Time series analysis of the climate change impacts of conventional agricultural practices

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Abstract

Agricultural activities have a considerable impact on the environment. In Hungary, crop production covers nearly half of the country's land, approximately 5.1 million hectares as of 2022. Sustainable agricultural competitiveness hinges on two key pillars: maintaining environmental balance and mitigating the damages from climate change anomalies. Our research focuses on a time series analysis of the climate change impacts of conventional agricultural practices in the Lajta Project study area, using the Environmental Life Cycle Assessment (LCA) method. The investigation spans two decades, calculating the annual average percentage contribution of each crop per hectare to the overall environmental impact, the environmental ranking is as follows (in ascending order): rapeseed (1.0%) – silage maize (4.9%) – grain maize (7.1%) – winter barley (43.1%) – winter wheat (44.0%). The results obtained enhance the ability to assess environmental impacts, climate risks, and the effects of climate change related to arable crop production technologies. This, in turn, aids in selecting the most suitable technologies that are adapted to environmental sensitivities.

Keywords: *agricultural land use; carbon footprint; ranking; comparison; life cycle analysis*

Introduction

The fundamental change in the nature of the functioning of the economy (as a productive sector) since the industrial revolution has been a major cause of environmental problems. However, this sector (including agriculture) is also the easiest to regulate. Among the many regulatory principles already developed, voluntary regulation (including life cycle analysis, ISO 14040-44:2006) can provide an effective, proactive approach to addressing problems[1].

Monoculture agriculture plays a critical role in global food production, occupying nearly 50% of habitable land and contributing significantly to climate change—food systems alone are responsible for approximately 26% of global greenhouse gas emissions[2]. Within agricultural emissions, crop production accounts for around a quarter of food-related emissions, while livestock contributes roughly 31%[3].

Extensive machinery usage and high input levels, including synthetic fertilizers and pesticides, dominate emissions. Studies show that expanding farm size increases carbon emissions per hectare when evaluated with LCA[4]. Conventional tillage and nitrogen application not only produce CO_2 and N_2O but also degrade soil organic carbon[2].

Monocultures over large areas disrupt habitat continuity, leading to biodiversity decline. For example, insect populations—including critical pollinators—are significantly reduced in landscapes dominated by monoculture cropping systems with high pesticide use. Moreover, the simplification of agroecosystems reduces resilience to climate shocks, such as droughts and pest outbreaks[5].

In Hungary, crop yields from arable farming show greater fluctuations than necessary, partly due to weather conditions, soil quality, technological factors, and low irrigation capacity. The yields of major agricultural crops remain close to the levels of two or three decades ago[6].

Several researchers, however, emphasize that the production of biomass on arable land is only justified if technologies are applied that meet both environmental and sustainability criteria. Dinya[7] highlights the importance of decision-making that prioritizes professional considerations, fits into a broader system, and focuses on long-term thinking and value chains, both at local and national levels.

Footprints can be used individually or collectively to characterise steps towards sustainability and are a good tool for benchmarking environmental performance[8]. The carbon footprint shows the total - direct and indirect - greenhouse gas (GHG) emissions of an activity, person, organisation, event or product, expressed in carbon dioxide equivalents. The larger the carbon footprint of an activity or individual, community or society, the greater its impact on global warming[8].

To examine the environmental impacts of crop production, we need to understand the resources required for production. These resources include the soil, moisture (water), heat, light, CO2 (air), and living organisms[9]. In addition to these, we must consider the landscape, which can be significantly altered by agricultural activities. Besides the needs of the plants, we must also account for technological processes and machinery, as they are significant influencing factors.

According to Kreybig[10], there is an extensive, interactive relationship between agriculture and the environment. Environmental factors fundamentally determine the nature, effectiveness, and even the existence of agricultural activities, while the reverse is also true, as agriculture exerts a direct and significant impact on the environment. Agriculture is one of the most important and fundamental human activities, which, by utilizing elements of the natural environment, also brings about significant changes in their condition. Agricultural activity has always been associated with some form of environmental change, but the intensity and scope of these changes have been, and continue to be, highly variable in time and space[11].

Negative changes in the state of environmental elements can be significant, especially because of inappropriate cultivation and resource use, so the right choice of technologies and use of materials is crucial[9].

In our work, we set the goal of conducting a time-series analysis of the conventional arable farming operations associated with key crops (silage maize, grain maize, rapeseed, winter barley, winter wheat) cultivated in significant quantities in the Lajta Project study area, focusing on their impacts on climate change (technological carbon footprints), using the comparative environmental Life Cycle Assessment (LCA) method, which also allows for ranking.

Materials and methods

The examined Lajta Project research area (3065 ha) is in the northwestern corner of Hungary, in Győr-Moson-Sopron County. The area is typically farmed in an intensive conventional way, almost completely lacking a meadow-pasture environment. It has become an important area for the cultivation of wheat, winter barley, maize, sugar beet, lucerne and red clover.

The Lajta Project dates to the early 1980s, when the goal was to study the bustard (*Otis tarda*) population in the Moson Plain and the Hanság region. Even at that time, more complex, multifaceted research was being conducted, which laid the foundation for the ecological protection of the bustard population in Hungary. During this period, several comprehensive ecological studies were launched across the country, aimed solely at assessing conventional agricultural activities and investigating their impacts. One of the areas studied was the Lajta-Hanság State Farm. It was already established then that the bustard's habitat shift was not only caused by the loss of previous habitats but was also a natural response to environmental factors. Furthermore, the complex nature of the research highlighted the importance of other species coexisting with the bustard, although these were only secondary focuses at the time. Towards the late 1980s, another bird species, the Hungarian partridge (*Perdix perdix*), became a focus of the research, due to its declining population. Various efforts were made to increase the partridge populations, but with little success, as the causes of the decline were not identified, and the proposed solutions were inadequate. As part of this process, the Department of Wildlife Management at the Forestry and Wood Industry University launched a survey and study of wildlife species living in field habitats and their environments in the Mosonszolnok II area of the Lajta-Hanság State Farm. During this period, the Hungarian Partridge Protection Program, supported by the Ministry of Agriculture, was also established, with the partridge as its indicator species. This enabled the simultaneous implementation of scientific research and practical work, which helped record both biological and ecological baseline information that could be applied in wildlife management practices[12].

As part of the complex research of the Lajta Project regarding the ecological protection of the bustard population in Hungary, we conducted a life cycle assessment to identify the environmental impacts of conventional agricultural cultivation, with special emphasis on the development of the carbon footprint. The methodology applied for conducting the LCA complies with the requirements of the ISO 14040:2006[13] and ISO 14044:2006[14] standards. The analysis was carried out using the Sphera GaBi thinkstep Professional software[15]. The required steps of the LCA were as follows: 1. defining the goal, scope and system boundaries, 2. inventory analysis, 3. impact assessment, 4. interpretation of results.

The selection of the crops included in the analysis was justified by the significant cultivation area they occupy in the study region. We conducted a life cycle assessment of cultivation data for five crops: rapeseed, winter barley, winter wheat, silage maize, and grain maize, based on data from agricultural field records. Our functional unit was 1 hectare of cultivated land. The study covers nearly two decades (1991-2011).

There are several impact assessment methods available to calculate the carbon footprint, in our study we chose one of the most widely used in Europe, the CML2001 (January 2016 version) impact assessment method and used the global warming potential (GWP 100 y). Global Warming Potential is a relative measure of how much heat a greenhouse gas retains in the atmosphere. Global Warming Potential is calculated in carbon dioxide equivalents, which means that the greenhouse effect of an emission is given relative to CO2. Since the atmospheric residence time of gases is included in the calculation, the assessment period is set at 100 years.

To assess the overall environmental impact (expressing the impacts in a dimensionless number), we used the 'CML2001, Experts IKP (Central Europe)' method in the LCA software. This method allowed us to present the increasing environmental ranking of the annual average environmental burden per hectare for each crop.

Results and discussion

We present the global warming potential (GWP 100 y) values from the CML2001 mid-point, problem-oriented impact assessment method, which shows the carbon footprint of the cultivation technologies of the examined crops (which primarily represents the mechanized operations, fertilization, and chemical crop protection carried out on the cultivated area). The values for silage maize per hectare are illustrated in the following diagram *(Figure 1)*.

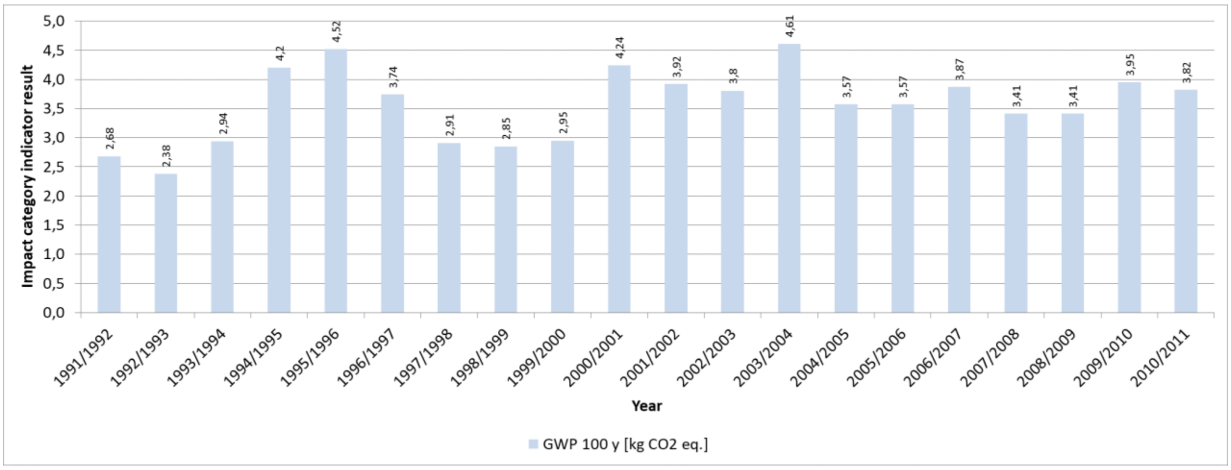

Figure 1: Time-series values of the technological carbon footprint using the CML2001-Jan. 2016 method in the case of silage maize per hectare

As the time series progresses, there is initially a slight increase in the impact category, followed by a more balanced pattern. There are also some standout years and periods that contributed significantly to the "GWP 100 y" value (as these years were characterized by more intensive mechanized operations and chemical crop protection on the cultivated area), namely the years from 1994/1995 till 1996/1997, 2000/2001, and 2003/2004.

The values for grain maize per hectare can be seen in *Figure 2*.

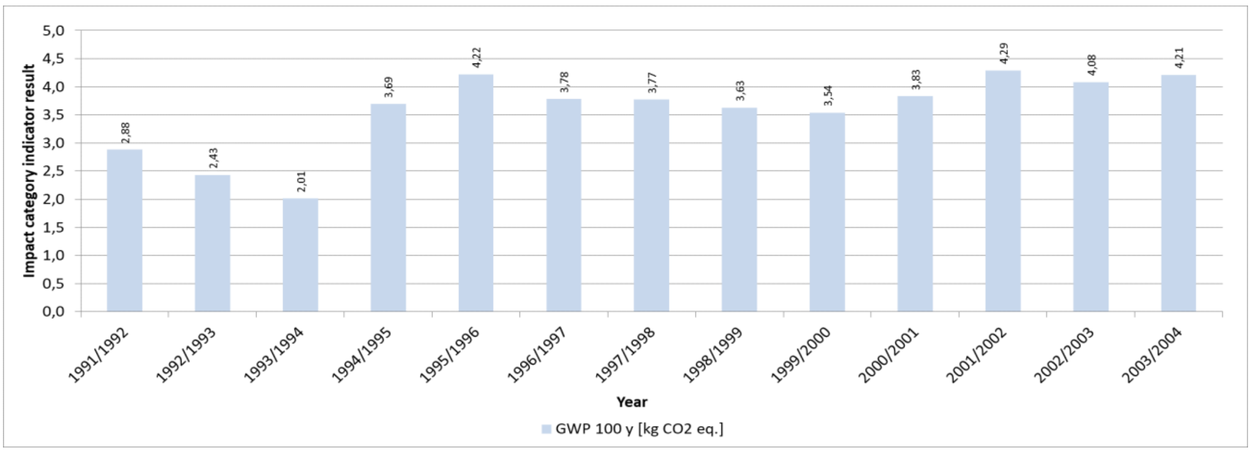

Figure 2: Time-series values of the technological carbon footprint using the CML2001-Jan. 2016 method in the case of grain maize per hectare

For grain maize, the impact was lower up until the 1993/1994 year. However, after that, the values increased in the global warming potential (GWP 100 y) impact category.

For rapeseed, the global warming potential (GWP 100 y) values per hectare are as follows *(Figure 3).* While the values are generally balanced, the years 1993/1994 and 2003/2004 experienced lower impacts.

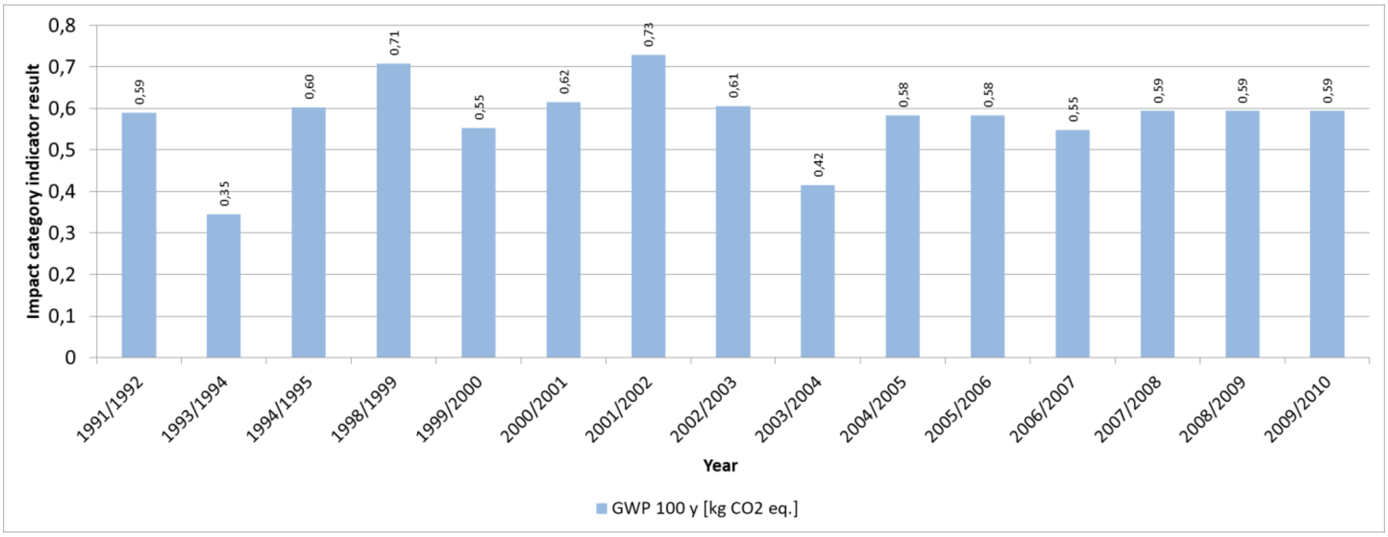

Figure 3: Time-series values of the technological carbon footprint using the CML2001-Jan. 2016 method in the case of rapeseed per hectare

The GWP 100 years indicator values for winter barley per hectare are as follows *(Figure 4)*. There are no standout values; only the year 2003/2004 experienced slightly higher values than the average.

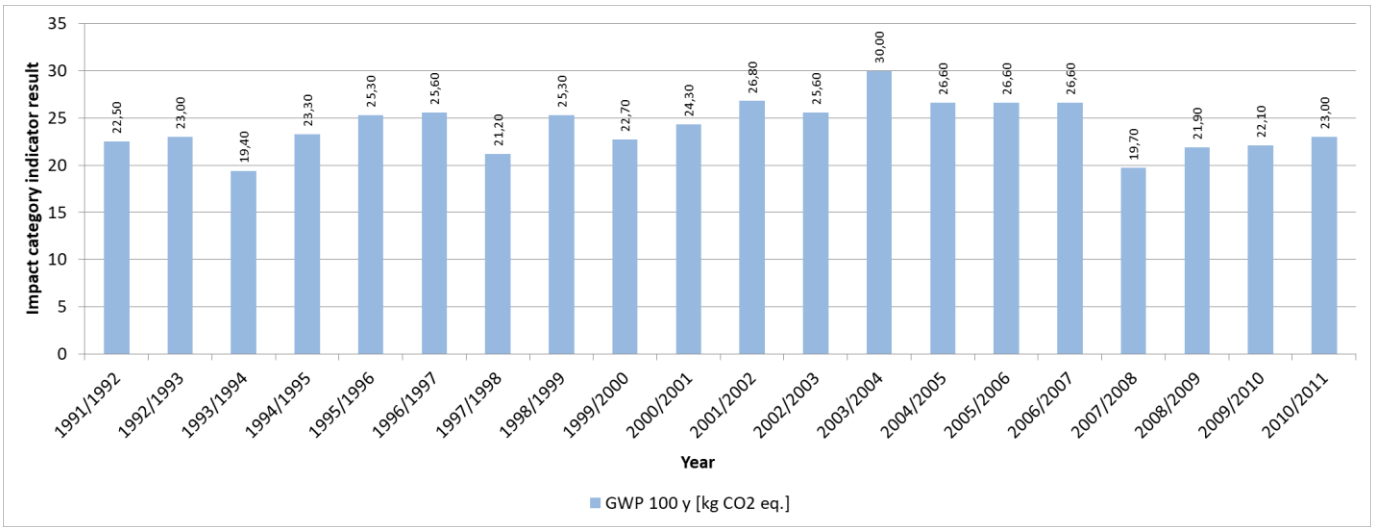

Figure 4: Time-series values of the technological carbon footprint using the CML2001-Jan. 2016 method in the case of winter barley per hectare

The indicator values for winter wheat per hectare are depicted in the following diagram *(Figure 5).*

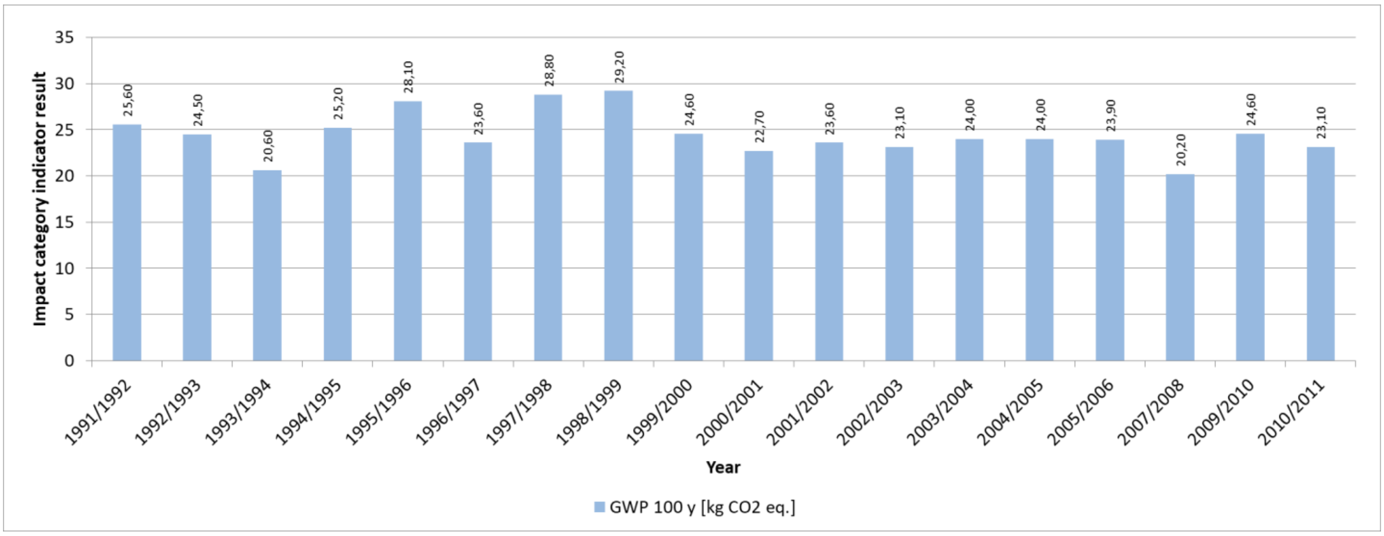

Figure 5: Time-series values of the technological carbon footprint using the CML2001-Jan. 2016 method in the case of winter wheat per hectare

The indicator values for the impact categories fluctuate in the first nine years. The following nine years show slightly lower, more uniform impacts. The exception is 2007/2008, which is characterised by lower values than the average for the period.

When calculating the environmental overall impact, the results for all CML 2001 impact categories can be viewed side by side in a dimensionless metric for each crop.

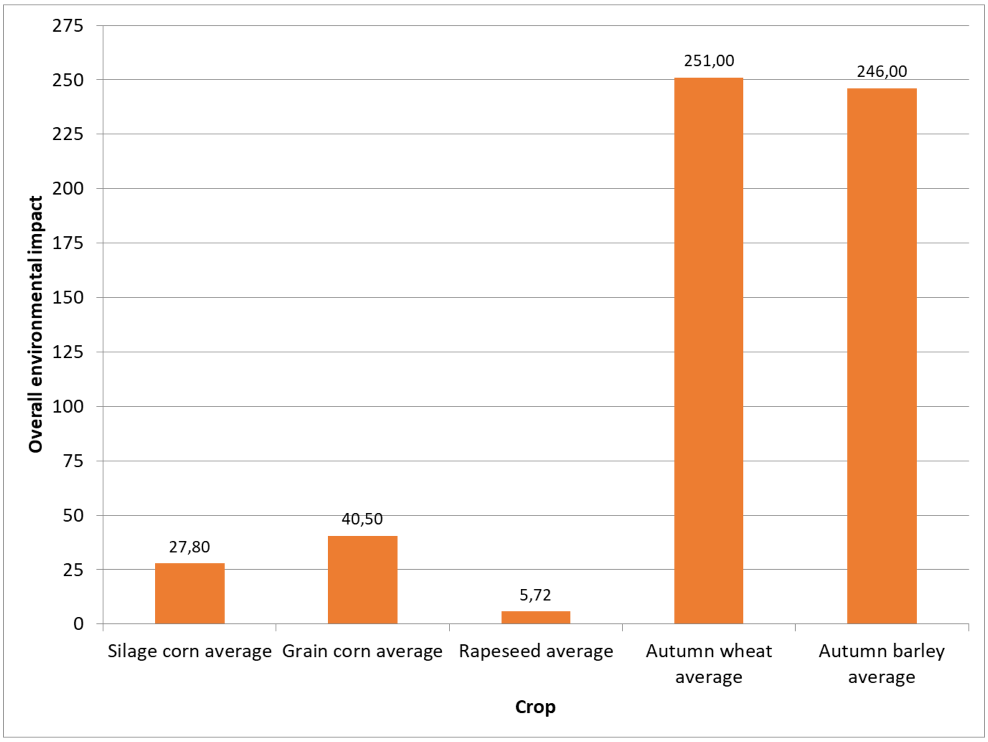

Figure 6: CML2001, IKP Experts (Central Europe) values per crop based on annual average inventory data

In the LCA, the values obtained from the mandatory impact assessment step, normalized for Central Europe (using the CML2001, IKP Experts (Central Europe) method)[16] *(Figure 6)*, show the following environmental ranking based on the percentage contribution of each crop (increasing order): rapeseed (1.0%) – silage maize (4.9%) – grain maize (7.1%) – winter barley (43.1%) – winter wheat (44.0%). The difference in the overall environmental impact between root and cereal crops is an order of magnitude, with cereal crops having values six to ten times higher.

Conclusion

In our research, we analyzed time series data related to the major field crop operations (silage maize, grain maize, rapeseed, winter barley, winter wheat) associated with the Lajta Project study area, focusing particularly on their impact on climate change (technological carbon footprints). This was achieved using a comparative Life Cycle Assessment (LCA) method, which also allows for ranking. The area is typically an intensive agricultural environment, with almost no presence of meadow-pasture environments.

The methodology used for the LCA complies with the requirements of ISO 14040:2006 and ISO 14044:2006 standards. We conducted a life cycle assessment of the cultivation data for five crops: rapeseed, winter barley, winter wheat, silage maize, and grain maize. Our functional unit was 1 hectare of cultivated land.

The time series carbon footprint analyses allowed for the presentation of the environmental impacts per functional unit for each crop across different years. This facilitated the understanding of the intensity of cultivation technologies, which in turn enabled further conclusions to be drawn from the time series evaluation of changes in the local plant and animal life.

When calculating the overall environmental impact of cultivation steps, the environmental ranking based on the percentage contribution for each crop is as follows (in increasing order): rapeseed (1.0%) – silage maize (4.9%) – grain maize (7.1%) – winter barley (43.1%) – winter wheat (44.0%).

Understanding these results will help to better identify the environmental impacts, climate risks, and roles of climate change in field crop cultivation technologies. It can also help in selecting appropriate cultivation technologies that align with the sensitivity of the environment.

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Analýza časových řad dopadů změny klimatu velkoplošných zemědělských praktik

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Souhrn

Zemědělské činnosti mají značný dopad na životní prostředí. V Maďarsku pokrývá rostlinná výroba téměř polovinu rozlohy země, přibližně 5,1 milionu hektarů k roku 2022. Udržitelná konkurenceschopnost zemědělství závisí na dvou klíčových pilířích: udržování environmentální rovnováhy a zmírňování škod způsobených klimatickými anomáliemi. Naše výzkumná práce se zaměřuje na analýzu časových řad dopadů změny klimatu na velkoplošné zemědělské praktiky ve studijní oblasti projektu Lajta, a to pomocí metody posuzování životního cyklu (LCA). Šetření pokrývá období dvou desetiletí a vypočítává průměrný roční procentuální podíl každé plodiny na hektar na celkovém dopadu na životní prostředí. Environmentální žebříček je následující (vzestupně): řepka (1,0 %) – silážní kukuřice (4,9 %) – zrnová kukuřice (7,1 %) – ozimý ječmen (43,1 %) – ozimá pšenice (44,0 %). Získané výsledky zlepšují schopnost hodnotit environmentální dopady, klimatická rizika a účinky změny klimatu související s technologiemi produkce orné půdy. To následně pomáhá při výběru nejvhodnějších technologií, které jsou přizpůsobeny environmentálním citlivostem.

***Klíčová slova**: využití zemědělské půdy; uhlíková stopa; hodnocení; srovnání; analýza životního cyklu*