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SOIL BIOLOGICAL PROPERTIES IN THE AGROECOSYSTEMS WITH DIVERSE AND MULTIFUNCTIONAL CROP CULTIVATION

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The multifunctional cropping system is important for improving soil properties, both quantitatively and qualitatively. The roots of different plant species take up moisture and nutrients at different rhythms and intensities. Interactions between plants and interspecific competition between them promote plant rooting. Competition is also largely avoided during the course of vegetation. Growing multifuctional crops is not only important for more efficient use of nutrients, but also contributes to mitigating climate change by meeting EU environmental requirements. Research shows that the cultivation of multipurpose crops has reduced CO_2 emissions from the soil. The decrease in CO_2 emissions from the soil in multifunctional crops is due to carbon sequestration. The field experiment was carried out in 2019, 2020 and 2021 at the VMU Academy of Agriculture Experimental Station. The aim of the study was to compare soil biological properties (plant root dry biomass, CO_2 emission from the soil and soil aggregate-size distribution) in sole (spring barley, spring wheat, peas, caraway), binary (spring barley and caraway, spring wheat and caraway, peas and caraway) and trinary (spring barley, caraway and white clover, spring wheat, caraway and white clover, and peas, caraway and white clover) crops. The binary and trinary crops produced a significantly higher plant root dry biomass in the main crops (1.5 to 2.2 times), second (2.8 to 3.4 times), and third (up to 2.9 times) years of caraway cultivation compared to the sole crop. The plant root dry biomass was found to be significantly higher in the trinary crop than in the binary crop. In the main crops, the second and third years of caraway cultivation, the CO_2 emission from the soil increased most in the trinary crop compared to the sole and binary crop. The significantly lowest soil CO_2 emission was found in the black fallow left after the caraway harvest.

Keywords: *multifunctional crop; soil CO_2 emission; root biomass; biodiversity, soil structure.*

INTRODUCTION

Over the last fifty years, advancements in agricultural technology have successfully met the escalating demands for food, feed, and fiber of the global human population (Hertel, 2011; Hemathilake, Gunathilake, 2022). Nevertheless, the consequential ecological imbalances and the decline in soil health are propelling the quest for innovative technological remedies (Massawe et al., 2016). Effectively addressing and mitigating the impacts of climate change in agriculture necessitate the development of uncomplicated, cost-effective, and broadly scalable approaches (Lizarazo et al., 2020; Naulleau et al., 2021). These approaches must ensure the sustainable, long-term utilization of resources and promote eco-efficiency (Keating et al., 2010; Coluccia et al., 2020; Belucio et al., 2021; Wang et al., 2022).

Biodiversity plays a pivotal role in the resilience and stability of natural ecosystems. The incorporation of multifunctional crops is a strategy to adapt this diversity to agroecosystems (Frick et al., 2017). Plant roots play a crucial role in various ecosystem processes, influencing the carbon cycle, metabolism, soil formation, structural stability, and the diversity and ratio of soil organisms (Hirte et al., 2017). In the context of multi-cropping, the distribution of resource uptake and competition among plant roots is more evenly spread throughout the growing season, with peak nutrient uptake occurring at different stages.

The cultivation of a multifunctional cropping system holds substantial significance in enhancing both the quantity and quality of soil properties. Different plant species display diverse rhythms and intensities in their uptake of moisture and nutrients through their roots. The dynamic interactions and interspecific competition among plants stimulate robust root development. Skilful navigation of competition occurs throughout the vegetation cycle. Beyond efficient nutrient utilization, the cultivation of multifunctional crops aligns with EU environmental standards, making a valuable contribution to climate change mitigation.

Caraway (*Carum carvi* L.), a valuable biennial herb of the celery family (*Apiaceae*), is native to Europe, Asia, and North Africa (Lizarazo et al., 2021). This commercially important plant serves not only as a culinary spice but also finds applications in the pharmaceutical and cosmetic industries (Raal et al., 2012). Given its biennial nature, it can be strategically cultivated alongside annuals such as peas and beans, as well as various herbs like mustard, dill, or coriander Lizarazo et al., 2021). Notably, caraway yields seeds in both the second and third years of cultivation.

The agriculture sector emitted around 429 Mt of CO_2 equivalent in 2019, around 11% of Europe's total greenhouse gas (GHG) emissions. Agricultural CO_2 (which accounts for almost 3% of the total GHG emissions from the agricultural sector) is due to soil management and land use change (Andrés et al., 2022). In 2021, the airborne CO_2 concentration was 414.72 ppm (Lindsey, 2022). Lithuania is committed to reducing GHG emissions from the agricultural sector as part of the UN Framework Convention on Climate Change and the EU's environmental requirements. Chai et al. (2014), Hu et al. (2017) point out that CO_2 emissions from soils have been decreasing in multi cropping. Beedy et al. (2010) point out that decreasing CO_2 emissions from soils in multifunctional crops are due to carbon sequestration. Skinulienė et al. (2019) report that the highest intensity of CO_2 emission from soil was found after a pre-crop leaving a high amount of plant residues in the soil. Romaneckas et al. (2022) reported that in multifunctional crops, CO_2 concentration and soil respiration depended mainly on soil structural composition, temperature and moisture content.

The study aimed to evaluate soil biological properties, encompassing plant root dry biomass, CO_2 emission from the soil and soil aggregate-size distribution. This assessment spanned across sole crops (spring barley, spring wheat, peas, caraway), binary combinations (spring barley and caraway, spring wheat and caraway, peas and caraway), and trinary configurations (spring barley, caraway, and white clover; spring wheat, caraway, and white clover; peas, caraway, and white clover).

The adoption of multifunctional crops emerges as a promising agricultural strategy, not only enhancing soil quality and nutrient cycling but also optimizing caraway seed yields through strategic integration into the cultivation process.

RESEARCH METHODS

The studies were carried out in 2019, 2020 and 2021 at the VMU Academy of Agriculture's Experimental Station. The soil is a carbonate stagnant leached soil (*Endocalcaric Amphistagnic Luvisol*) (WRB, 2015). The pH of the topsoil is 6,69, humus is 2,14 %, mobile nutrients in the soil are: P_2O_5 - 305 mg kg^{-1}, K_2O - 118 mg kg^{-1}. The trials were carried out in 4 replications. The initial plot size was 50 m^2 and the reference plot size was 20 m^2.

The experimental field was ploughed in autumn. In the spring of 2019, the field was treated twice with the germinator KLG-4.0 and fertilised with the complex fertiliser NPK 8-20-30 (300 kg ha^{-1}). On 18 April, spring barley (*Hordeum vulgare* L.) ʿCrescendoʾ (180 kg ha^{-1}), spring wheat (*Triticum aestivum* L.) ʿWickiʾ (250 kg ha^{-1}) and spring pea (*Pisum sativum* L.) ʿSalamancaʾ (225 kg ha^{-1}) were sown. On 18 April, a sole crop of caraway (*Carum carvi* L.) ʿGintarasʿ (7 kg ha^{-1}) was sown, and caraway and white clover (*Trifolium repens* L.) ʿSūduviaiʿ (2 kg ha^{-1}) were sown in barley, wheat and peas. On 19 April, after sowing, the caraway, pea, pea and caraway binary crops were sprayed with Fenix® herbicide (3 l ha^{-1}). On 10 June, a sole crop of caraway was sprayed with the herbicide Agil (100 g l^{-1}). On 20 June, a sole crop of peas, peas with caraway and white clover was sprayed with Actara insecticide (80 g ha^{-1}) and Signum fungicide (1,0 kg ha^{-1}). Sole crops of spring wheat and spring barley were sprayed on 8 May with Elegant 2 FD (0,40 l ha^{-1}) and Trimmer (0,10 kg ha^{-1}). The insecticide Karate Zeon CS (0,15 l ha^{-1}) and the fungicide Bumper 25 EC (0,50 l ha^{-1}) were sprayed on 31 May on sole crops of wheat and barley, on binary of caraway and on trinary of white clover and caraway. On 30 April, the sole crops of wheat and barley, the binary crops of wheat and barley with caraway and the trinary crops of wheat and barley with caraway and white clover were sprayed with ammonium nitrate at 150 kg ha^{-1}. The pea harvest took place on 29 July and the spring barley and spring wheat harvests on 5 August. After harvesting the spring wheat, spring barley and pea crops, the fields were discarded and deep ploughed. On 8 April 2020 and 19 April 2021, a levelling crop of spring barley ʿCrescendoʾ (180 kg ha^{-1}) was sown. This crop, like the sole barley crop, was sprayed with herbicides and fertilised with mineral fertilisers. The caraway crop was not fertilised with mineral fertilisers and no plant protection products were applied in the second and third year of its growth. After the harvest of the sole caraway crop in 2020, black fallow was left. On 15 July 2020 the caraway crop was harvested and on 24 August the spring barley catch crop was harvested. On 7 July 2021 the caraway crop was harvested and on 5 August the spring barley catch crop was harvested.

CO_2 emission from the soil (μmol m^{-2} s^{-1}) was determined in the 0–10 cm ploughsoil layer with a portable analyzer Li-Cor 6400-09 before the main crops harvesting, and before the second and third-year harvest of the caraway. In each experimental field, CO_2 emission was measured at two recording sites. The surveys were carried out between 11.00 and 16.00 h.

Root surveys were carried out using the small monolith method (10x10x10 cm) after the harvest of the main crops and in the second and third years of caraway cultivation after the harvest of the caraway. Samples were taken from two soil layers: 0–10 and 10–20 cm in each field at 3 locations. The roots were washed with sieves and dried in a drying oven at 105 ^{0}C. The root biomass of the plants was converted into the absolute dry matter in t ha^{-1}.

The data were statistically evaluated using a one-factor analysis of variance for quantitative traits (Raudonius, 2017). The Duncan criterion was used to assess significant differences between the means of the treatment options. Statistical analysis of the data was carried out using the computer program ANOVA from the software package SELECTION (Tarakanovas, Raudonius, 2003).

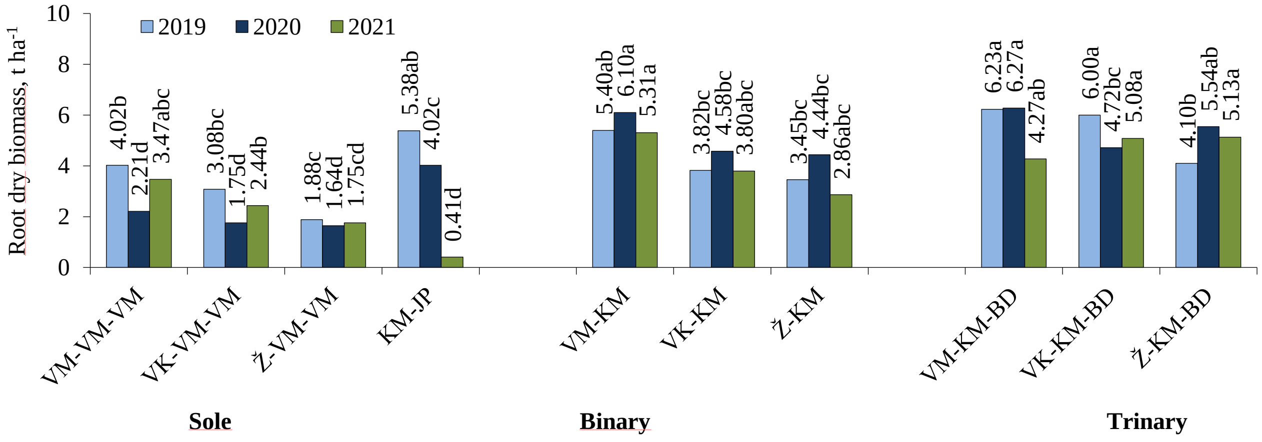
RESEARCH RESULTS AND DISCUSSION

Plant roots are essential for all ecosystem processes: carbon cycling, metabolism, soil and structural stability and soil organisms (Hirte et al., 2017). Well-developed roots cover a larger volume of soil, resulting in a higher uptake of phosphorus and potassium, but also of other elements (Li et al., 2013), such as organic carbon, nitrogen (Wang et al., 2021). Studies have also shown that perennial bean crops in multifuctional crops have much lower nitrate leaching, as nitrate and water uptake takes longer than in sole crops (Eskandari et al., 2009; Ghanbari, Lee, 2003). The denser root system of plants, where the roots of several different plants are intertwined, also plays an important role in this process (Zuo et al., 2003).

In 2019 (the year of main crop cultivation), spring barley, spring wheat and pea grown in a three-row crop with caraway and white clover were found to have a significantly higher plant root biomass, 1.5, 1.9, 2.2 times higher, respectively, compared to their sole crops (Figure 1).

In 2020 (the second year of caraway cultivation), caraway is grown after spring barley, spring wheat and peas without white clover (binary crops) and together with white clover after spring barley, spring wheat and peas (trinary crops), the root biomass of the plants was significantly higher compared to the sole crops, 2.8, 2.6, 2.7 and 2.8, 2.7, 3.4 times, respectively (Figure 1). The root biomass of the plants was found to be 1.4 to 1.6 times lower in the sole crop of caraway compared to the binary crop of spring barley and caraway and the trinary crop of spring barley and peas with caraway and clover.

In 2021 (the third year of caraway cultivation), when caraway is grown after spring wheat and peas together with white clover, the root biomass of the plants is significantly higher compared to a sole crop, by a factor of 2.1 and 2.9 respectively. In the black fallow left after caraway harvest, the plant root biomass was found to be significantly lower by a factor of 6.8 to 13.0 compared to the binary and trinary crops (Figure 1). Pappa et al. (2012) found that roots of different plant species take up moisture and nutrients at different rhythms and intensities. Interactions between plants and interspecific competition between them promote plant rooting (Hauggaard-nielsen, Jensen, 2005). Competition is also largely avoided during the course of vegetation (Dusa, Stan, 2013; Nasar et al., 2022). In contrast to the work cited above, Bellostas et al. (2004) found that, according to the researchers, the formation of a multifunctional binary crops can lead to a negative competitive effect through root intermingling in the early stages of plant growth. According to the same authors, two weeks after planting a binary crop, the dry matter accumulation of the plants was reduced by 15–20% compared to a sole crop (Bellostas et al., 2004). It can be argued that a more abundant and dense rhizome has a higher suction capacity and is therefore better able to take up nutrients from the soil and supply them to the plants to make them better prepared for adverse environmental conditions.



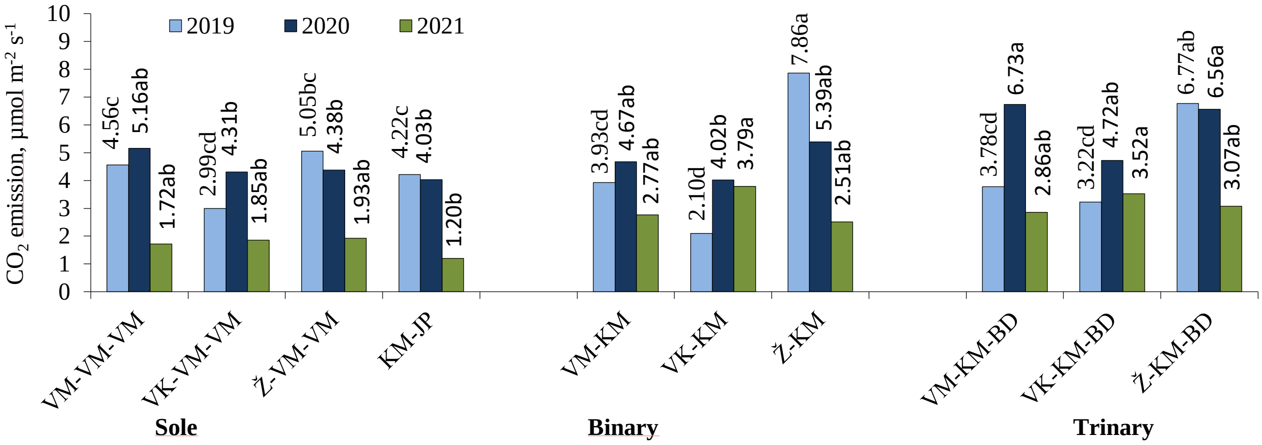
Note: VM – spring barley, VK – spring wheat, Ž – peas, KM – caraway, JP – bare fallow, BD – white clover. Differences between the averages of treatments marked with different letters (a, b, c...) are significant ($P < 0.05$).

Figure 1. Root dry biomass in multifunctional crops, 2019–2021

In 2019 (the year of main crop cultivation), CO_2 emissions from the soil of main crops (spring barley, spring wheat, peas) before harvest were found to be significantly 55.6% higher in the binary crop of peas and caraway, compared to the sole crop of these crops (Figure 2). Soil CO_2 emissions were found to be significantly 1.9 and 1.6 times lower in the sole crop of caraway than in the crop of peas with caraway and the crop of peas with caraway and clover.

In 2020 (the second year of caraway cultivation), before the caraway harvest, CO_2 emissions from soil in the trinary crop of caraway and white clover under peas were found to be significantly 49.8% higher than in a sole crop of these crops. Caraway in the trinary crop after spring barley and peas with white clover showed significantly higher soil CO_2 emissions of 67.0 and 62.8 % compared to a sole crop of caraway (Figure 2).

In 2021 (the third year of caraway cultivation), prior to the harvest of caraway, higher CO_2 emissions from the soil were found in the binary crops after spring barley, spring wheat and pea, and in the trinary crops of the above crops, but no significant differences were found when compared to the sole crop of these plants. In the binary crop after spring wheat without white clover and in the trinary crops with white clover, the CO_2 emission from soil was found to be significantly 3.2 and 2.9 times higher than in the black fallow left after the clover harvest (Figure 2).



Note: VM – spring barley, VK – spring wheat, Ž – peas, KM – caraway; JP – bare fallow, BD – white clover. Differences between the averages of treatments marked with different letters (a, b, c...) are significant (P < 0.05).

Figure 2. CO_2 emission from the soil in multifunctional crops, 2019–2021

Cereal and bean multifunctional crop systems use less fertiliser because bean plants fix nitrogen biologically, so GHG emissions are generally lower in cereal and bean multifunctional crop systems than in cereal sole crops (Lupwayi, Kennedy, 2007), although in some cases bean plants may release higher levels of CO_2 (Rochette, Janzen, 2005). Field measurements of CO_2 emissions by Ibrahim et al. (2013) showed that wheat root respiration is more intense in sole crops than in multifunctional crops with bean plants, and at the same time, it was found that a decrease in bean plant root vigour leads to an increase in microbial respiration. Another group of researchers found that CO_2 concentrations were higher in the root zone of a sole crop of bean plants compared to a multifunctional crop. Higher biomass of nodules formed by tuber bacteria in bean plants was also found (Latati et al. 2014). Yan et al. (2010) describes this mechanism as follows: multifunctional crops systems influence the soil respiration rate by influencing the above- and below-ground biomass of plants, and an increase in below-ground biomass leads to an increase in CO_2 emissions from the soil.

The formation of stable soil aggregates is an important process for the sustainable use of agroecosystems, as well as for improving soil hydraulic conductivity and root respiration, and for accelerating soil gas diffusion and plant growth (Alagöz, Yilmaz, 2009). Soil aggregate structure is also strongly influenced by tillage intensity. Tillage mechanically breaks down persistent soil aggregates (reducing the amount of persistent aggregates (>0.25 mm)), changes soil properties and accelerates the decomposition of organic matter (Balesdent et al., 2000).

In 2019 (the year of main crop cultivation), spring wheat grown with caraway seed showed a significant 56.5% decrease in mega-aggregates and a significant 48.5% increase in macro-aggregates when compared to the sole crop (Table 1). In the other crops, there was no significant difference in the content of macro aggregates. The amount of soil micro-structural aggregates did not differ significantly in all experimental fields. In the sole crop of caraway, the mega, macro and micro aggregate content did not differ significantly from the binary and trinary crops.

In 2020 (the second year of caraway cultivation), the amount of mega and macro aggregates in the soil of the sole crop was not significantly different from that of the binary and trinary crops (Table 1). Caraway with white clover after spring barley showed a significant 2.0 fold increase in micro-aggregates compared to the binary crops.

Table 1. Soil aggregate-size distribution % in the multifunctional crops, 2019–2021

Multifunctional crops	Soil aggregate-size distribution %								
	mega > 10 mm			makro 0,25–10 mm			mikro < 0,25 mm		
	2019	2020	2021	2019	2020	2021	2019	2020	2021
Sole									
VM-WM-VM	53,4a	48,0a	55,6a	35,1d	46,4a	39,0a	11,5ab	5,65ab	5,40a
VK-VM-VM	42,1ab	59,5a	49,9a	47,2bcd	36,4a	44,7a	10,8ab	4,20bc	5,50a
Ž-VM-VM	42,5ab	62,0a	55,8a	46,7bcd	34,7a	41,4a	9,80b	3,35bc	2,90b
KM-JP	22,9bc	55,7a	60,8a	66,1ab	41,8a	36,5a	11,1ab	2,58bc	2,70b
Binary									
VM-KM	35,7abc	62,4a	49,5a	48,5bcd	34,1a	46,5a	15,8a	3,53bc	4,10ab
VK-KM	18,3c	59,2a	53,0a	70,1a	38,5a	44,6a	11,5ab	2,30c	2,50b
Ž-KM	29,1bc	54,0a	45,7a	60,1abc	43,0a	52,6a	10,8ab	2,95bc	1,70b
Trinary									
VM-KM-BD	41,7abc	44,8a	61,7a	42,7bcd	48,1a	35,4a	15,7a	7,20a	2,90b
VK-KM-BD	35,9abc	49,5a	59,6a	51,5bcd	46,0a	38,1a	13,1ab	4,50abc	2,30b
Ž-KM-BD	40,0abc	63,1a	49,0a	49,3bcd	34,1a	49,1a	10,7ab	2,83bc	2,00b

Note: VM – spring barley, VK – spring wheat, Ž – peas, KM – caraway, JP – bare fallow, BD – white clover. Differences between the averages of treatments marked with different letters (a, b, c...) are significant (P < 0.05).

In 2021 (the third year of caraway cultivation), the amount of mega-aggregates did not differ significantly in all experimental fields (Table 1). The amount of macro-structured aggregates followed the same trend as the amount of macro aggregates.

CONCLUSIONS

In conclusion, the implementation of binary and trinary cropping systems has demonstrated a substantial positive impact on plant root dry biomass across various stages of caraway cultivation. Remarkably, these systems yielded a significantly higher plant root dry biomass in the main crops (1.5 to 2.2 times), second (2.8 to 3.4 times), and third (up to 2.9 times) years in comparison to the sole crop. Furthermore, the trinary crop outperformed the binary crop, showcasing even greater plant root dry biomass, particularly in the main crops.

The ecological implications of these findings extend beyond plant root development. The study also revealed noteworthy differences in CO_2 emission from the soil. In the main crops, second and third years of caraway cultivation, the trinary crop exhibited the highest increase in soil CO_2 emission compared to both the sole and binary crops. This suggests that the trinary cropping system not only enhances plant biomass but also influences soil processes, potentially contributing to carbon cycling and overall soil health.

Interestingly, the investigation into soil CO_2 emission unveiled that the black fallow left after the caraway harvest had the significantly lowest emission levels. This indicates the potential for fallow periods to play a role in mitigating carbon release and maintaining soil stability post-crop harvest.

Delving into soil structure, the study identified a significant increase in macro-structural aggregates in the binary and trinary crops during the main crops and the second year of caraway cultivation. Additionally, in the third year of caraway cultivation, the binary crops displayed a notable increase compared to the sole crop. This signifies that not only do these cropping systems impact root biomass and soil CO_2 emission, but they also influence the macro-structural composition of the soil, potentially contributing to improved soil structure and stability.

In essence, the adoption of multifunctional binary and trinary cropping systems emerges as a holistic approach that goes beyond enhancing plant productivity. It actively influences soil dynamics, contributing to increased biomass, improved carbon cycling, and favorable changes in soil structure. These findings underscore the potential of such cropping systems in promoting sustainable agricultural practices with positive ramifications for both plant and soil health.

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REFERENCES

1. Alagöz, Z., & Yilmaz, E. 2009. Effects of different sources of organic matter on soil aggregate formation and stability: A laboratory study on a Lithic Rhodoxeralf from Turkey. *Soil and Tillage Research*, *103*(2), 419–424. https://doi.org/10.1016/j.still.2008.12.006
2. Andrés, P., Doblas-Miranda, E., Rovira, P., Bonmatí, A., Ribas, À., Mattana, S., & Romanyà, J. 2022. Research for AGRI Committee—Agricultural Potential in Carbon Sequestration-Humus Content of Land Used for Agriculture and CO_2 Storage. *European Parliament, Policy Department for Structural and Cohesion Policies: Brussels, Belgium*, 103.
3. Balesdent, J., Chenu, C., & Balabane, M. 2000. Relationship of soil organic matter dynamics to physical protection and tillage. *Soil and tillage research*, *53*(3-4), 215–230. https://doi.org/10.1016/S0167-1987(99)00107-5
4. Bellostas, N., Hauggaard-Nielsen, H., Andersen, M. K., & Jensen, E. S. 2003. Early interference dynamics in intercrops of pea, barley and oilseed rape. *Biological agriculture & horticulture*, *21*(4), 337–348. https://doi.org/10.1080/01448765.2003.9755277
5. Belucio, M., Rodrigues, C., Antunes, C. H., Freire, F., & Dias, L. C. 2021. Eco-efficiency in early design decisions: A multimethodology approach. *Journal of Cleaner Production*, *283*, 124630. https://doi.org/10.1016/j.jclepro.2020.124630
6. Chai, Q., Qin, A., Gan, Y., & Yu, A. 2014. Higher yield and lower carbon emission by intercropping maize with rape, pea, and wheat in arid irrigation areas. *Agronomy for Sustainable Development*, *34*(2), 535–543. https://doi.org/10.1007/s13593-013-0161-x
7. Coluccia, B., Valente, D., Fusco, G., De Leo, F., & Porrini, D. 2020. Assessing agricultural eco-efficiency in Italian Regions. *Ecological Indicators*, *116*, 106483. https://doi.org/10.1016/j.ecolind.2020.106483
8. Dusa, E. M., & Stan, V. 2013. The effect of intercropping on crop productivity and yield quality of oat (*Avena sativa* L.)/ grain leguminous species (pea – *Pissum sativum* L., lentil – *Lens culinaris* L.) cultivated in pure stand and mixtures, in the organic agriculture system. *European Scientific Journal*, 9, 69–78.
9. Eskandari, H., Ghanbari-Bonjar, A., Galavi, M., & Salari, M. 2009. Forage quality of cow pea (*Vigna sinensis*) intercropped with corn (*Zea mays*) as affected by nutrient uptake and light interception. *Notulae Botanicae Horti Agrobotanici Cluj-Napoca*, *37*(1), 171–174.
10. Frick, B. L., Telford, L., Martens, J. T., & Wallace, J. 2017. *Organic Field Crop Handbook*. Canadian Organic Growers, Incorporated, Ontario, Canada, 169–176.

11. Ghanbari-Bonjar, A., & Lee, H. C. 2003. Intercropped wheat *(Triticum aestivum* L.) and bean (*Vicia faba* L.) as a whole-crop forage: effect of harvest time on forage yield and quality. *Grass and forage science*, *58*(1), 28–36. https://doi.org/10.1046/j.1365-2494.2003.00348.x
12. Hauggaard-Nielsen, H., & Jensen, E. S. 2005. Facilitative root interactions in intercrops. *Root physiology: From gene to function*, 237-250. https://doi.org/10.1007/1-4020-4099-7_13
13. Hemathilake, D. M. K. S., & Gunathilake, D. M. C. C. 2022. Agricultural productivity and food supply to meet increased demands. In *Future Foods* (pp. 539–553). Academic Press. https://doi.org/10.1016/B978-0-323-91001-9.00016-5
14. Hertel, T. W. 2011. The global supply and demand for agricultural land in 2050: A perfect storm in the making?. *American journal of agricultural Economics*, *93*(2), 259–275. https://doi.org/10.1093/ajae/aaq189
15. Hirte, J., Leifeld, J., Abiven, S., Oberholzer, H. R., Hammelehle, A., & Mayer, J. 2017. Overestimation of crop root biomass in field experiments due to extraneous organic matter. *Frontiers in plant science*, *8*, 284. https://doi.org/10.3389/fpls.2017.00284
16. Hu, F., Feng, F., Zhao, C., Chai, Q., Yu, A., Yin, W., & Gan, Y. 2017. Integration of wheat-maize intercropping with conservation practices reduces CO_2 emissions and enhances water use in dry areas. *Soil and Tillage Research*, *169*, 44-53. https://doi.org/10.1016/j.still.2017.01.005
17. Ibrahim, H., Hatira, A., & Pansu, M. 2013. Modelling the functional role of microorganisms in the daily exchanges of carbon between atmosphere, plants and soil. *Procedia Environmental Sciences*, *19*, 96–105. https://doi.org/10.1016/j.proenv.2013.06.011
18. Keating, B. A., Carberry, P. S., Bindraban, P. S., Asseng, S., Meinke, H., & Dixon, J. 2010. Eco-efficient agriculture: Concepts, challenges, and opportunities. *Crop science*, *50*, 109. https://doi.org/10.2135/cropsci2009.10.0594
19. Latati, M., Blavet, D., Alkama, N., Laoufi, H., Drevon, J. J., Gerard, F., ... & Ounane, S. M. 2014. The intercropping cowpea-maize improves soil phosphorus availability and maize yields in an alkaline soil. *Plant and Soil*, *385*, 181–191. https://doi.org/10.1007/s11104-014-2214-6
20. Li, X., Mu, Y., Cheng, Y., Liu, X., & Nian, H. 2013. Effects of intercropping sugarcane and soybean on growth, rhizosphere soil microbes, nitrogen and phosphorus availability. *Acta Physiologiae Plantarum*, *35*, 1113–1119. https://doi.org/10.1007/s11738-012-1148-y
21. Lindsey, R. 2022. Climate Change: Atmospheric Carbon Dioxide. [Accessed 05.08.2022]. Available online: https://www.climate.gov/news-features/understanding-climate/climate-change-atmospheric-carbon-dioxide
22. Lizarazo, C. I., Lampi, A. M., & Mäkelä, P. S. 2021. Can foliar-applied nutrients improve caraway (*Carum carvi* L.) seed oil composition?. *Industrial Crops and Products*, *170*, 113793. https://doi.org/10.1016/j.indcrop.2021.113793
23. Lizarazo, C. I., Tuulos, A., Jokela, V., & Mäkelä, P. S. 2020. Sustainable mixed cropping systems for the boreal-nemoral region. *Frontiers in sustainable food systems*, *4*, 103. https://doi.org/10.3389/fsufs.2020.00103
24. Lupwayi, N. Z., & Kennedy, A. C. 2007. Grain legumes in Northern Great Plains: impacts on selected biological soil processes. *Agronomy Journal*, *99*(6), 1700–1709. https://doi.org/10.2134/agronj2006.0313s
25. Massawe, F., Mayes, S., & Cheng, A. 2016. Crop diversity: an unexploited treasure trove for food security. *Trends in plant science*, *21*(5), 365–368. https://doi.org/10.1016/j.tplants.2016.02.006
26. Nasar, J., Shao, Z., Gao, Q., Zhou, X., Fahad, S., Liu, S., ... & Dawar, K. M. 2022. Maize-alfalfa intercropping induced changes in plant and soil nutrient status under nitrogen application. *Archives of Agronomy and Soil Science*, *68*(2), 151–165. https://doi.org/10.1080/03650340.2020.1827234
27. Naulleau, A., Gary, C., Prévot, L., & Hossard, L. 2021. Evaluating strategies for adaptation to climate change in grapevine production–A systematic review. *Frontiers in plant science*, *11*, 607859. https://doi.org/10.3389/fpls.2020.607859
28. Pappa, V. A., Rees, R. M., Walker, R. L., Baddeley, J. A., & Watson, C. A. 2012. Legumes intercropped with spring barley contribute to increased biomass production and carry-over effects. *The Journal of Agricultural Science*, *150*(5), 584–594. https://doi.org/10.1017/S0021859611000918
29. Raal, A., Arak, E., & Orav, A. 2012. The content and composition of the essential oil found in Carum carvi L. commercial fruits obtained from different countries. *Journal of Essential Oil Research*, *24*(1), 53–59. https://doi.org/10.1080/10412905.2012.646016
30. Raudonius, S. 2017. Application of statistics in plant and crop research: important issues. *Zemdirbyste-Agriculture*, *104*(4), 377–382. https://doi.org/10.13080/z-a.2017.104.048
31. Rochette, P., & Janzen, H. H. 2005. Towards a revised coefficient for estimating N_2O emissions from legumes. *Nutrient Cycling in Agroecosystems*, *73*, 171–179. https://doi.org/10.1007/s10705-005-0357-9
32. Romaneckas, K., Balandaitė, J., Sinkevičienė, A., Kimbirauskienė, R., Jasinskas, A., Ginelevičius, U., ... & Petlickaitė, R. 2022. Short-Term Impact of Multi-Cropping on Some Soil Physical Properties and Respiration. *Agronomy*, *12*(1), 141. https://doi.org/10.3390/agronomy12010141
33. Tarakanovas, P., & Raudonius, S. 2003. Statistical analysis of agronomic data using computer programs ANOVA, STAT, SPLIT-PLOT from the SELECTION package and IRRISTAT. Akademija, 56.

34. Wang, D., Zhao, P., Xiang, R., He, S., Zhou, Y., Yin, X., & Long, G. 2021. Nitrogen fertilization overweighs intercropping in promotion of dissolved organic carbon concentration and complexity in potato-cropped soil. *Plant and Soil*, *462*, 273–284. https://doi.org/10.1007/s11104-021-04876-2
35. Wang, G., Shi, R., Mi, L., & Hu, J. 2022. Agricultural eco-efficiency: Challenges and progress. *Sustainability*, *14*(3), 1051. https://doi.org/10.3390/su14031051
36. Yan, J. J., Yang, L. F., & Pang, J. 2010. Effects of soybean and cotton growth on soil respiration. *Acta Agronomica Sinica*, *36*(9), 1559–1567.
37. Zuo, Y., Li, X., Cao, Y., Zhang, F., & Christie, P. 2003. Iron nutrition of peanut enhanced by mixed cropping with maize: possible role of root morphology and rhizosphere microflora. *Journal of Plant Nutrition*, *26*(10–11), 2093–2110. https://doi.org/10.1081/PLN-120024267