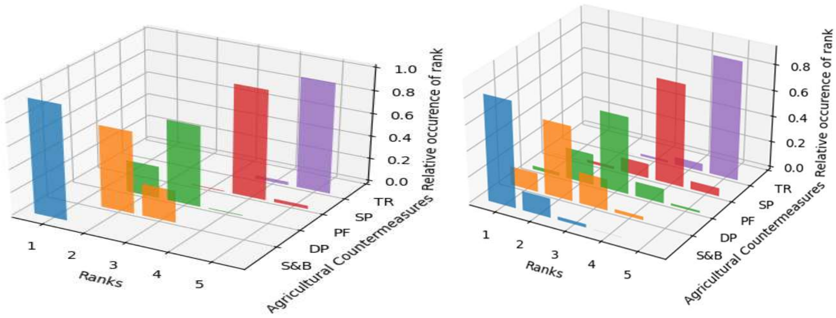

Fig. 3. The rank acceptability index, based on the relative occurrence of the alternatives in that rank, with low disagreement between decision makers (left) and significant disagreement (right) for skim & burial ploughing (S&B), deep ploughing (DP), the addition of potassium fertiliser (PF), shallow ploughing (SP) (Abrams et al., 2022a).

When using the sDSS on a regional and local scale, the proposed remedial plan results in a very complex spatial pattern for remediation. The clustering of individual entities into larger, homogeneous, actionable units can improve feasibility and reduce the cost of remediation (due to economies of scale), especially when interventions are costly and technically challenging to perform. A spatio-temporal clustering approach was created to determine homogenous clusters of multiple parcels and interventions. The clustering approach for 12 parcels and 3 techniques is visualised in Figure 4.

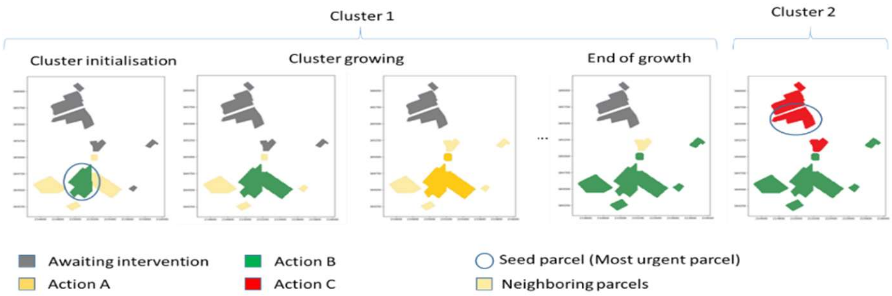

Fig. 4. The cluster growing procedure applied on 12 parcels, considering three possible actions, resulting in two clusters, each with one action (Abrams et al., 2022b).

As seen in Fukushima and Chornobyl, remediation takes place over decades. Therefore, remediation efforts need to be optimised over time. The sDSS was expanded to propose remediation trajectories, a sequence of multiple remedial actions in time. A linear programming (LP) model that reconciles the economic and productive aspects of remediation for agricultural areas was proposed. With this LP model, decision-makers can optimise remediation over time and determine the impact of different scenarios (Table 1).

Table 1: The impact of different compensation cost scenarios for farmers.

	Scenario 1	Scenario 2	Scenario 3
Total cost (from which compensation)	1 326 281 (0)	1 399 093 (72 811)	1 398 465 (91 668)
Production years lost	212	251	258
years to return to full production	4	5	5

During the government-led decontamination program in the Niida catchment in Japan, the decontamination actions lowered the Cs-137 concentration in the topsoil considerably. However, due to the nature of the decontamination practices (e.g., mainly the removal of the topsoil), these efforts resulted in an increased share of bare or barely vegetated land and hence increased soil erosion and sediment delivery into the rivers (Bin et al., 2022),extending the criteria considered in the sDSS to include off-site impacts. These off-site criteria occur when an action impacts a location away from the intervention site. These off-site impacts are typically found in flow phenomena like erosion. An iterative framework called the CAMF approach (Cellular Automata-Based Heuristic for Minimizing Flow) was used to model and reduce the off-site impacts of soil remediation in the Niida watershed. By directly afforesting the decontaminated sites, erosion at these sites can be minimised. The OREFA model was used to find the locations with the highest off-site impact, and targeting these sites would result in the highest reduction in sediments reaching the river. The decision-makers are informed by the model with priority maps, showing the most important areas for action (Figure 5).

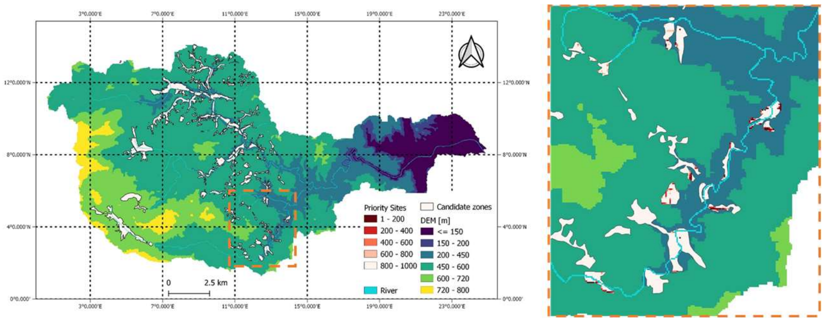

Fig. 5. The Niida catchment, with the decontaminated cells of 2014 (white) as the candidate cells for afforestation (left); zoom of a river branch, with a subset of the 1000 priority cells for afforestation (right).

Spatially targeted afforestation of the 1000 best cells (40 ha) reduces the sediment quantity, resulting from the decontamination work, by 15.4%, compared to 0.8% when selected randomly (Figure 6), which clearly shows the importance of using these optimization models.

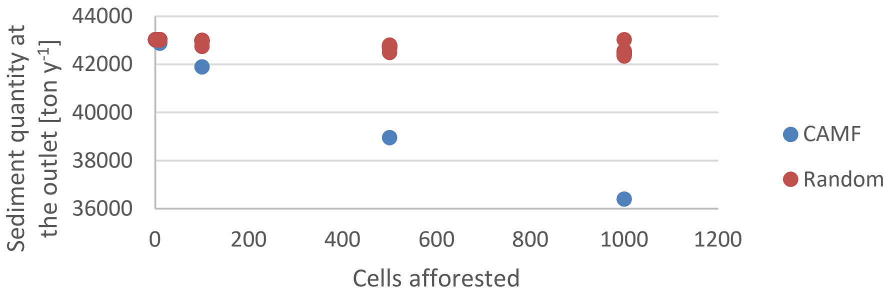

Fig. 6. Sediment reduction [ton y-1] at the outlet after afforestation on 1, 10, 100, 500 and 1000 cells using a spatially targeted approach compared to a random selection approach.

The OREFA sDSS shows the incredible complexity decision-makers face during the recovery phase. An sDSS, like OREFA, could decision-makers navigate this complex decision process.

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Advanced soil moisture forecasting using Cosmic Ray Neutron Sensor and Artificial Intelligence (AI)

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By the year 2050, the global population is projected to hit 9 billion, intensifying the demand for food production and presenting substantial challenges to water resources. To bolster sustainable agricultural practices, there exists a pressing need to develop climate-smart irrigation techniques, notably precision irrigation. This method involves applying the precise amount of water to the soil at the opportune moment, thereby enhancing water-use efficiency.

In this context, the monitoring and prediction of soil moisture play a pivotal role in the adoption of precision irrigation and the effective management of agricultural water. Cosmic Ray Neutron Sensors (CRNS), a nuclear technology tailored for estimating soil moisture content across expansive areas (up to 40 hectares, contingent on sensor sensitivity and location), have exhibited their potential in supporting agricultural water management, hydrology research, land surface modeling, and could serve this purpose admirably.

The Soil and Water Management & Crop Nutrition Laboratory has embarked on exploring and refining advanced soil moisture forecasting using a decade-long dataset (2013 to 2023) obtained from CRNS at the Hydrological Open-Air Laboratory (HOAL) in Petzenkirchen, employing Artificial Intelligence (AI) methodologies.
The amalgamation of CRNS data with AI holds the promise of revolutionizing agricultural water management in various aspects, particularly in forecasting soil moisture for precision irrigation applications,ensuring the right water quantity is administered at the right time.

Preliminary findings display a promising alignment between predicted and measured soil moisture over a two-day period (See Figure 1). The model achieved a coefficient of determination (R2) of 67%, a Root Mean Square Error (RMSE) of 4%, and a Mean Absolute Error (MAE) of 2.7%.

These initial outcomes are encouraging, highlighting the potential for the fusion of Cosmic Ray Neutron Sensors with Artificial Intelligence to usher in a new era in agriculture and facilitate the adoption of precision irrigation. Nonetheless, further modeling, testing, and validation remain ongoing imperatives at this stage.

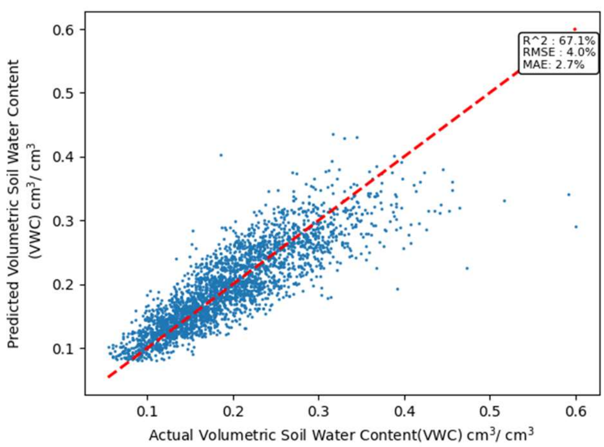

Fig. 1. Comparison of predicted soil moisture and actual soil moisture for 48 hours based on a 10 year CRNS dataset for the Hydrological Open-Air Laboratory (HOAL) in Petzenkirchen.

Analytical Services

Christian Resch, Reinhard Pucher, Arsenio Toloza

In 2023, 9170 samples were analysed for stable isotopes and 150 samples were measured for fallout radionuclides in the SWMCN Laboratory. Most analyses were carried out supporting Research and Development activities focused on the design of affordable isotope and nuclear techniques to improve soil and water management in climate-smart agriculture.

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