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ANALYSIS OF GREENHOUSE GAS EMISSIONS AND DROUGHT AND THEIR IMPACTS ON THE AGRICULTURAL SECTOR

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ANALYSIS OF GREENHOUSE GAS EMISSIONS AND DROUGHT AND THEIR IMPACTS ON THE AGRICULTURAL SECTOR

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1. INTRODUCTION

In recent years, the world's population has increased rapidly, and is expected to increase from 7.2 billion people to 9.6-12.3 billion in 2100 (*Gerland* et al. 2014). This increase constitutes a pressure on natural resources and the terrestrial ecosystem in many parts of the world to meet the increasing demand of human needs (*Samir and Lutz,* 2017). Thus, the United Nations launched the Sustainable Development Goals (SDGs), which include an ambitious goal for zero hunger globally (SDG2) by 2030 (*Mason-D'Croz et al*. 2019). However, the changing climate makes this a serious challenge for policy makers, scientists, and researchers, since climate change amplifies the hunger in our world by affecting food availability, health, and reducing agricultural production (*Springmann et al*., 2016), and poverty and hunger cause the death of almost 25000 people every day (*Tripathi et al*. 2019). Nonetheless, climate change (CC) has rapidly affected many ecosystems earlier than predicted, which requires an international effort for climate mitigation and adaptation all over the world (*Bates et al*. 2008). Even though GHGs exist naturally, human activities have released huge amounts of it, leading to more trapping of the sun's heat, which exceeds the needs of the earth, and which is known as "global warming - GW". This global warming has directly affected weather patterns on a global scale, causing "climate change - CC". In this context, the United Nations Framework Convention on Climate Change (UNFCCC) defined CC as a "change of climate that is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and that is in addition to natural climate variability observed over comparable time periods". However, CC has been shown to be a shifting of weather conditions over the long term, which could be recognized by changing rainfall, temperature and other climate components.

1.1. Justification of the study

GHGs are predominantly made out of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), which are quickly expanding in the air, causing worldwide environmental and causing global climate change (*Yang et al*. 2014; *Mei et al*. 2019). Unfortunately, the current GHGs projection reveal that the CO_2 concentration will reach 590 ppm by the end of the 21st century (*Li et al*. 2014), which poses a great challenge against sustainability in different dimensions.

GHGs emissions have expanded markedly since 1750 (industrial revolution) (*Ayalon et al*. 2000) because of rapid expansions in fuel utilization and the development of anthropogenic activities in various sectors like the economy, energy, coal mining, and farming. In view of crafted by Herzog (2009), the GHG emanations can be highlighted as follows: 31.6% from industrial activities, 12.2% from changes of land use, 24.9% from power sector, 14.3% from transportation, 13.8% from the agricultural sector, and 3.2% from waste industry. The final outcome of GHG emissions is comprised of 77% CO_2, 15% CH_4 and 7% N_2O.

In a global scale, and after 25 years of international diplomacy work based on the ***United Nations Framework Convention on Climate Change (UNFCCC-1992)*** (Earth Summit in Rio de Janeiro); finally, the world leaders of 177 countries and 144 states signed the ***Paris Agreement (PA)*** (April 2017). The PA which is designed at COP 21 (Paris, December 2015) was a hybrid approach combining two previous framework the first one was ***Kyoto protocol*** (2002) "top-down" and ***Copenhagen agreement*** "bottom-up" (*Asadnabizadeh* 2019). Where the main issue was to minimize the world emissions of GHGs to keep GW below 2 °C (*Parker et al.* 2018; *Rogelj et al*. 2016). In this sense, many countries were reduced their emissions significantly; for instance, Russia reduced the emission by 5.4% (1990-2013), USA by 7% (1990-2013), and the EU-28 8.4% (1990-2013) (*Kijewska and Bluszcz* 2016). Numerous studies have attempted to follow and identify GHG emanations in different parts of the world. *Bennetzen et al*. (2016) reported that GHG emissions from agricultural sector (emissions per unit crop) was decreased by 94% in Oceania, 57% in Central and South America, 56% in Europe, and 27% in sub-Saharan Africa. Nonetheless, the universal C-footprint was accounted to be 39% in 2007 lower than 1970 from crop production and 44% in 2007 lower than 1970 from livestock (*Bennetzen et al*. 2015). However, 3Gt/y of GHGs emission till 2050 is predicted to be emitted just to meet the rapid increase of human population (*Tilman et al*. 2011). Markedly, the anthropogenic activity alters the biogeochemical cycle and tiger the dynamic interaction between terrestrial ecosystem and element cycle. In this regard, agricultural activities lead to emit 1.7 and 4.8 Tg N_2O yearly from soil, while rice production is accountable for 24–30 Pg C a yearly, that is almost 50% of the emissions from livestock sectors (*Bispo et al*. 2017).

Despite the fact that numerous projects have been attempted to show the connection between environmental change and GHGs all over the world. Limited research has been completed in Eastern and central Europe. In this sense, majority of this projects was delt with one single perspective, like industry and energy consumption, agriculture, or transport like those in

Hungary (*Radicetti et al*. 2020; *Molnár,* 2014; *Molnár,* 1996), Romania (*Boiangiu* 2015; *Proorocu et al*. 2010), Bosnia and Herzegovina (*Milosavljević et al*. 2018), Bulgaria (*Hristov and Stefanov*, 2019; Nakaten et al. 2013), and Russia (Rüstemoğlu, Andrés 2016). To the best of our knowledge, only *Kijewska and Bluszcz* (2016) have tried to group emissions from the EU using the k-means method. Our study adopts a different approach and its main aim is to characterize the trend of GHG emissions in the EU by using the Mann-Kendall (MK) test, then tracking drought events in Hungary (1960-2010) and their impact in different sector, with an overview of CO2 emission from two different regions.

1.2.Research goals

Since 1981 monitoring of GHGs emissions in Hungary was started (*Haszpra* 2010). However, in the 1990s monitoring of GHGs budget was allocated in different ecosystems (*Haszpra* 2010). On a national scale, many steps were taken to minimize GHGs emissions from different sectors, especially that Hungary is subjected to reduce emissions by 10% in 2020 compared with the base line of 2005 (*Talamon et al*. 2019). To the best of the author knowledge, limited number of researches were discussed this issue from different perspectives. Thus, the main aims of this research were to:

1. Track GHG emissions from the agricultural sector in the EU between 1990 and 2016, to highlight the changes and the impact of different climate polices
2. Track current and future GHGs from agricultural sector in Hungary.
3. Track spatial and temporal variability of agricultural and hydrological drought in Hungary between 1960 and 2010 as one of the consequences of a global increase in GHG emissions.
4. Analyze the impact of agricultural drought on maize and wheat production on a regional scale in Hungary.
5. Track CO_2 emissions from two different agricultural ecosystems on a regional scale (Debrecen vs Tehran)

Overall, the research goals will answer the following ***questions***:

1- Is there a negative trend in GHGs emissions from the agricultural sector in the EU?
2- Is there a negative trend in GHGs emissions from agricultural sectors in the Hungary?
3- How did drought episodes evolve in Hungary between 1961 and 2010?
4- How has drought affected crop production in Hungary?

5- Can different climate regions affect the CO_2 emissions from the agricultural sector?

To follow the study goals and answered the research questions, this work was divided into 7 chapters. Chapter number one is an introduction about the topic and the research goals, while the chapter number 2 was design to give an overview of climate change from world perspective, sources of greenhouse gases emission including soil, then climate change impacts on agricultural sector with especial focused on drought and its impact. Chapter number 3 contains data collection, analysis, and other methods that’s adopted in this study to meet the research questions. In chapter number 4 results were extensively presented and discussed from different perspective. The conclusion was placed in chapter number 5 which depicted the answers of research questions that presented in chapter number 1. Chapters number 6 and summarized the whole work and its applicability through “new scientific results” and “practical utilization of the result”

2. LITERATURE REVIEW

2-1- Climate change

The Earth's atmosphere is full of gases, some of which are greenhouse gases (GHGs); these gases trap the sun's heat and keep earth warm for life. However, accelerated civilizational development and industrialization increased the concentration of GHGs in the earth's atmosphere. In this sense, CO_2 reached 410.6 ppm in 2019, compered with 280 ppm in the 1760s (*Zhang et al*., 2019). This increase led to rapid climate change (CC). *Reddy* (2015) summarized the main indicators of CC as follows: 1) an increase in temperature, 2) an increase in ocean heat content, 3) an increase in sea level and surface temperatures, 4) an increase in continentality, 5) tropospheric temperature, 6) a decrease in sea ice, 7) a decrease in snow cover, and 8) a decrease in sea ice glaciers. The causes of CC can be summarized in two categories (*Reddy* 2015):

1. Natural causes: which include: 1) continental drift, 2) volcanic eruptions (ash, SO_2, H_2O, dust), 3) ocean currents (heat transport), 4) and the earth's tilt.
2. Human causes: various human activities can cause CC, such as burning of fossil fuels and land use changes, which emit huge amounts of GHGs.

Consequently, the sunlight trapped by the earth's atmosphere - in other words, reflected heat (infrared) - cannot pass freely to the atmosphere due to a layer of GHGs, which already exist due natural and human causes (Figure 1). As a result, the earth's temperature is increasing (i.e. GW). In this context, GHGs contribute in different ways to GW; for instance, the contributions of CO_2, CH_4, and N_2O are 60%, 15%, and 5%, respectively (*IPPC* 2007). In terms of heat trapping (global warming potential (GWP), N_2O is 298 times more effective than CO_2, and CH_4 25 times more. More details regarding GHGs will be discussed in the following paragraphs.

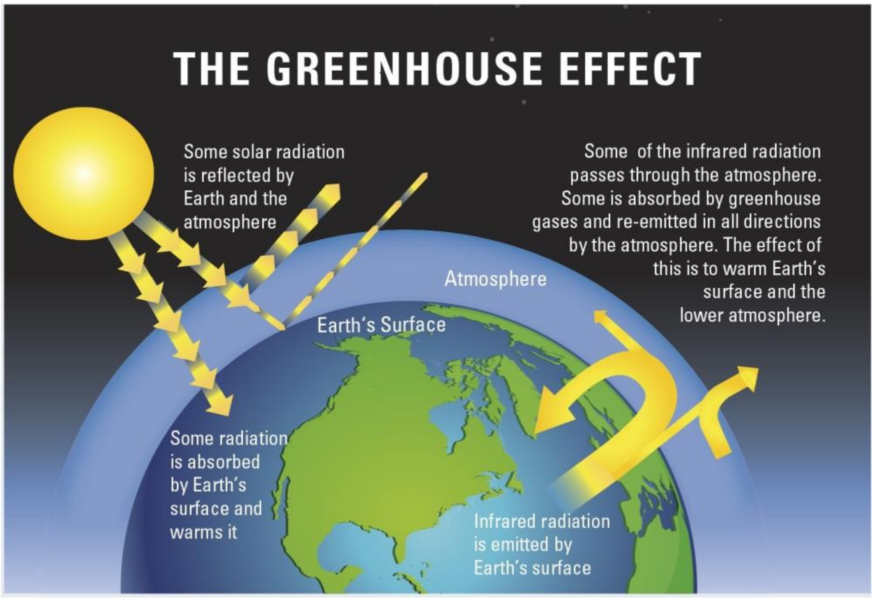

Figure 1 Schematic overview of GHGs effects **(I1)**

2-2 Sources and impacts of greenhouses gases:

Different gases in the atmosphere form GHGs, such as CO_2, CH_4, N_2O, hydrofluorocarbons (HFCs), and many others.

2-2-1 Carbon dioxide (CO_2)

There are many sources of CO_2, which can be divided into: 1) natural sources (decomposition of organic matter, forest fires, volcanic eruptions), and 2) anthropogenic sources (land use changes, deforestation, industrial activities, fossil fuels) (*Laruelle et al*. 2018, IPCC 2013). However, earth has many sink pools such as soil, oceans, and atmosphere. Forest removes CO_2 from the atmosphere at various rates (*Luyssaert et al*. 2008). *Laruelle et al*. (2009) reported that 57% of each year's CO_2 emissions were sunk, both in land and in the oceans. Unfortunately, CC in the last 50 years has affected carbon sink pools, which has led to an increase in the CO_2 that remains in the atmosphere.

Before the industrial revolution CO_2 did not exceed 300 ppm (*Lüthi et al*. 2008) (Figure2). Since then, different activities have led to a rapid increase in CO_2 emissions due to coal use (*Boden et al*. 2017), which increased fossil fuel emissions by 100% (from 1.5% to 3%) between 1980 and 2000 and 2000-2012 (*Hansen et al*. 2013) (Figure3), and by 29% from 2000 to 2008 (*Le Quéré et al*. 2009). The CO_2 concentration has reached 389 ppm and will continue to rise to reach 1200 ppm in 2100, unless some action is taken (*IPCC* 2001). In recent decades, an increase in partial pressure of CO_2 by 1.8ppmv per year has been recorded, due to the factors mentioned above (*Laruelle et al*. 2018).

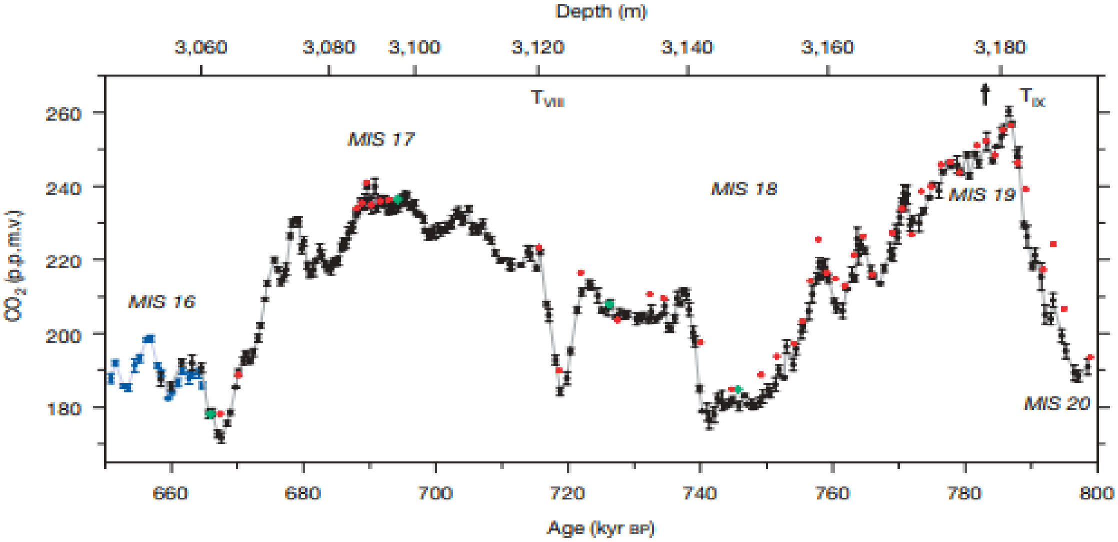

Figure 2. CO_2 concentrations before the industrial revolution as published by Nature (*Lüthi et al*. 2008).

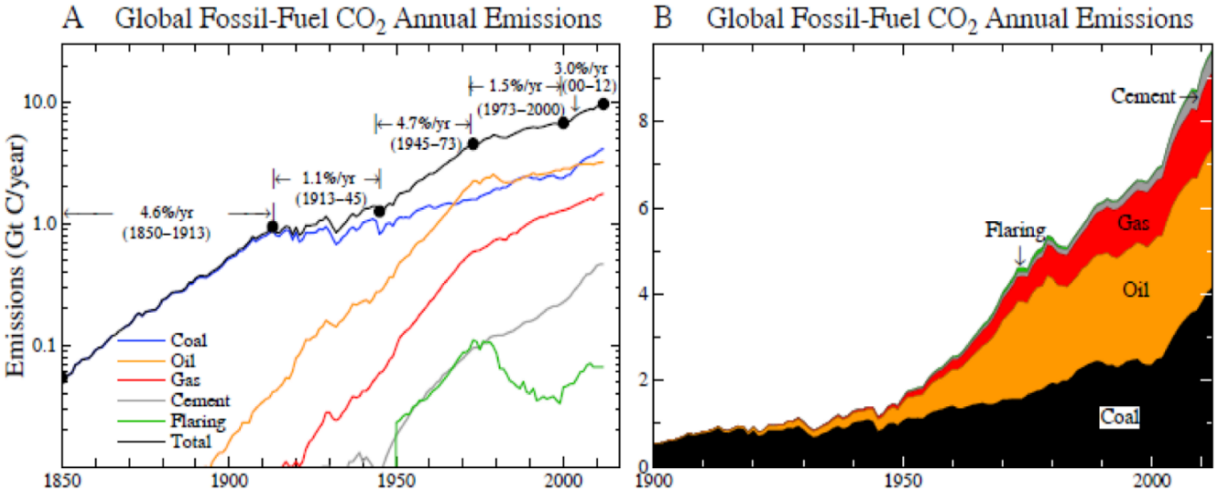

Figure 3. Emissions of CO_2 (Gt C/year) from different sources between 1850 and 2012 on a global scale (*Hansen et al*. 2013)

2-2-2 Methane (CH_4)

Methane is one important GHG, which contributes to more than 20% of global warming (*Kirschke et al*. 2013). Sources of CH_4 can be divided into: 1) biogenic sources which are produced by microbes (*Cicerone and Oremland* 1988), 2) thermogenic - fossil fuel which has formed over many previous centuries (*Kirschke et al*. 2013), and 3) pyrogenic, which is produced during incomplete burning of wildfires, fossil fuels, and biofuels (*Kirschke et al*. 2013). The CH_4 sinks around the earth, on the other hand, are distributed as follows: 1) 90% in the atmosphere through the oxidation process, 2) 4% through oxidation by methanotrophic bacteria (*Curry*, 2007), 3) 3% through chemical reactions with other materials and elements in the stratosphere (oxygen radicals, chlorine radicals) (*Cicerone and Oremland* 1988), and 4) 3% in the boundaries between sea and land through chemical reactions with chlorine radicals (*Allan et al*. 2007).

Since 1980, CH_4 emissions have fluctuated, as can be seen from Figure 4. This fluctuation shows an imbalance in the methane budget, although the cause of this imbalance is not yet known (*Kirschke et al*. 2013, *Cicerone and Oremland* 1988). Notably, CH_4 levels increased in the 1980s, decreased in the 1990s, stabilized between 1999 and 2006 (1773 ppb), before rising again to reached 1799 ppb in 2010 (*Rigby et al*. 2008; *Kirschke et al*. 2013). However, an increase in ocean surface temperature as a function of climate change could alter the stabilization of methane hydrates in the Arctic area, which would increase emissions of CH_4 by a large quantity (*Berchet et al*. 2020). Methane in the atmosphere increases the mass-based radiation effect for 100 years relative to CO_2 (*Bond-Lamberty et al*., 2020) and its production shows significant temporal and spatial variability often associated with climate and redox conditions. This contributes to significant uncertainty in global methane budgets (*Bond-Lamberty et al*., 2020; *Friedlingstein et al*., 2019).

On a global scale, wetlands play an important role in the C-cycle, first as a main source of CH_4 (115 Tg CH_4 yr^{-1}), and second as a carbon storage (76 Tg C yr^{-1}, high-latitude only). Thus, the dynamic interaction between different factors (temperature, rainfall, groundwater level, topography) determine CH_4 emissions and C- sequestration, which has undoubtedly affected the global climate system (*Bohn et al*. 2007). However, climate projections emphasize a doubling of CH_4 emissions annually in high-latitudes only, e.g. Siberia (*Bohn et al.* 2007). It is important to mention here ruminant livestock as another remarkable source of CH_4 emissions. This sector produces almost one quarter of total CH_4 through the enteric fermentation process (*Boden et al*. 2017).

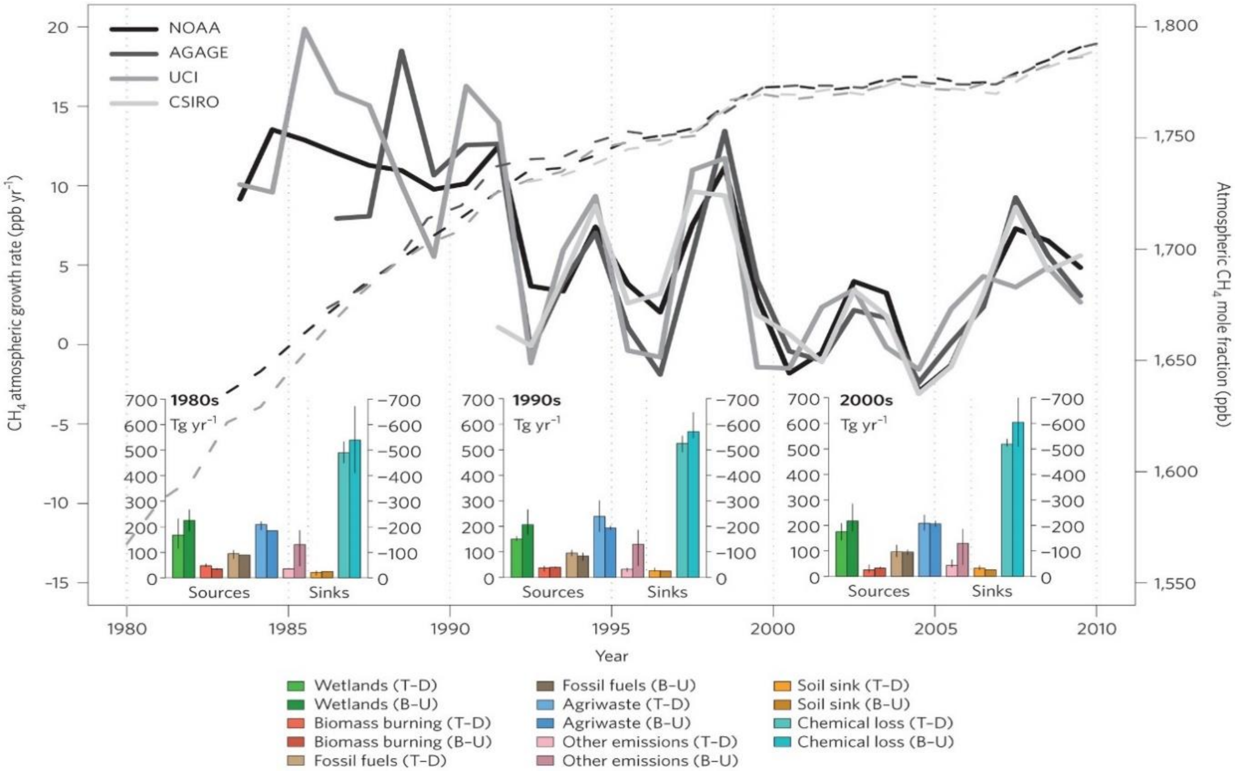

Figure 4. Sources, concentration and sinks of CH_4 from different world databases (NOAA, AGAGE, UCI and CSIRO) published by Nature (*Kirschke et al*. 2013).

2-2-3 Nitrous Oxide (N_2O)

The concentration of N_2O has increased by 2% each decade over the last 150 years, which has led to a depletion of stratospheric ozone and CC (*Prather et al*. 2015, *Tian et al*. 2020). *Tian et al*. (2020) reported that atmospheric N_2O had reached 331 ppb in 2018, compared to 270 ppb in 1750, representing a 20% total increase, with the most rapid increase being recorded in the last five decades (*Hall* 2007). Meanwhile, human-induced emissions due to agricultural activities (i.e. nitrogen fertilizer) has increased to 7.3 teragrams of N/year in the last four decades, which is responsible for most of the atmospheric concentration increase (*Tian et al*. 2020).

According to *Tian et al*. (2020), sources and sinks of N_2O can be classified in six groups: 1) natural sources, 2) agricultural activities (nitrogen fertilization), 3) anthropogenic activities (biomass burning, industry, fossil fuel, waste sector), 4) emission from ecosystems changes enhanced by CC, CO_2, and land cover, 5) indirect N_2O emissions as described by the Intergovernmental Panel on Climate Change (IPCC), and 6) atmospheric sinks (Figure 5).

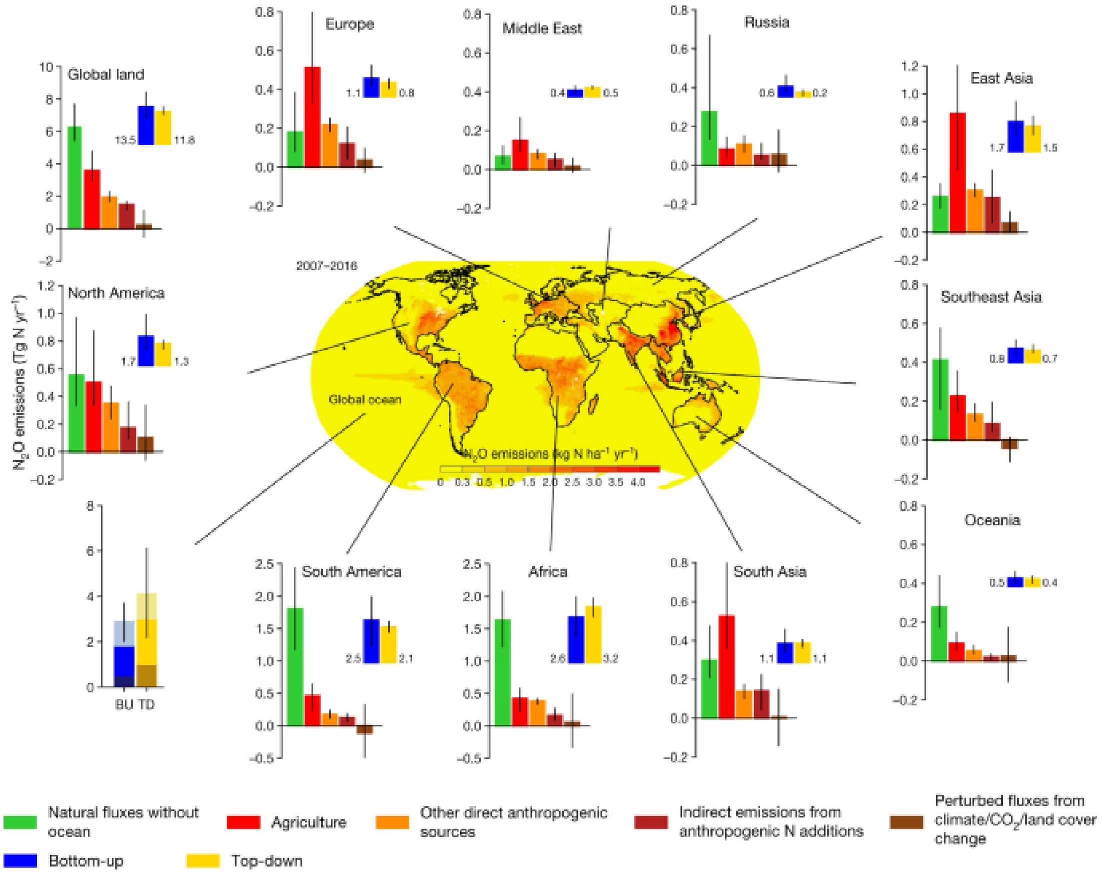

Figure 5. Sources and concentrations of N_2O from different sectors around the world, published by Nature (*Tian et al*. 2020)**.**

The highest N_2O emissions were recorded in Brazil, China and India, due to economic development. Interestingly, the current global N_2O emissions values exceed the highest projected scenarios (*Gidden et al*. 2019, *Davidson et al*. 2012), which impose the necessity of a global mitigation action plan.

2-2-4 Chlorofluorocarbons (CFCs)

CFCs form due to various industrial anthropogenic activities, which are/were used in air-conditioning, refrigeration, and many others (*Willey et al*. 2004). Interestingly, CFCs are responsible for the depletion of 35% of the stratospheric ozone layer and 10% of CC (*Fraser et al*. 2020, *Myhre and Shindell* 2014). A considerable reduction in CFCs was recorded in 2015, reaching 120 Gg compared to 1100 Gg/year in 1988 (Figure 6). Even though most national reports showed near-zero emissions, measurements also revealed an increase in

CFC-11 (*Montzka et al*. 2018; *Rigby et al*. 2019), which drew attention to the effectiveness of the Montreal Protocol (*Lickley et al*. 2020)

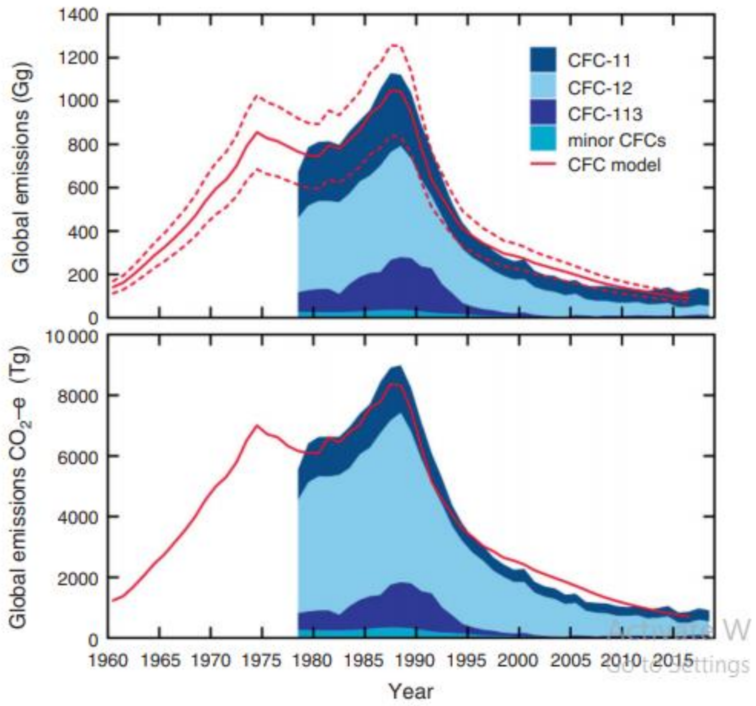

Figure 6. Global CFC emissions between 1969 and 2018 (*Fraser et al*. 2020).

2-3 Greenhouse Gas Emissions from Soil

Soil serves as a source and sink for GHGs (*Oertel et al*. 2016). Researchers have reported that the amount of total carbon stored in the top soil layer (1m) is around 1500 Pg, while the total stored nitrogen is 136 Pg (*Schaufler et al*., 2010, *Oertel et al*. 2016). Nonetheless, soils emit about 98 Pg C a^{-1}, which is higher than fossil fuel consumption (*Bahn et al*. 2020). By 2030, the IPCC (2007) projected an increase in N_2O and CH_4 from the agricultural sector of 30-60% and 60%, respectively, due to an increase in world population and food demand.

The GHGs budget reveals that 35% of CO_2, 47% of CH_4, 53% of N_2O, and 21% of NO is emitted from soil (IPCC, 2007). There are three different sources of GHGs in the soil, CO_2 sources could be divided into three sources: 1) respiration of soil (roots and biota), 2) ecosystem respiration (aboveground plants), and 3) net exchange in the ecosystem (respiration – photosynthesis) (*Oertel et al*. 2016). Anaerobic conditions enhance the production of CH_4 by methanogenesis (anaerobic bacteria) (*Fenchel et al*. 2012). N_2O is mainly produced in the soil through nitrification and denitrification (*Oertel et al*. 2016). Anaerobic conditions with high C and high concentrations of NO_3^- accelerate the reduction of NO_3^- to N_2O and N_2 (i.e. denitrification) (*Horváth et al*. 2008, *Kavehei et al*. 2020; Gold et al. 2019). However, aerobic conditions lead to the oxidation of NH_4^+ to produce N_2O (*Oertel et al*. 2016).

GHG emissions from soil are related to many processes and affected by many driving factors, which can be summarized as follows (Figure 7):

1- **Soil moisture (M_{soil})**: M_{soil} is one of the leading factors that controls soil emissions, due to the fact that M_{soil} controls both the C-cycle and the N-cycle. For instance, when M_{soil} is less than 10%, the NO emissions decrease significantly (*Brümmer et al*., 2008). Similarly, an increase of M_{soil} soil above 30% accelerates N_2O emissions, with an optimum situation in which 60% of the soil pores are filled by water (*Gao et al*. 2014). In a similar context, CO_2 emissions are reported to be higher when 20-60% of the soil pores are filled by water (*Wang et al*. 2011). On the contrary, CH_4 sinks into the soil when aerobic conditions are dominant (*Dutaur, and Verchot* 2007); however, rice production areas and wetlands are the main sources of CH_4 (*Wang et al.* 1996, *Hwang et al*. 2020).

2- **Soil temperature (T_{soil})**: an increase in T_{soil} leads to an increase in soil emissions due to the enhancement of microbial metabolism (*Oertel et al*. 2016). Many researchers have noticed an exponential relation between an increase in T_{soil} and NO and CO_2 emissions (*Tang et al*. 2003). Similarly, an increase in T_{soil} results in an exponential increase in N_2O emissions, while the consumption of CH_4 increases linearly (*Mosier et al*. 1996). Also, an increase by 5°C of T_{soil} accelerates CO_2 emissions by 25–40% (*Rustad and Fernandez* 1998). Field research studies have shown that seasonal changes in T_{soil} and M_{soil} lead to seasonal changes in soil GHG emissions (*Schaufler et al*. 2010), whereas the highest emissions recorded in summer seasons (peak) (Kitzler et al. 2006) are considered an optimal M_{soil} value. However, once M_{soil} decreases, CO_2 and N_2O fluxes are inhibited directly (*Toro and Harsányi* 2019; *Garten et al*., 2009, *Schaufler et al*. 2010). It is important to highlight the contradictory results regarding the dynamic interaction between soil systems and added fertilization in terms of GHG emissions (*Wang et al*. 2011), which can mainly attribute to M_{soil} (*Liu et al*. 2008), and T_{soil} (*Moore and Dalva* 1993). However, M_{soil} along with T_{soil} explains 86% of the total variance of N_2O emissions, and 74% of the total variance of N_2O emissions (*Schindlbacher et al*. 2004).

3- **Site specific criteria (S_p)**: *Sp* extends to include location, topography, elevation, and cover, which all together affect M_{soil} and T_{soil}. For instance, N_2O emissions are higher in lowlands or mountain foothills than on slopes and hills, due to the accumulation of soil moisture, which is higher than in other landscapes (*Oertel et al*. 2016).

4- **Exposure to fires**: fires in any ecosystem can affect the GHG budget, where burning areas show lower flows of carbon dioxide and nitrous oxide compared to unburned areas one month after fire (*Kim*, 2013).

5- **Soil pH**: this factor affects microbial activity; thus, it influences total GHG emissions from soil. Low emissions have been reported in acidic soil (*Oertel et al*. 2016). Scientifically, moderate pH (pH neutral) is optimal for GHG emissions. CO_2 emissions are higher in neutral pH than other pH-values (*Čuhel et al*. 2010), however CH_4 production needs pH values between 4 and 7 (*Dalal and Allen* 2008). Interestingly, *Pilegaard et al*. (2006) reveals an absence of a correlation between NO and N_2O and pH.

6- **Soil nutrient availability** (N_{soil}): the availability of C and N play an important role in GHG emissions from soil, as both of them are essential for microbial respiration. The interaction between different soil gases and nutrients can be summarized as follows:

- A negative correlation between N_{soil} (i.e. C/N) and N_2O emissions; the optimum value for releasing N_2O is C/N= 11 (Pilegaard et al. 2006)
- Low pH values and drought, besides C/N<20, N_2O emissions can be significantly curbed (*Christiansen et al.* 2012)
- Application of N fertilization and conventional tillage increases N2O emissions (*Malhi et al*. 2006)
- Application of animal manure increases CO_2, and N_2O emissions, while a mixture of manure and inorganic fertilizer significantly increases CH_4 uptake (*Deng et al*. 2020)

- A positive correlation between ***N_{soil}*** (i.e. C/N) and CO_2, and CH_4 emissions; the optimum value for releasing N_2O is C/N= 11 (*Pilegaard et al*. 2006)
- On a global scale, a positive relation between increases in reactive N from the atmosphere or fertilization and CH_4 in the atmosphere (*Zheng et al. 2006*)

7- **Land cover** (***LC***): *LC* extends to include vegetation type and age, which directly affect soil respiration. Young trees are recorded to have high soil respiration, which decreases gradually with stand age; this point can be explained by the loss of young hair roots (*Oertel et al*. 2016). Mixed *LC* trees and grasslands, with variety of *C3* and *C4* have led to an increase in C-sinks in the soil (*Fornara and Tilman* 2008)

8- **Land use and land use changes** (***LULUCs***): changing the terrestrial ecosystem from one land use to another alters the carbon budget and leads to an increase in GHG emissions. For example, in the last few decades forest and peat lands have been transformed into agricultural land, which has led to a tremendous loss of soil carbon, estimated to be over 30% of the total carbon in the top soil layer (70 mm) (*DeGryze et al.* 2004).

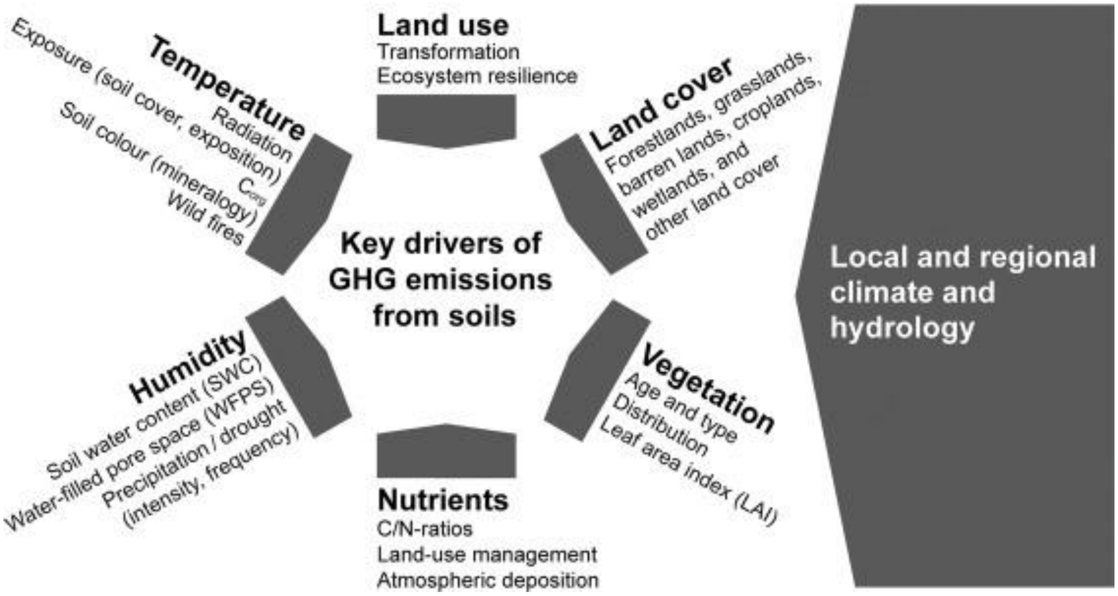

Figure 7. Schematic illustration of driving factors controlling soil GHG emissions, as proposed by *Oertel et al. (2016)*

In natural ecosystems, there is no single factor that determines GHG emissions from soil, but the above-mentioned factors interact with each other to reach the final yield of total emissions. However, these factors have been separated in order to give a comprehensive view of their various roles in this process.

2-4 Impact of climate change on the agricultural sector

The agricultural sector as a complex agroecosystem is affected by ongoing CC, directly or indirectly. On one side, the enrichment of the atmosphere by CO_2 enhances plant growth, while on the other side the accumulation of GHGs in the atmosphere leads to extreme climate events (drought, flood, extreme events, etc.) which minimize agricultural production. Recently, many studies have assessed the impact of climate change on agricultural sectors in many parts of the world, for instance, in China (*Zhong et al*. 2019), the Nordic area (*Wiréhn et al*. 2018), California- USA (Pathak ET AL. 2018), the Himalayas (*Bocchiola et al*. 2019), Taiwan (*Huang et al*. 2020), Egypt (Mahmoud 2017), Syria (*Mohammed et al*. 2020), and Hungary (*Mohammed et al.* 2020; *Gaál et al*. 2014, *Li et al*. 2017). Aggarwal et al. (2009) summarized the impact of CC on different components of agroecosystems, as is shown in Table 1.

Table 1. CC impacts on different agroecosystem components

Agroecosystem components	**Factor**	**Evaluation**	**CC impacts**
Crop	CO_2 enrichment	+	Enhanced photosynthesis especially for C3 crops (i.e. wheat, rice)
	Yield	-	Decrease in grain-filling duration, due to decrease in rainfall (R), as well as, increase in evapotranspiration and extreme events.
	Rainfed system	-	Reduction in R due to climate shifting
	Product quality	0	May be affected
	Pest and diseases	+	Climate shifting leads to rapid pathogen transmission and invasion of new areas.
	Biodiversity	–	Increase in temperature (T) and decrease in R amounts
Water	Irrigation	+	Increase in T and decrease in R amounts
	Runoff	+	Increase in extreme events
	Water balance	-	Change in climate variables
	Groundwater	-	Less rainfall

Soil	Organic matter (OM) content	-	Rapid mineralization of OM
	Plant residual decomposition	-	Elevated CO_2 leads to high C/N
	T_{soil}	-	Rapid mineralization of OM
Livestock	Feed and fodder	-	Decrease in production, water scarcity and increase in T
	Disease	+	Climate shifting
	Production	-	Heat stress
Fisheries	Breeding and migration	-	Increase in T
	Production	-	Increase in T

Moreover, the productivity of the different agricultural sectors in terms of ongoing CC is another relevant question. It was well established that agricultural production is very sensitive and vulnerable to CC (*Zhong et al*. 2019), and the impact of extreme climate events and CC on agricultural production has been well recognized. For instance, a sudden increase in temperature hastened wheat maturation in India (2004), leading to a production loss of 4 million Mg. A similar event was also observed in 2009-2010 which caused a loss of 6% of wheat production in north-eastern India (*Aryal et al.* 2016). *Asseng et al.* (2011) reported a reduction in wheat yield of 10% in Australia, and 15% in the United States annually due to rising temperatures during the grain filling stage and anthesis. An extreme rainfall event in China (1988) flooded 21 Mha, causing damage of US$20 billion (*Piao et al.* 2010). Lower maize yields in southern and central Europe (Hungary, Romania, Bosnia) are closely connected with low rainfall and high temperature (*Kovacevic et al*. 2013). Interestingly, *Huzsvai et al*. (2020) emphasize that increasing of heat stress units due to climate change badly affected maize yield over Hungary.

The future climate is projected to cause a significant reduction in crops in South Africa (30% for maize) and South Asia (10% for basic foodstuffs (i.e. rice), and reductions of more than 10% for some other crops like maize (*Lobel et al.* 2008). An increase in temperature of 1-3 degrees Celsius may increase crop productivity in medium to high latitudes. Crop production in lower latitudes will be affected negatively by temperature change. Moreover, shifting climates have enhanced outbreaks of pests and diseases (*Chakraborty and Newton*, 2011; *Garrett et al.* 2016). Along the same lines, *Alcamo et al.* (2007) estimated that about 82–139 million people in the 2070s will suffer from food production shortfalls in Russia. However, *Deryng et al.* (2014) concluded that the projected climate indicates an increase in extreme events, which are expected to adversely affect crop yields and global food production. Thus, a climate adaptation plan is a necessary step for minimizing the negative impacts of climate change on the agricultural sector.

2-5 Drought as an indicator of climate change

Assessing the economic impacts of CC is difficult, because of the complexity of the relationship between CC, local society and the global economy (*Hallegatte et al*. 2011). The IPCC announced a decrease in the number of cold days and an increase in warm days, which reveals a warmer trend of the earth's temperature; meanwhile, drought intensity and duration are more likely to increase (*Solomon et al*. 2007). Besides, researchers from different parts of the world have noticed a positive increase in the earth's temperature of 0.5°C during the 20th century, which was to be the warmest century of the last five (*Pollack et al*. 1998). In a related context, *Dai* (2011) reported an increase in earth's surface temperature by 1–3°C between 1950 and 2008 (Figure 8a), while precipitation decreased (Figure 8b), and river runoff also decreased (Figure 8c). Notably, *Romanovsky et al*. (2002) reported an increase in the permafrost temperature in the Arctic region by 2 to 4°C in the last century.

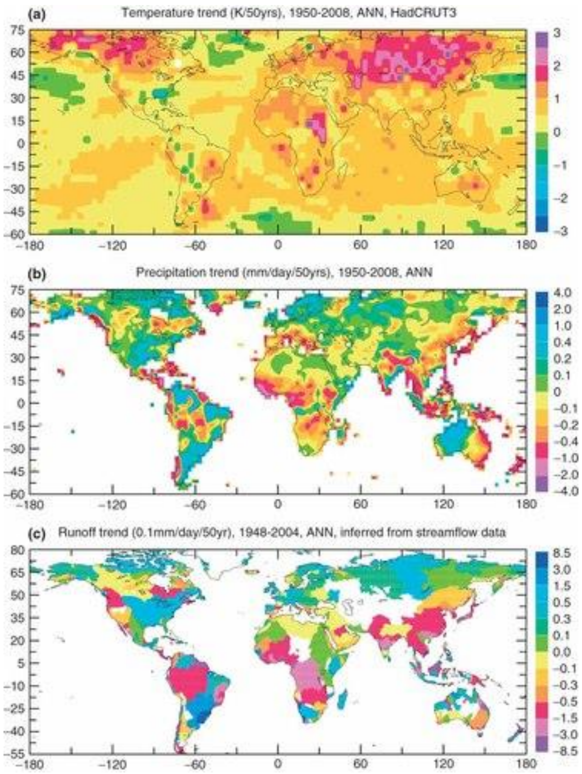

Figure 8. Trends in T(a), P(b), and runoff (c) between 1950 and 2008, as presented by *Dai (2011)*

As a complex phenomenon, drought is markedly affected by CC, and has begun to affect new terrestrial ecosystems all over the world, which will have huge impacts on vegetation cover and the carbon cycle (*Mohammed and Harsányi* 2019; *He et al*., 2018). On a global scale, of all-natural disasters drought is reported to be the costliest one. Between 1900 and 2011 drought killed around 11 million people and badly affected approximately 2 billion people (*Mohammed and Harsányi* 2019; *Ivits et al*. 2014). Notably, the impact of drought has been amplified over the last decade (1999-2010) which has affected more than 900 million people (*Spinoni et al*., 2014). *Dai* (2011) concludes that average drought damages range between $ 6 and 8 billion per year in the USA alone. Drought events cost California $2.2B, among them agricultural losses calculated at $810M (*Berg and Sheffield* 2018). Moreover, between 1949 and 1995 drought events cost China more than US $12 billion (*Dai et al*. 2020). Along the same lines, *Mehrabi, and Ramankutty*, (2017) estimated the loss of global crop production due to drought and heat events between 1961 and 2014 at $237 billion.

Europe is one of the continents that has witnessed the evolution of drought as a direct consequence of a rapid increase in GHGs emissions. Between 1976 and 2006 drought damages exceeded 100 billion Euros (*Van Huijgevoort et al*. 2012). Interestingly, drought has cost European Union countries € 5.3 billion per year since 1991 (EU 2007). However, the immense impact of drought events in 2003 cost the EU at least € 8.7 billion (*EU* 2007; *Feyen, and Dankers* 2009).

Tracking extreme events over Europe reveals that southern Europe is more vulnerable to extreme drought events in terms of intensity, frequency, duration, and severity, especially the Carpathian region (*Spinoni et al*., 2018). Northern Europe, however, is subjected to increasing rainfall and a wetter climate (*Kingston et al*., 2015). However, these changes have affected river flow, ecosystems, and catchment due to water stress in different parts Europe, due to an increase in drought episodes (*Feyen, and Dankers* 2009; *Ivits et al.*, 2014). Unfortunately, the projected climate over the EU indicates changing rainfall patterns, higher temperatures, and an increasing probability of extreme climate events and drought episodes (*Beniston et al*., 2007).

In terms of carbon emissions, drought, heat waves and other extreme climate events alter the carbon cycle and lead to a huge amount of soil carbon (sink) being released into the atmosphere (*Sippel et al.* 2018). For instance, the heat waves and drought that hit Europe in

2003 affected the C-cycle and led to the loss of four years of accumulated carbon in the terrestrial ecosystem. The losses are estimated to be 0.5 PgC (*Ciais et al.* 2005), equivalent to half of human CO_2 emissions in 2015 (EU-28) (0.99 PgC) (*Sippel et al*. 2018). This dramatic change in the C-cycle (i.e. sink vs. release) draws attention to the importance of climate adoption and mitigation measures, and to the interaction between extreme climate events, especially drought and C-cycle feedbacks (*Sippel et al*. 2018).

2-5-1 The definition of drought

The simple definition of drought is a significant decrease in precipitation below the average for a sustained period (*McKee et al*. 1993). There is no unified definition of drought, due to the peculiarity of each geographical area and the different stages of drought evolution from one region to another as a result of the complex interaction between different ecosystem components and climate variables (*Olukayode* 1985, Soule 1990, *Tate and Gustard* 2000).

Numerous efforts have been made by international organizations to define drought incidents and the potential responses, based on different criteria (Table 2). However, an absence of a precise definition of drought in specific cases is an obstacle to tackling drought, and taking appropriate actions (*Wilhite* 2000). Since the importance of drought lies in its consequences and the damage it causes (Figure 9), an accurate definition of drought at a regional scale is a necessary step towards reducing the consequences, and drawing up an appropriate action plan (*Wilhite and Glantz* 1985, *Wilhite* 2000).

Table 2. Criteria for drought definition by different international organizations

Organization	**Criteria for drought definition**	**Reference**
World Meteorological Organization	Rainfall deficiency for a continued period of time	*WMO*, (1986)
Secretary-General of the United Nations	Links between rainfall and land resource production systems	*UN Secretariat General*, (1994)
Food and Agriculture Organization	Links between soil moisture and crops failure	FAO, (1983)

By surveying the literature, *Wilhite and Glantz* (1985) identified six drought categories: 1) agricultural, 2) meteorological, 3) atmospheric, 4) hydrologic, 5) climatological, and 6) water management. *Tate and Gustard* (2000) divided drought into five groups: 1) Climatological, 2) Agro-meteorological, 3) River flow, 4) Ground-water drought, and 5) Operational.

Typically, drought can be categorized into four groups, which are explained in different dimensions, as follows:

1- ***Meteorological drought (MD)***: can also be referred to as climatological drought, and is recognized as the origin of other drought types (Guo et al. 2020). MD is caused by a deficit in precipitation over a considerable period of time (*Spinoni et al*. 2020). However, MD is magnified by other climate factors such as wind, evapotranspiration and temperatures (*Wilhite and Glantz* 1985)

2- ***Agricultural drought (AD)***: mainly refers to a deficit in soil moisture, which leads to direct failures in meeting crop water requirements, causing tremendous damage to crop production (*Sánchez et al.* 2018, *Hu et al.* 2020). Among different drought types, AD is regarded as the only one that has an immediate and direct impact on the ecosystem (*Martínez-Fernández et al*. 2016). The severity of AD is determined by many factors, such as: 1) plant characteristics, 2) weather conditions, 3) plant phenological stage of growth, and 4) soil properties (soil texture, soil organic matter, field capacity, water holding capacity). When dealing with AD it is important to take into consideration the plant growth stage and soil deficit layer. For instance, if the soil water deficit appears in the subsoil, and the plant(s) in a germination stage there is no impact of AD on plant growth or yield. However, the economic impact of drought first appears in the agricultural sector, as soil moisture is quickly depleted (*Wilhite* 2000).

3- ***Hydrological drought (HD)***: refers to a deficit in surface and/or subsurface water in comparison with the normal situation (i.e. below the long-term average) for a given period in the past (*Boergens et al.* 2020). Usually, HD develops slowly as it needs time to be discovered in the ecosystem (e.g. reservoirs, groundwater). Notably, HD occurs at a later stage together with other forms of drought (i.e. MD, AD).

4- ***Socio-economic drought (SED)***: refers to the failure of the ecosystem to meet the water demands to produce a particular economic good. For instance, an increase in population increases the demand for some good (hydroelectric power, water), so when the demand exceeds the supply due to weather conditions or climate change, this is referred to as SED (*Sandford* 1979). The mismanagement of terrestrial ecosystems increases vulnerability to SED by increasing vulnerability to water shortages. For example, overgrazing in marginal ecosystems (i.e. semiarid regions: South Africa, Australia) increases soil erosion and minimizes animal carrying capacity, which intensifies the consequences of and vulnerability to future droughts (*Wilhite* 2000)

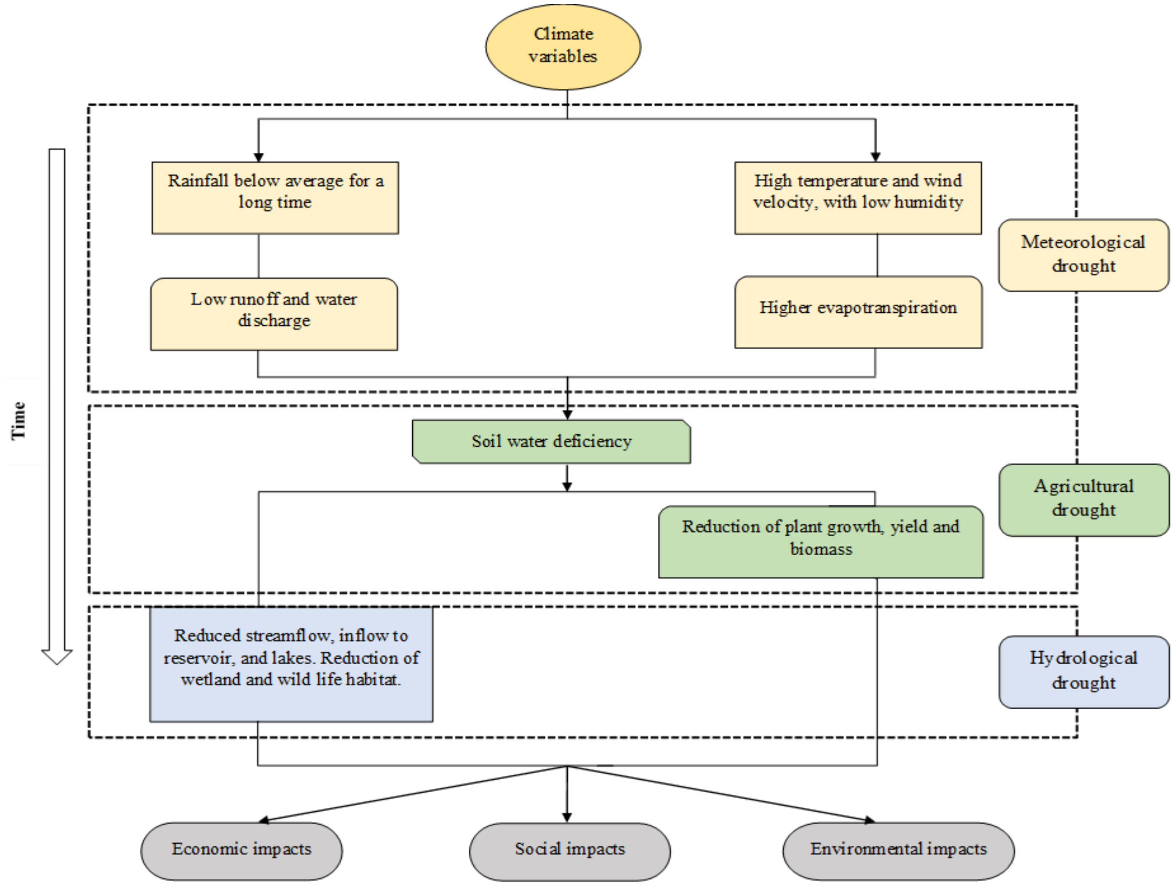

Figure 9. Drought classification and impacts (adapted from *Wilhite* (2000))

2-5-2 Drought indices

As one of the serious natural hazards, more than 150 indices have been developed for tracking the evolution, duration, severity and intensity of droughts through different time scales (*Zargar et al*, 2011; *Alsafadi et al.* 2020). Drought indices vary in their complexity; some need only rainfall data to give a comprehensive overview of drought in a given region, while others utilize temperature, evapotranspiration, and water resource supply. Nevertheless, all drought indices serve as a good tool for drought monitoring and preparing a road map to overcome the consequences of drought. However, *Eslamian et al*. (2017) recommended applying multiple indices to explore drought situations before the adaptation of any plans.

Drought *indices* is a quantitative approach that defines drought levels based on data from one or several sources (i.e. *indicators*), such as R, ET_0, and T. This transformation from *indicators* (raw data) to *indices* (real combined values) facilitates the possibility of understanding drought levels and potential impacts. A comprehensive overview of the common drought *indices* is presented in Table 3.

Table 3. Some drought indices

Drought indices	Abbreviation	Reference	Input parameters	Disadvantage	Application	Reference
Palmer drought severity index	PDSI	Palmer (1965)	• Rainfall, • Temperature, • Local water content	• Underestimation of Runoff. • Responding slowly to dry spell evolution	China	*Zhang et al*. (2019)
					Iran	*Dehghan* et al. (2020)
					Mongolian Plateau	*Shi et al*. (2020)
					Europe	*Briffa et al*. (1994)
Standardized precipitation index	SPI	McKee et al. (1993)	• Rainfall	• Availability of monthly R data for a long period. • Depends only on R and neglected other factors	Syria	*Mohammed et al*. (2020)
					Hungary	*Mohammed et al*. (2020)
					China	*Li et al*. (2020)
					Mongolian	*Pei et al*. (2020)
					India	*Bhunia et al*. (2020)
Standardized precipitation evapotranspiration index	SPEI	Vicente-Serrano et al. (2010)	• Rainfall, • Temperature, (ET_0)	• Using Thornthwaite equation for calculating potential ET_0	China	*Li et al*. (2020)
					Mongolian	*Pei et al*. (2020)
					Argentinian	*Bohn et al*. (2020)
					Turkey	*Danandeh et al*. (2020)
Soil moisture deficit index	SMDI	Narasimhan, and Srinivasan (2005)	• Soil moisture • Land cover • Soil type	• Input data not easy to acquire	China	*Chen et al*. (2020), *Bai et al*. (2018)
					Brazil	*Paredes-Trejo and Barbosa* (2017)
Vegetation condition index	VCI	Kogan, 1995	NOAA-AVHRR NDVI data	Not applicable in winter time	India	*Singh et al*. (2020)
					China	*Liang et al*. (2017)
					United States	*Jiao et al*. (2016)
					Chile	*Zambrano et al*. (2016)
					India	*Dutta et al*. (2015)
					Greece	*Domenikiotis et al* (2004)

2-5-3 Hungary and climate change:

In central Europe, drought incidents have become more active and larger, correlated with raised temperatures and shortages of rainfall, as reported by many researchers, including *Bartholy et al.* (2013) in Hungary, *Kern et al.* (2016) in Central Europe, and *Cheval et al.* (2014) in Romania.

As in other European countries, Hungary is subjected to CC, where drought episodes have started to hit Hungary regularly in the last few decades, causing diverse impacts in different sectors (*Csete et al*., 2013, *Gálos et al*., 2007). Interestingly, *Gálos et al*. (2007) projected that drought events would continue to hit Hungary until the end of the 21st century, with a special tendency in summer. Within this context, heatwave cycles were reported to have increased in the Carpathian Region (including Hungary), while cold waves were shorter and less frequent (*Spinoni et al.* 2015). *Sábitz et al.* (2014) recommended urgent mitigation and adaptation measures over the whole Carpathian Region to mitigate the region's positive drought trend.

Since CC, and particularly drought, represents a significant threat to Hungarian terrestrial ecosystems, many researchers have addressed this issue and its impacts from different perspectives. For instance, an increase in the Hungarian ecosystem's vulnerability to drought due to CC was reported by *Blanka et al.* (2013). Similarly, *Kocsis and Anda* (2017) reported a remarkable decrease in the average rainfall in Keszthely. *Domonkos* (2003) noted a significant reduction of rainfall in the summer season, associated with increased drought events. Future precipitation (i.e. 2070-2100) over Hungary will be subjected to a substantial change, with summers becoming drier (*Bartholy et al.* 2013). Unpredictably, *Kertész* (2016) debated whether Hungary will be prone to desertification due to climate change.*Alsafadi et al.* (2020) used the CARPATCLIM database and analyzed drought intensity and severity (1961–2010) and reported that the southern part of Hungary is more vulnerable to drought, while drought events were less pronounced in the north-eastern region. However, the frequency of drought was concentrated in the central part of Hungary. *Mohammed et al*. (2020) used the SPI-3 (i.e. agricultural drought) to analyze drought in the eastern part of Hungary from 1950 to 2010 and discovered 103 events of severe agricultural drought and a positive ($p < 0.05$) correlation between SPI and NDVI (Figure 10). *Mohammed et al*. (2019) reported that the drought in 2011 was the worst - especially in Siófok – during the reference period 1985-2016. Meanwhile, *Makra et al.* (2002) reported that over the last few decades, Hungary has witnessed drier conditions, comparing with the early years of the last century – i.e. between 1901 and 1940 - when wetter conditions were recorded. In that same context, *Szép et al*. (2005) highlighted that drier soil conditions were observed in the 20th century.

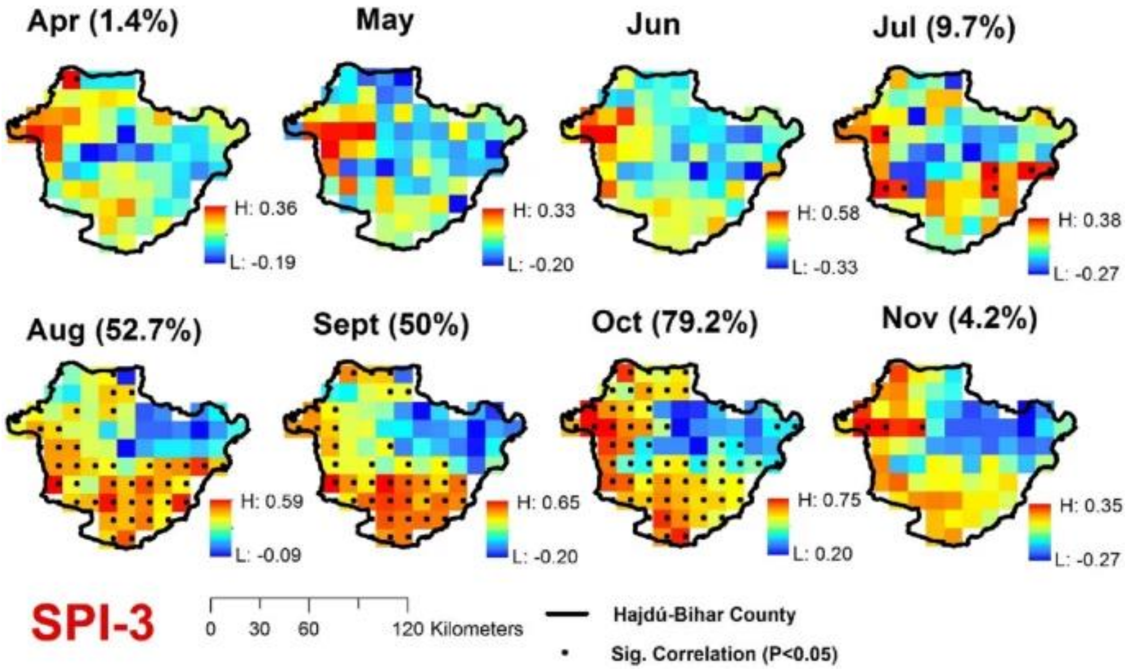

Figure 10. Correlation between SPI and NDVI (1981 - 2010) (*Mohammed et al*. 2020)

Hungary's agricultural sector is vulnerable to drought; 36% of all agrarian losses (1983-1995) are caused by drought episodes (*Szinell et al*. 1998). Also, drought and heatwaves affect crops in the Great Plain of Hungary with a significant yield loss (40-50%) (*Fiala et al*. 2014). Unfortunately, a massive drought event in 2003 cost Hungary more than 55 billion HUF (*Puskás et al*. 2012). Even though climate models are effective tools for capturing CC, the accuracy of these models in capturing CC on a regional scale is questionable (*Reyes-García et al*. 2016). Thus, one of the main goals of this research was to investigate climate change on a regional and subregional scale in Hungary between 1960 and 2020. Although many studies have dealt with CC change, to the best of the author's knowledge, none have used SPI and SPEI to track drought in Hungary.

3. Material and Methods

3.1. Study framework

Few studies were tried to link GHGs emission and climate change on different dimensions. In central Europe, many researches were conducted to track climate change, GHGs emission, climate policies, and mitigations plans. However, there is a few attempts to compile the GHGs emission and climate change (i.e. drought) in a regional scale. In this regard, the dimension of this research varies from the continental scale (Europe) to the farm scale (Tehran and Debrecen). This research was designed to track GHGs emissions from agricultural sector in EU countries, then at the Hungarian level (country level), and finally on a local scale (i.e. Tehran and Debrecen). Also, the consequences of rapid increase in GHGs emissions all over the world were addressed through analysing drought trend, variability and duration over Hungary between 1960-2010. The novelty of this scientific work could be highlighted through summarizing GHGs emission from the agricultural sector over EU and Hungary, and providing the first analysis about drought trend over Hungary and its impact on agricultural sector. It is good to mention here that the comparative experiment was chosen to give first insights about the difference in CO_2 emission between two different climate regions, where the agricultural activities almost similar.

3.2. Data collections

GHGs emissions available data in thousands of tonnes of CO_2 equivalent were collected from The Organization for Economic Co-operation and Development (OECD) website (I2), for EU countries (Austria; Ireland; Portugal; Slovenia; Estonia; Greece; Luxemburg; Italy; Spain; Belgium; the Czech Republic; Denmark; Finland; France; Germany; Hungary; Latvia; Lithuania; Netherlands; Poland; Slovak Republic; Sweden). Data included: GHGs emissions by countries, GHGs emissions by agricultural and energy sectors. For tracking GHGs emissions from different sectors in Hungary, the GHGs emissions data (thousand tonnes) was obtained from the Hungarian Central Statistical Office (1985-2016) (I3). The total cultivated area and total production of maize, and wheat from 1960 to 2016 for Hungary were collected from (I4); also, the available data on a county scale was collected for 2000 to 2018. The standardized precipitation index (SPI), and the standardized precipitation evapotranspiration index (SPEI), were collected from the Climate of the Carpathian region project-CARPATCLIM platform (1961-2010) *(Szalai and Vogt*, 2011, *Szalai et al*. 2013). In this database Hungary was covered by 1045 gridded points (at spatial resolution: 0.1°x 0.1°

grid (10 km × 10 km)), as shown in Figure 11. Each grid represents the SPI/SPEI values over 3-, 6-, and 12-months in the form of a two-dimensional array. The data quality and homogeneity were ensured by the CARPATCLIM team (*CARPATCLIM*, 2012).

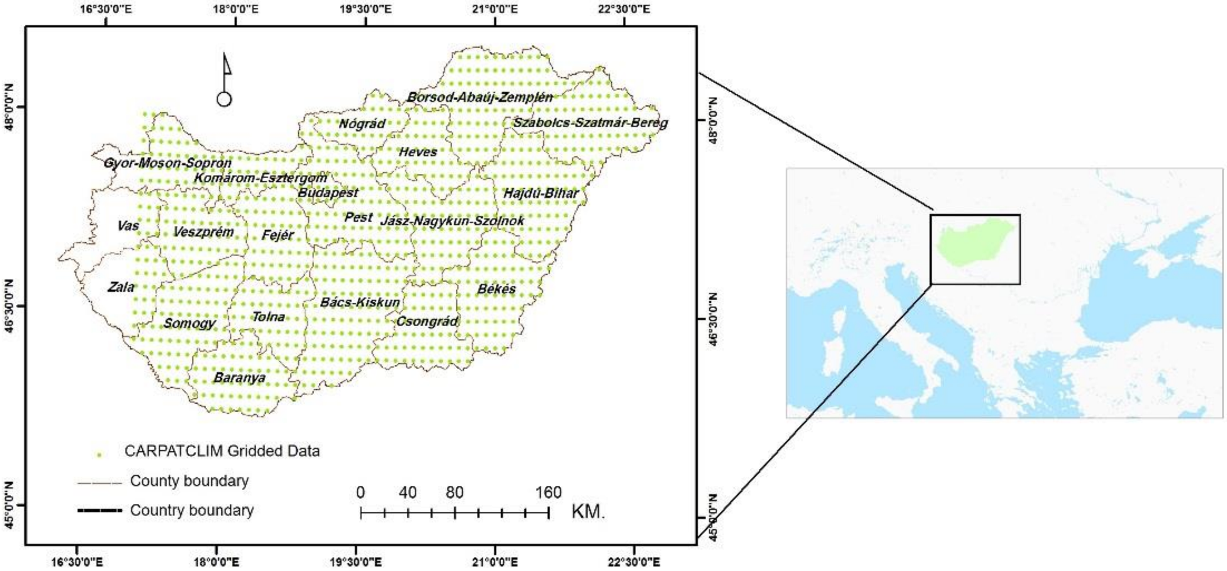

Figure 11. Location of Hungary in Europe (right) and the distribution of climate gridded points over Hungarian counties**.**

3.3. Data analyses

3.3.1. Trend analysis using the Mann-Kendall test

Trend of GHGs emission was analyzed using the Mann–Kendall (MK) test (Kendall, 1975; Mann, 1945). The MK test is a non parametric test with no-assumptions about data distribution which calculated as follow:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} singn(x_j - x_k) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. \mathbf{1}$$

S: MK test statistics, x_j, x_k annual values for studied varible in years j and k (j > k).

Also, Sen’s slope method (Sen, 1968) was applied to estimate the value of change by time (i.e. slope), which calculated as follow:

$$q_i = \frac{x_j - x_k}{j - k} \; for \; i = 1,2,3 \ldots . n \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \mathbf{2}$$

3.3.2. Correlation analysis

In this research we used the Pearson correlation coefficient (r) to analyse the statistical relationship between two or more variables, and this gives further information about the direction of the correlation (i.e. positive, negative). The Pearson correlation coefficient (r) can be expressed as follows:

$$r = \frac{\sum_{i=1}^{n}(x_i - \bar{x})\,(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2}\,\sqrt{\sum_{i=1}^{n}(y_i - \bar{y})^2}}$$

where x_i, y_i (i = 1, 2, 3, . .. , n) is the time series variability of the studied variables, and $\bar{x}$ and $\bar{y}$ are the averages of the time series.

Notably, r < 0 indicates a negative correlation, whereas r > 0 suggests a positive correlation

3.3.3. Fisher's Least Significant Difference (LSD)

To analyse the mean for the principal bunch with different other ones, the Fisher's Least Significant Difference (LSD) was used. The LSD approach is applied in ANOVA analysis. So, in case of showing a significant result, it reveals that in any case one variable significantly different from the others (*Williams, and Abdi*, 2010).

3.3.4. The Mann–Whitney U test

The Mann–Whitney U test is a multivariate, non-parametric test (*Peterson et al*. 1990) recognized as an alternative to the t-test, if its assumptions are not met. In this test, H_0 indicates the absence of any statistical difference between the two averages of studied groups (variables). In contrast, H_1 states a significant difference between the two averages of studied variables (*Giammanco et al*. 2009). In this research we use the Mann–Whitney U test to detect whether the studied variables varied significantly from each other or not.

3.4. Drought analysis

3.4.1. Drought indices SPI and SPEI

The well-known indices SPI and SPEI were employed for drought analysis over Hungary. The SPI is based on gamma distribution and can be calculated as follows (*Mc Kee et al*., 1993):

$$g(x) = \frac{1}{B^{a}\acute{\Gamma}(a)} x^{a-1} e^{-x/B} \qquad for\ x > 0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots .. \mathbf{3}$$

where: $g(x)$: gamma probability density function (pdf), x Rainfall, a: shape parameter (a> 0), B: scale parameter (B> 0), $\acute{\Gamma}(a)$: the gamma function.

Since the gamma function is not defined for zero (*x*= 0), and a rainfall distribution may contain zero values, the following function is used to calculate the cumulative probability:

$$H(x) = q + (1 - q)\, G(x) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \mathbf{4}$$

where *q* refers to a probability of a zero value and is calculated as follows:

$$q = \frac{m}{n} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \mathbf{5}$$

where m shows the number of zero values in the time series of length n.

The cumulative probability *H(x)* is transformed into a standard normal random variable Z, which is calculated as the inverse of the standard normal cumulative distribution function. Finally, to switch from gamma distribution to normal distribution as a random variable Z, we use the following equations:

$$Z = SPI = -\left(t - \frac{2.515517 + 0.802853t + 0.010328t^2}{1 + 1.432788t + 0.189269t^2 + 0.001308t^3}\right) for\ 0 < H(x) \leq 0.5 \ldots\ldots\ldots\ldots\ldots\ldots \mathbf{6}$$

$$Z = SPI = +\left(t - \frac{2.515517 + 0.802853t + 0.010328t^2}{1 + 1.432788t + 0.189269t^2 + 0.001308t^3}\right) for\ 0 < H(x) < 1 \ldots\ldots\ldots\ldots\ldots\ldots \mathbf{7}$$

$$t = \sqrt{In(\frac{1}{(H(x))^2})} \quad for\ 0 < H(x) \leq 0.5 \ldots\ldots\ldots\ldots\ldots\ldots \mathbf{8}$$

$$t = \sqrt{In(\frac{1}{1 - (H(x))^2})}\ for\ 0 < H(x) < 1 \ldots\ldots\ldots\ldots\ldots\ldots \mathbf{9}$$

where the SPI values for drought classifications are as can be seen in Table 4. The positive values indicate wet conditions, while negative values indicate drought conditions (less than median rainfall) (*Mohammed* et al. 2020; *Bordi and Sutera*, 2001)

Similarly, to the SPI, the SPEI (*Vicente-Serrano et al* 2010) uses monthly rainfall data, but also employs the impact of temperature by using the Thornthwaite equation (Thornthwaite 1948). Thus, the probability density function could be shown as follows:

$$f(x) = \frac{\alpha}{\beta}(\frac{x - \gamma}{\alpha})^{\beta - 1}\left[1 + (\frac{x - \gamma}{\alpha})^{\beta}\right]^{-2} \ldots\ldots\ldots\ldots\ldots\ldots \mathbf{10}$$

where $\boldsymbol{\alpha}$, $\boldsymbol{\beta}$, and $\boldsymbol{\gamma}$ are parameters related to the equation. With some mathematical steps, SPEI can be defined as:

$$SPEI = W - \frac{C_0 + C_1W + C_2W}{1 + d_1W + d_2W^2 + d_3W^3} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \mathbf{11}$$

C_0, C_1, C_2, d_1, d_2, d_3 are constants and can be obtained from *Vicente-Serrano et al* (2010), and SPEI values for drought classifications can be seen in Table 4.

Table 4. Drought categories based on Agnew's scheme (*Mohammed et al*. 2020).

SPI and SPEI values	**Drought category**
> 0	Free drought
0 to -0.5	Half drought
-0.5 to -0.84	Lower drought
-0.84 to -1.28	Upper moderate drought
-1.28 to -1.65	Up drought
> -1.65	Mega drought

In our study, the SPI and SPEI data were exported from the CARPATCLIM database, which is freely available for everyone, with the CARPATCLIM team ensuring the homogeneity of the data.

As the SPI and the SPEI are statistical indices and could be calculated for different times, e.g. 1-, 3-, 6-, 9-, or 12-month time scales, in this study we calculated the SPI and SPEI in two different time scales. For tracking the agricultural drought, the 3-, or 6-month period was chosen, while the 12-month scale was chosen for hydrological drought, as suggested by *Tan et al.* (2015).

For tracking drought trends over Hungary, SPI and SPEI 3-, 6-, and 12- month scales for the1045 gridded points (i.e. 6207 gridded points in total) for the M-K test were applied at the 95% confidence level. Also, the Sen slope was determined for tracking drought magnitudes for both hydrological and agricultural drought. For illustrating drought trends over Hungary, the results of the M-K test were keyed to ArcMap software to produce the spatial distribution of the gridded points that show significant trends, as well as the decadal changes of the SPI/SPEI-3, -6, and -12 (*Mohammed* et al. 2020).

3.4.2 Determination of drought variability

In order to determine the spatial and temporal changes in the drought pattern (i.e. the agricultural drought pattern and the hydrological drought pattern) principal component analysis (PCA, *Rencher*, 1998) was applied. PCA is one of the common multivariate statistical analysis techniques (non-parametric), which is widely used in environmental studies (*Bengraïne and Marhaba* 2003). Generally, PCA summarizes big data to a few newly representative data values called principal components (PCs) (*Mohammed* et al. 2020), where the first group of PCs (i.e. PC1, PC2, PC3, etc.) has the highest values of variance. Nonetheless this transformation is a linear one (*Mathbout et al*, 2018). Mathematically, PCA relies upon an eigenvector decomposition of the covariance or correlation matrix. In this research, a varimax rotation is performed to address the problem of variables loading moderately (or equally) on one or more of the axes. Finally, all results were keyed to GIS software for map productions.

3.4.3 Total drought duration (TDD)

TDD refers to all drought events that hit the study area (N_i) where SPI/SPEI is less than zero for a certain period of time (*Alsafadi et al*. 2020; *Fang et al*. 2018). The TDD is expressed as follows:

$$\text{TDD (\%)} = \frac{n_i}{N_i} \times 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \mathbf{12}$$

where n_i is drought events, and N_i accumulative month numbers during the monitoring period.

3.4.4. Drought impact on the Hungarian agricultural sector:

The impact of drought (i.e. agricultural drought indices (SPI-3, SPEI-3, SPI-6, SPEI-6)) on crop productivity was analysed using the Standardized Yield Residual Series (SYRS) as proposed by *Potopová et al.*, (2016), by using the following equation:

$$\mathbf{SYRS}_{\boldsymbol{c,r,y,t}} = \frac{(\boldsymbol{y}^{\boldsymbol{T}}_{\boldsymbol{c,r,y,t}} - \boldsymbol{\varphi}^{\boldsymbol{T}}_{\boldsymbol{c,r,y,t}})}{\boldsymbol{\chi}^{\boldsymbol{T}}_{\boldsymbol{c,r,y,t}}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. \mathbf{13}$$

where $\boldsymbol{c}$: crop, $\boldsymbol{r}$: region, $\boldsymbol{y}$: year, $\boldsymbol{t}$: timescale, $\boldsymbol{T}$: year, $\mathbf{SYRS}_{\boldsymbol{c,r,y,t}}$**:** Standardized Yield Residual Series, $\boldsymbol{y}^{\boldsymbol{T}}_{\boldsymbol{c,r,y,t}}$: detrended value of crop yield, $\boldsymbol{\varphi}^{\boldsymbol{T}}_{\boldsymbol{c,r,y,t}}$: mean of $\boldsymbol{y}^{\boldsymbol{T}}_{\boldsymbol{c,r,y,t}}$, $\boldsymbol{\chi}^{\boldsymbol{T}}_{\boldsymbol{c,r,y,t}}$: standard deviation of $\boldsymbol{y}^{\boldsymbol{T}}_{\boldsymbol{c,r,y,t}}$. The classification of the SYRS is given as follows (Table 5):

Table 5. SYRS classification

Yield	$\mathbf{SYRS}_{\boldsymbol{c,r,y,t}}$
Acceptable	$-0.5 < \mathbf{SYRS}_{\boldsymbol{c,r,y,t}} \leq 0.5$
Low impact	$-0.5 < \mathbf{SYRS}_{\boldsymbol{c,r,y,t}} \leq -1.0$
Upper low impact	$-1.0 < \mathbf{SYRS}_{\boldsymbol{c,r,y,t}} \leq -1.5$
Exceed impact	$-1.5 < \mathbf{SYRS}_{\boldsymbol{c,r,y,t}} < -2.0$
Mega impact	$\mathbf{SYRS}_{\boldsymbol{c,r,y,t}} \leq -2.0$

In this research we investigated the impact of agricultural drought on maize and wheat yields, by using the above-mentioned method.

After calculating the SYRS, the crop yield resilience to drought ($\boldsymbol{CYR_T}$) was analysed using the following equation (*Sharma and Goyal* 2018; *Guo et al*. 2019):

$$\boldsymbol{CYR_T = \frac{y_T^O}{y_T^d} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 14}$$

where: $\boldsymbol{CYR_T}$: crop yield resilience to drought, $\boldsymbol{y_T^O}$: observed crop yield, $\boldsymbol{y_T^d}$: de-trended yield in driest year. The classification of $\boldsymbol{CYR_T}$ is given as follows (Table 6):

Table 6. CYR_Tvalue classification

Crop yield resilience to drought	$\boldsymbol{CYR_T}$ **value**
Resilient	$CYR_T > 1$
Slightly non-resilient	$0.9 < CYR_T < 1$
Moderately non-resilient	$0.8 < CYR_T < 0.9$
Severely non-resilient	$CYR_T < 0.8$

Finally, to show the impact of agricultural drought (SPI-3, SPI-6, SPEI-3, SPEI-6) on crop yields (i.e. maize, wheat); the coefficient of determination (R^2) was carried out. For each region, the R^2 value between $\boldsymbol{SYRS_{c,r,y,t}}$ and agricultural drought (SPI-3, SPI-6, SPEI-3, SPEI-6) was obtained on a monthly scale between 2000 and 2010. Then, the maximum and minimum R^2 values were keyed to GIS to produce the correlation maps.

3.5. Comparative analysis of CO_2 emissions from two different agricultural ecosystems

3.5.1. Site characteristics and experimental design

To achieve the study goal, two different climate locations were chosen; the first one in Tehran (Agriculture Research Station of the College of Agriculture and Natural Resources, University of Tehran, Karaj, Iran) (50˚ 58′ E, 35˚ 48′ N, 1308 elevation), and the second one in Debrecen (the Latokep field, Hungary) (47° 33’ É, 21° 26’ N).

In this research, Tehran was chosen as a representative of a semi-arid climate with mean air temperature and rainfall of 13.7˚C and 245.5 mm, respectively. While, Debrecen was representative of a continental climate with mean air temperature and rainfall of 11˚C and 600 mm, respectively. Table 7 shows monthly rainfall (mm) and mean air temperature (˚C) during the experimental period in both study sites, however, experimental sites in Tehran were irrigated to meet the crop requirements of maize.

Table 7 Monthly rainfall (mm) and mean air temperature (˚C) during the experimental period in the study sites.

Month	Debrecen		Tehran (Iran)		
	Rainfall (mm)	Temperature (˚C)	Rainfall(mm)	Temperature (˚C)	Irrigation rate (mm)
Mar	12.8	8.1	120.3	8.5	0
Apr	32.6	12.4	39.2	12.3	15
May	76.4	13.6	12.7	20.6	25
Jun	32	22	0	27.3	50
Jul	98.9	20.5	0	29.5	130
Aug	15	22.2	0	26.9	130
Sep	35.3	16.3	0	22.6	130

In each climatic region, two fields under maize cultivation with contrasting management history of 1) conventional tillage (CT), and 2) no-tillage (NT) systems were selected (Fig.12). In this sense, tillage characteristics and land preparation were almost the same.

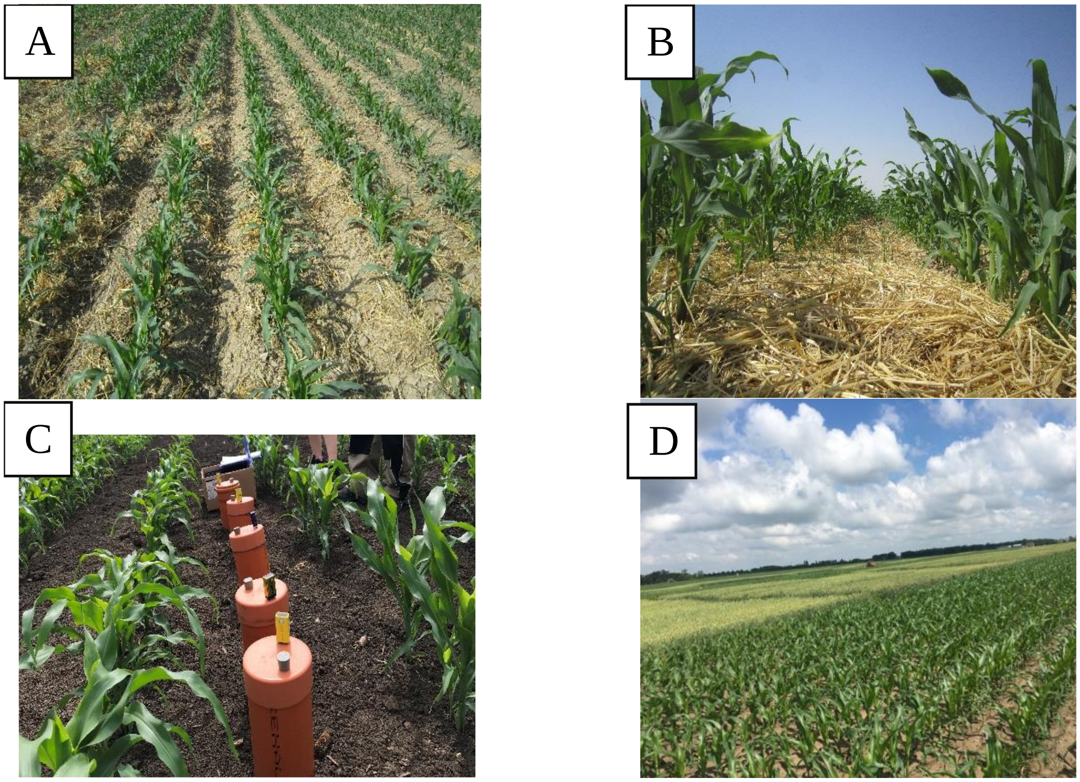

Figure 12 View of the experimental site. A) conventional tillage (CT) (Tehran), B) no-tillage (NT) (Tehran), C) CT (Debrecen), D) NT (Debrecen),

Before sowing season, soil samples (0–20cm) were collected, then analysed in the laboratory as presented in **Table 8**. The experiments were laid out as randomized complete block design (RCBD) with three replications in each climatic region.

Table 8. Soil properties of 0 – 20 cm soil depth in the fields at the studied areas

Soil properties	Debrecen (Hungary)	Tehran (Iran)
Sand (%)	11	25
Silt (%)	65	57
Clay (%)	24	18
Texture	Silt Loam	Silt Loam
pH $_{KCl}$	6.46	7.73
EC (ds m^{-1})	0.4	0.74
OM%	2.3	1.2
CaCO3%	0	1.5
Soil depth (cm)	80	80
Phosphorous mg k^1 (P_2O_5)	133	34
Potassium mg kg^{-1} (K_2O)	240	300
Classification	Calcareous chernozem/ Mollisol-Calciustoll	Xeric Haplocalcids

3.5.2. CO$_2$ Emission Measurements

Gas sampling was performed at 7–10-day intervals at each subplot based on the protocol suggested by *Parkin and Venterea*, (2010); and *Tenesaca et al*. (2015). This protocol includes GHG sampling approach for Trace Gas Flux Measurement.Hence a chamber chambers (15 cm ∅, 12.5 cm height) method was used to measure the quantity of CO_2 emission, which previously applied by Oertel et al., (2012). The chambers were mad from polyvinyl chloride (PVC) with ports for gas sampling.

In each subplot in each climate region, two chambers with tree replicants were used. One of the champers were placed between rows, while the other one was within the plant rows. After reading the emission value from each chamber in each treatment; the total emission was considered as the average from each two champers. However, to avoid the impact of soil disturbance on CO_2 emission Gas emission was harvested after 24 hours of placing the PVC champers in each subplot.

For Teheran experiments, gas emission samples were collected in the early morning between 8-10 am, then analysed by using gas chromatography in laboratory of soil science at Bouk University-Austria.

For Latokep field (Debrecen), a direct emission was measure using Testo 535 (0560 5350) CO_2 measuring instrument.

However, temperature of the soil and soil moisture content was measured directedly after each recorded data for all treatments.

4. RESULTS AND DISCUSSION

4.1. GHG emissions from agricultural sector in the EU

As a part of the UNFCCC (United Nations Framework Convention on Climate Change), the EU committed to keeping net emissions to a 10% increase beyond 1990 levels, as mentioned in the Kyoto Protocol. Thus, in this section, we will track changes in GHG emissions from the agricultural sector in the EU between 1990 and 2016 (available data), where the relevant question was “What was the trend of GHG emissions in the EU between 1990 and 2016?”. Figure13 shows a clear reduction in total emissions of GHGs from AG, especially in the last ten years. However, the M-K test and Sen's slope showed that all EU countries witnessed a remarkable reduction (Table 9). The negative but not significant trend was detected in all EU countries except for Estonia, Hungary, Iceland, Latvia, Lithuania, and Spain.

Table 9. Trends in GHG emissions (thousands of tonnes of CO_2 equivalent) from the AG in the EU between 1990 and 2016, and their significance ($P<0.05$)

EU	**Changes***	**P-value**	**EU**	**Changes***	**P-value**
Austria	-41.783	**< 0.0001**	Luxembourg	-2.4454	**0.0025**
Belgium	-109.4372	**< 0.0001**	Portugal	-22.9288	**0.0004**
Czech Republic	-113.7134	**< 0.0001**	Slovak Republic	-72.07	**< 0.0001**
Denmark	-95.0117	**< 0.0001**	Slovenia	-6.081	**< 0.0001**
Estonia	-4.4968	0.6206	Sweden	-39.3726	**< 0.0001**
Finland	-16.1237	**0.0007**	France	-229.8465	**< 0.0001**
Greece	-70.1134	**< 0.0001**	Germany	-268.7552	**< 0.0001**
Hungary	-13.1877	0.3416	Italy	-272.24	**< 0.0001**
Iceland	-0.4364	0.3631	Netherlands	-336.4756	**< 0.0001**
Ireland	-90.5264	**0.0002**	Poland	-285.5101	**< 0.0001**
Latvia	-7.2289	0.5358	Spain	-5.6002	1.0000
Lithuania	-19.403	0.1710			

** thousands of tonnes of* CO_2 *equivalent; grey colour indicates the significance level at P< 0.05.*

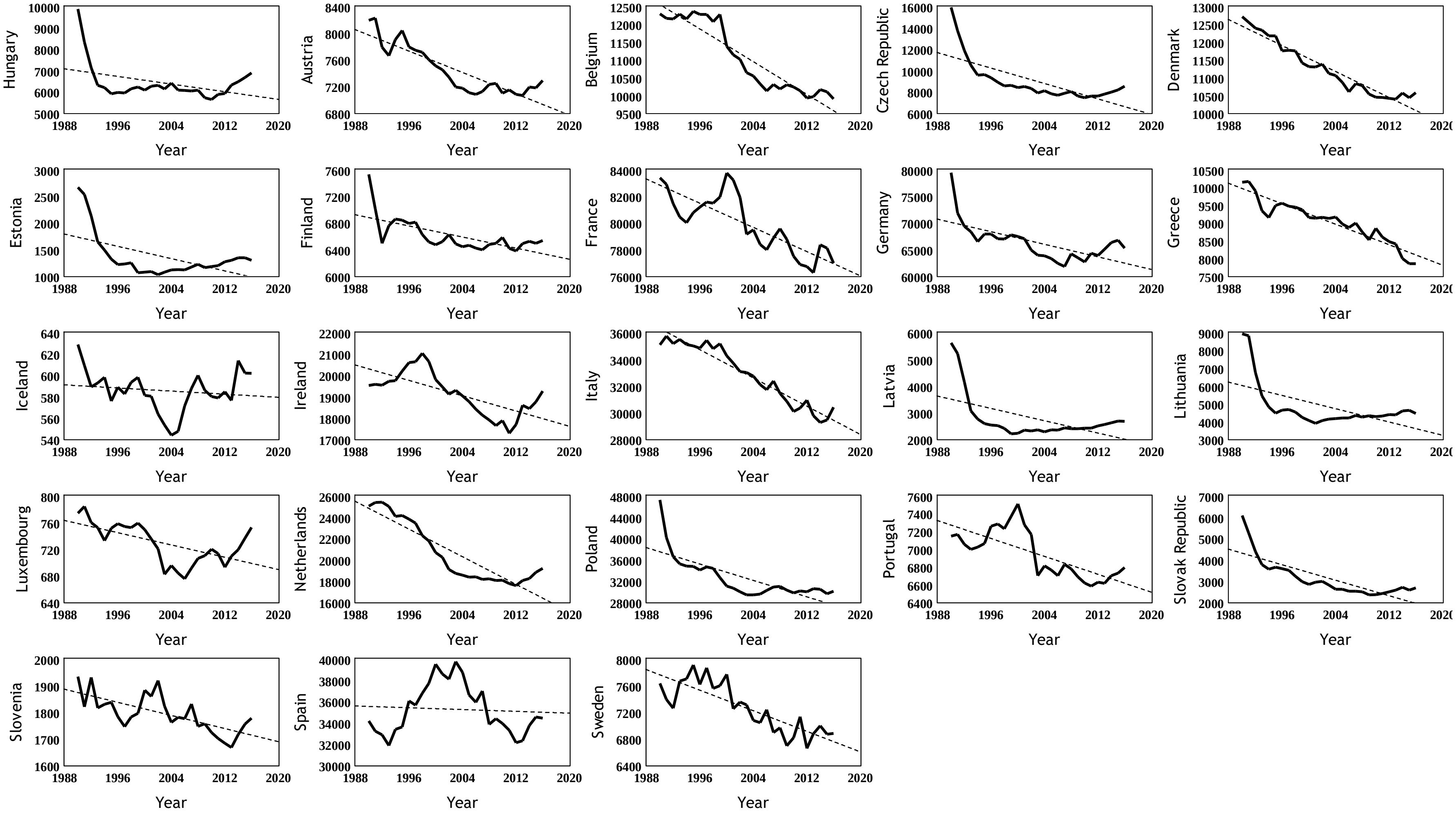

Figure 13. Trends in GHGs emissions (thousands of tonnes of CO_2 eq.) from the AG-sector in the EU between 1990 and 2016

The most significant ($P < 0.05$) reduction was noticed in the Netherlands (-336.4756 thousand tonnes of CO_2 equivalent); followed by Poland, Italy, Germany, and France. However, the least significant ($P < 0.05$) emissions reduction were in Luxembourg (-2.4454 thousand tonnes of CO_2 equivalent), and Slovenia (-6.081 thousand tonnes of CO_2 equivalent). Regardless of the amount of reduction, which varied within the EU countries, the boxplot analysis showed that the highest emissions were recorded in France, Poland, Italy, Germany, and the UK, which could partially explain the highest reduction values, as can be seen in Figure 14. In other words, countries that had high GHGs emissions (CO_2 equivalent) had the highest reduction rate, due to the many national and regional plans for achieving carbon neutrality.

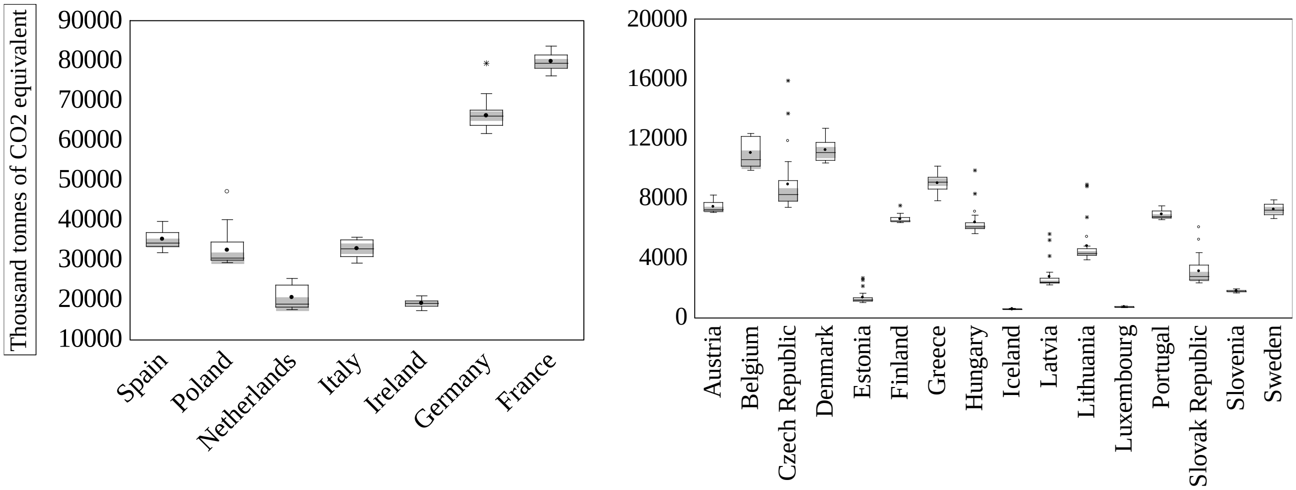

Figure 14. Boxplot analysis of GHGs emissions in thousand tonnes of CO_2 equivalent from the agricultural sector in the EU**.**

For instance, in France, the total emissions from the energy sector were low due to the nuclear power plant, while the emissions from the agricultural sector were due to extensive agricultural activities. Thus, making a balance between emissions from all sources in France was a high priority for policy-makers to achieve a significant reduction in 2020 (*Mohammed et al*. 2019; *De Cara and Jayet*, 2000). In a similar vein, Germany launched the climate protection program (CPP) which led to a reduction in CO_2 emissions of 25% (*Flessa et al.* 2002), as can be seen in Figure 13. On the other hand, carbon emissions from some countries did not show a significant negative trend, and even the amount of reduction was not relatively high (i.e. Iceland and Spain). This trend could be explained in Iceland due to land use changes

(LULUCF), while Spain's increasing population - associated with an expansion in demand -, notably enhanced carbon emissions (*Mohammed et al*. 2019, *Davíðsdóttir and Agnarsson* 2010; *Vargas-Amelin and Pindado*, 2014). Nonetheless, our results detected a negative trend in carbon emissions from agricultural sectors in all EU countries. Nonetheless, *Verge et al.* (2007) projected an increase of 50% in global GHG emissions from the agricultural sector, which contrasts with our findings (Table 9, Figure 14). This contradiction could be linked to the impact of the Common Agricultural Policy (CAP) reform in EU countries, where N_2O emissions decreased from 74 to 73 Tg CO_2 equivalent (*Mohammed et al*. 2019, *Verge et al*. 2007).

The agricultural sector is one of the sectors in the EU that has contributed significantly to the total emissions of GHGs (*Mohammed et al.* 2019). Agricultural practices have a great influence on the atmospheric carbon balance and carbon sink and sequestration (*Charkovska et al*. 2019). Globally, GHG emissions from the agricultural sector were recorded to be ~20–30% (in 2012) of total world emissions; interestingly, more than 53% of global non-CO_2 emissions originated from the agricultural sector (*Charkovska* et al. 2019; *Beach et al*. 2015; *Gerber et al*. 2016; *Vermeulen et al*. 2012). In the EU, around 42% of the total land is classified as agricultural land, revealing that the carbon cycle and other GHGs emissions are markedly affected by the agricultural system (*Mohammed et al.* 2019). For instance, *Freibauer* (2003) claims that 11% of the total emissions of GHGs are released from the agricultural sector in Europe (soils and livestock). Within the EU countries, the GHGs emissions from the agricultural sector can be divided into two sources, as follows:

1. *Emissions from agricultural soils*

Few studies have dealt with GHGs emissions from EU soils. However, emissions from the soil can be controlled by many factors (temperature, soil moisture, agricultural practice ...etc.). *Freibauer* (2003) reported that in the EU sandy arable areas GHG emissions were about 0.7 Mg ha^{-1} per year of CO_2-equivalents, while GHG emissions exceeded 25 Mg from organic soils. On the other hand, intensive agriculture in EU countries included intensive fertilization as a source of emissions, especially for N_2O and other nitrogen composites (*Charkovska et al*. 2019). Hence, soil plays a vital role in the carbon sink; in this regard, it is important to mention that the total of EU soils can sequester up to 16–19 Mt C per year which does not exceed 2% of European anthropogenic emissions (*Freibauer et al*. 2004)

2. *Emissions from livestock production systems (LPS)*

Since more than 65% of the EU's agricultural land is occupied by livestock production systems (LPS), the dairy sector has the highest GHG emissions in the EU-27, followed by the beef sector. It is remarkable that the EU-27 members produce 26%, 13%, and 22% of the world's milk, beef, and pork, respectively (*Lesschen et al*. 2011; *Mohammed et al*. 2019). The emissions of GHGs from LPS come from enteric fermentation for pigs, sheep, cows, and many others, where high amounts of CH4 are emitted during the digestive process of ruminants (*IPCC* 2006). On the other hand, the decomposition of animal manure emits large quantities of GHGs (*Charkovska et al*. 2019), which increases the importance of proper management of it.

As can be seen in Figures 13 and 14, GHG emissions from the agricultural sector vary between countries, which could mainly be attributed to climatic conditions, levels of development in the agricultural sector, adaptation and mitigation plans, and many other factors. These factors control GHG emissions from agricultural lands not only in the EU but all around the world. Our findings reveal that the highest emissions were recorded in France and Germany (Figure14). Similar results were illustrated by *Charkovska et al*. (2019) when they analysed GHG emissions from the European agricultural sector in 2012 and concluded that the highest were in France, Germany, and the UK.

As the agricultural sector emits considerable amounts of GHGs, which are expected to increase in the near future, a mitigation plan should be designed to minimize CO_2 emissions. This mitigation plan should be implemented in the form of low carbon emission strategies, which could be achieved by a concerted effort at different levels. These actions should be taken from the farm up to the sectoral level, in order to reduce emissions at the national level of each country in Europe. Thus, concrete practices to achieve the sustainability of the agricultural sector in terms of low carbon emissions for climate change adaptation (CCA) and disaster risk reduction (DRR), may include, but are not limited to:

- The enhancement of Climate-Smart Agriculture (CSA) in the sense that it significantly encourages the linkages between climate and agricultural policies in terms of environmental and socioeconomic factors (*Lipper et al.* 2014);
- The application of management practices that reduce soil organic matter decomposition rates and protect carbon storages (i.e. low carbon emissions). For

example, reduced tillage, cropping intensification and increased crop yield, forestation and low carbon energy practices, among others (*Paustian et al*. 2000).

4.2. GHGs emission from agricultural sector in Hungary

In general, 10% is the contribution of agricultural sector to total GHGs emissions in Hungary. Nonetheless, 65% of the total N_2O originated from agricultural sector in Hungary.

The current GHGs emission from agricultural sector in Hungary showed a positive trend for both CO_2 (Fig.15) , and N_2O (Fig.17), while a negative trend for CH_4 (Fig.16)

In this research, we applied ARIMA model (Autoregressive integrated moving average) to predict future GHGs emissions from agricultural sector in Hungary. Results, indicate clearly a gradual increase of CO_2 emission from agricultural sector in Hungary till 2040. In contrast, CH_4, and N_2O showed a remarkable decrease between 2016-2040. The M-K test results showed that CO_2 emissions were increased significantly ($p<0.05$) by +368.72 thousand tonnes/year. While, CH_4 emission was subject to a significant decrease ($p<0.05$) by -2.37 thousand tonnes/year. Nonetheless, Fig.18 showed that the average of CO_2 emission between 1985-2016 is lower than predicted one, while it is higher for both CH_4, and N_2O.

The output of this research could be explained by the change of economy in Hungary (*Molnár*, 2014), high awareness of the people (*Hunkár* 2012), and many collaborations and local programmes in a regional scale to reduce emissions and mitigate climate change (*Szirmai et al.* 2008). In this sense, it is good to mention that Hungary committed to reduce GHGs emissions by 30% compared with 1990 level, which enhanced national reduction strategies from different sectors (energy, transportations, industry) for mitigations and adaptations (*Szlávik et al.*, 2000; *Tolon-Becerra et al.*, 2010).

In terms of agriculture, more than 50% of lands in Hungary are agricultural one, thus, emission should be track to minimize the emission. Our results are along with *Jambor and Sirone* (2014), *Dace and Blumberga* 2016 and *Molnár et al*. (2011). However, the reduction from agricultural sector could be attributed to implementations of some strategies such climate reduction strategies (*Fogarassy and Nabradi* 2015; Bai et al. 2017; *Freibauer et al*. 2004; *Smith et al*. 2007, 2008; *Smith et al*. 2008). However, the adaptations of this new technology in the agricultural sector are still in the early stage, thus an increase of CO_2 was projected (Fig. 15).

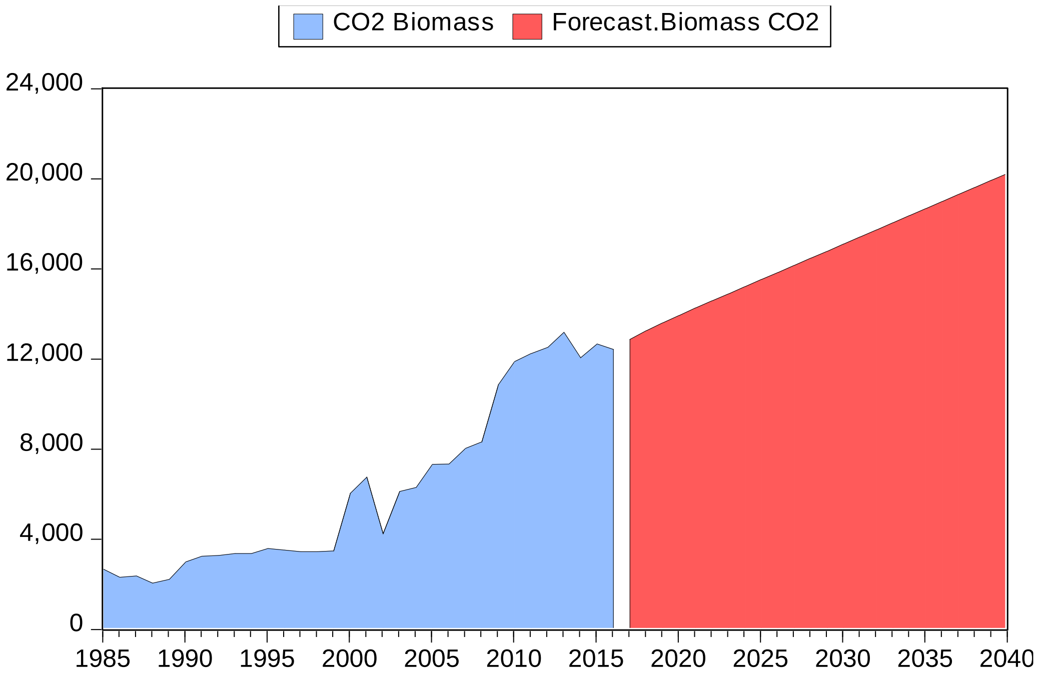

Figure 15 Current and future CO_2 emissions from agricultural sector in Hungary

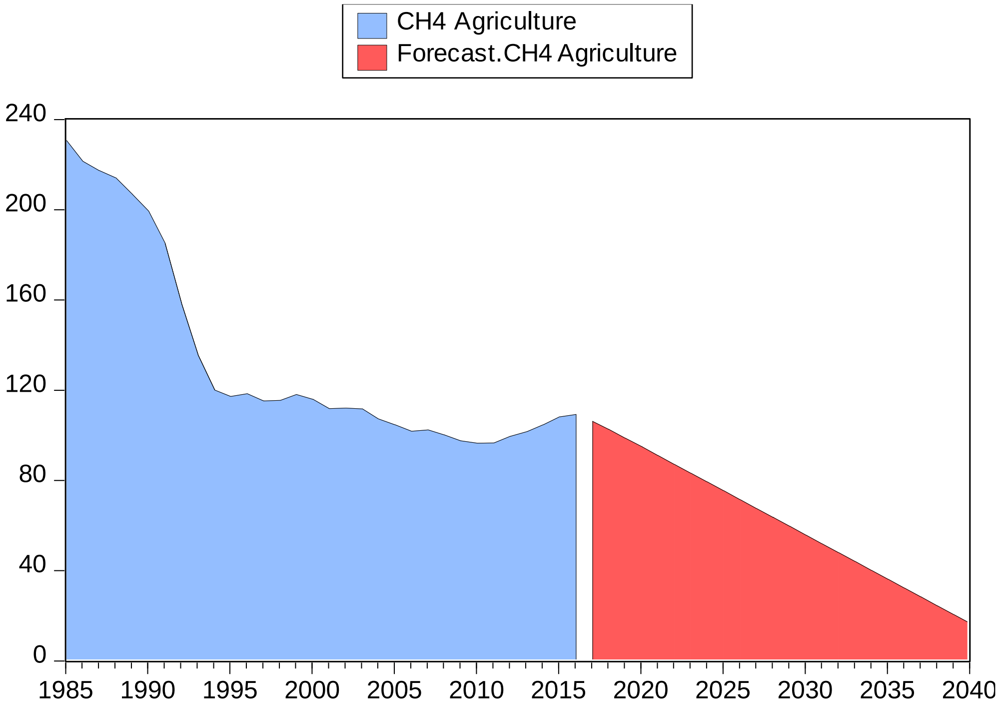

Figure 16 Current and future CH_4 emissions from agricultural sector in Hungary

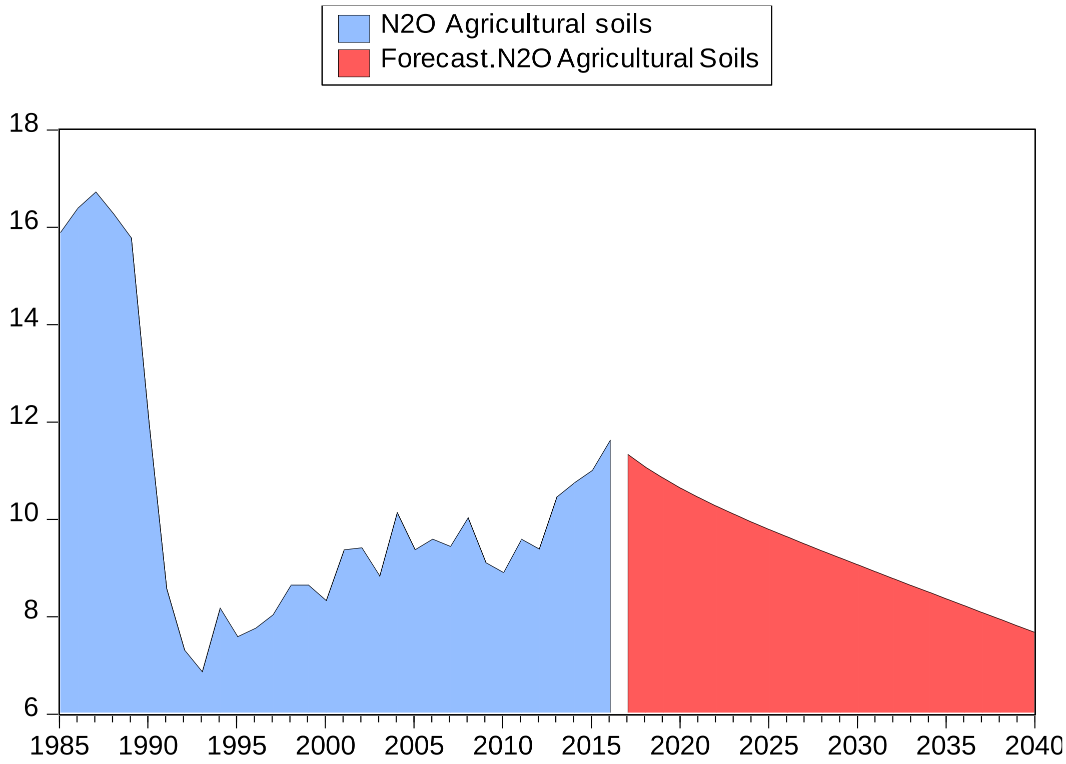

Figure 17 Current and future N_2O emissions from agricultural sector in Hungary

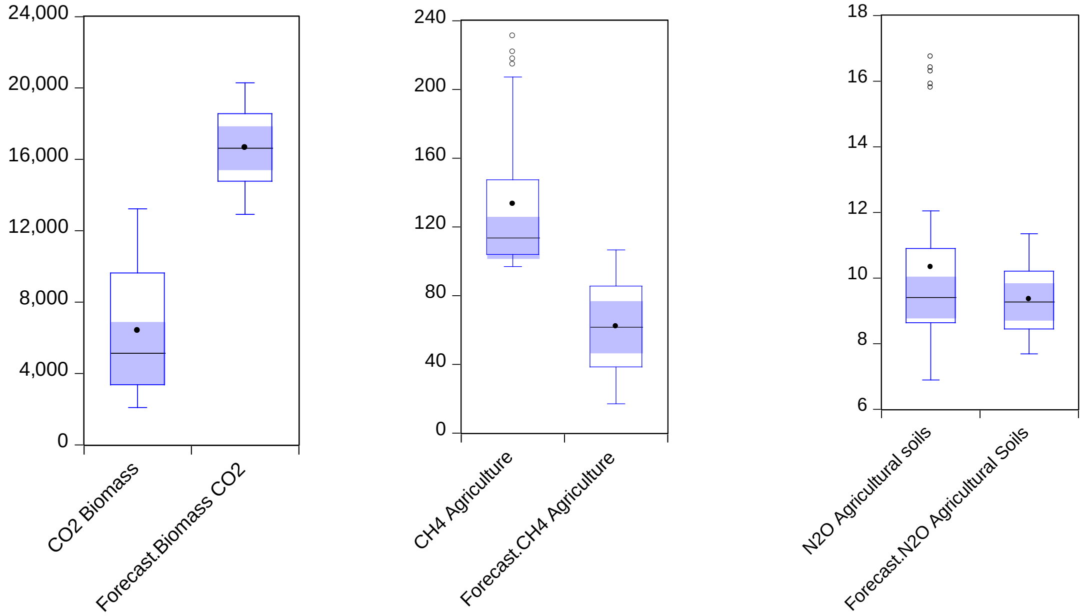

Figure 18 Boxplot of Current (1985-2016) and future (2016-2040) GHGs emissions from agricultural sector in Hungary. (median (——); mean (•); median 95% confidence (shaded).

4.3. Agricultural drought in Hungary

4.3.1. Trends in agricultural drought in Hungary

The M-K trend test for the SPI (-3, -6) and the SPEI (-3, -6) showed that the eastern part of Hungary was less prone to agricultural drought, while agricultural drought in the western part was more pronounced. Figure 19 shows a negative trend of the Sen slope analysis (shown in brown) in the western part, where most of the studied points have a significant trend (*p> 0.05*).

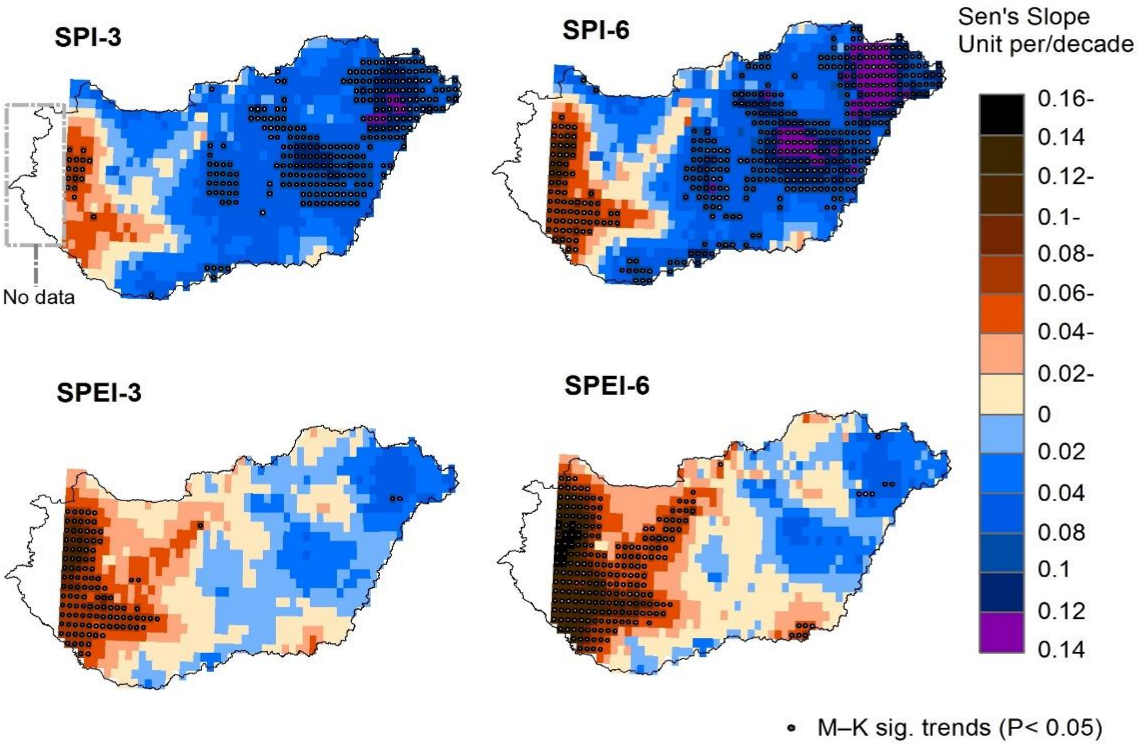

Figure 19. Agricultural drought trends (Sen's slope estimator M-K statistic test) in Hungary between 1961 and 2010; significant trends at P<0.05 illustrated by black points.

In terms of the SPI-3 trend analysis results, only 1.53% of the total gridded points (1045) showed a significant agricultural drought trend (p> 0.05), while the proportion increased to 6.89% gridded points when the SPI-6 trend was analysed. On the other hand, agricultural drought seems to be more vigorous in terms of the SPEI, where 10.43% and 14.45% of the total gridded points showed a significant agricultural drought (*p> 0.05*) for SPEI-3 and SPEI-6, respectively (Table 10).

Table 10. Trend analysis for agricultural drought between 1961 and 2010 in Hungary

Index	**Sig. positive points**	**Sig. negative points**	**Total points**	**Positive (%)**	**Negative (%)**
SPEI-3	2	109	111	0.19	10.43
SPEI-6	6	151	157	0.57	14.45
SPI-3	259	16	275	24.78	1.53
SPI-6	366	72	438	35.02	6.89

4.3.2. Spatial variability of agricultural drought in Hungary

Figure 20 shows the spatial distribution of the rotated loading (the correlation matrix between PCA and the drought index in each gridded point), revealing that Hungary is divided into five different sub-regional areas, characterized by different drought variabilities.

For SPI-3, the first region to be noted (i.e. PC1) is located in the eastern part of Hungary, which explains 21.6% of the variance. PC2 predominates in the western part, covering the Transdanubia region, and explains 19.6% of the variance. Both PC3 and PC4 occur in southern Hungary (Great Plain), and explain 19.3% and 16.6% of the total variance. However, PC5 dominates in northern Hungary. For the SPEI-3, the PC1 predominates in the southern Great Plain (22.3%), PC2 in western Transdanubia (21.9%), and PC3 (21.4%) in the eastern part of Hungary. PC4 (13.6%) is located in southern Transdanubia, and PC5 (12.9%) in northern Hungary. Notably, PC2, PC4, and PC5 were similar for SPI-3 and SPEI-3. In terms of the six-month period, PC1 appeared in Western Transdanubia (i.e. western Hungary) for both SPI-6 and SPEI-6. PC3 was dominant in northern Hungary, and PC5 in the eastern part of Hungary, for both SPI-6 and SPEI-6. PC2 explained 22.9%, and 24.5% of the total variance for SPI-6 and SPEI-6, and predominates in the eastern and northeast part of Hungary, respectively. Finally, PC3 occurs in the north-eastern and eastern parts of Hungary for SPI-6 and SPEI-6, respectively.

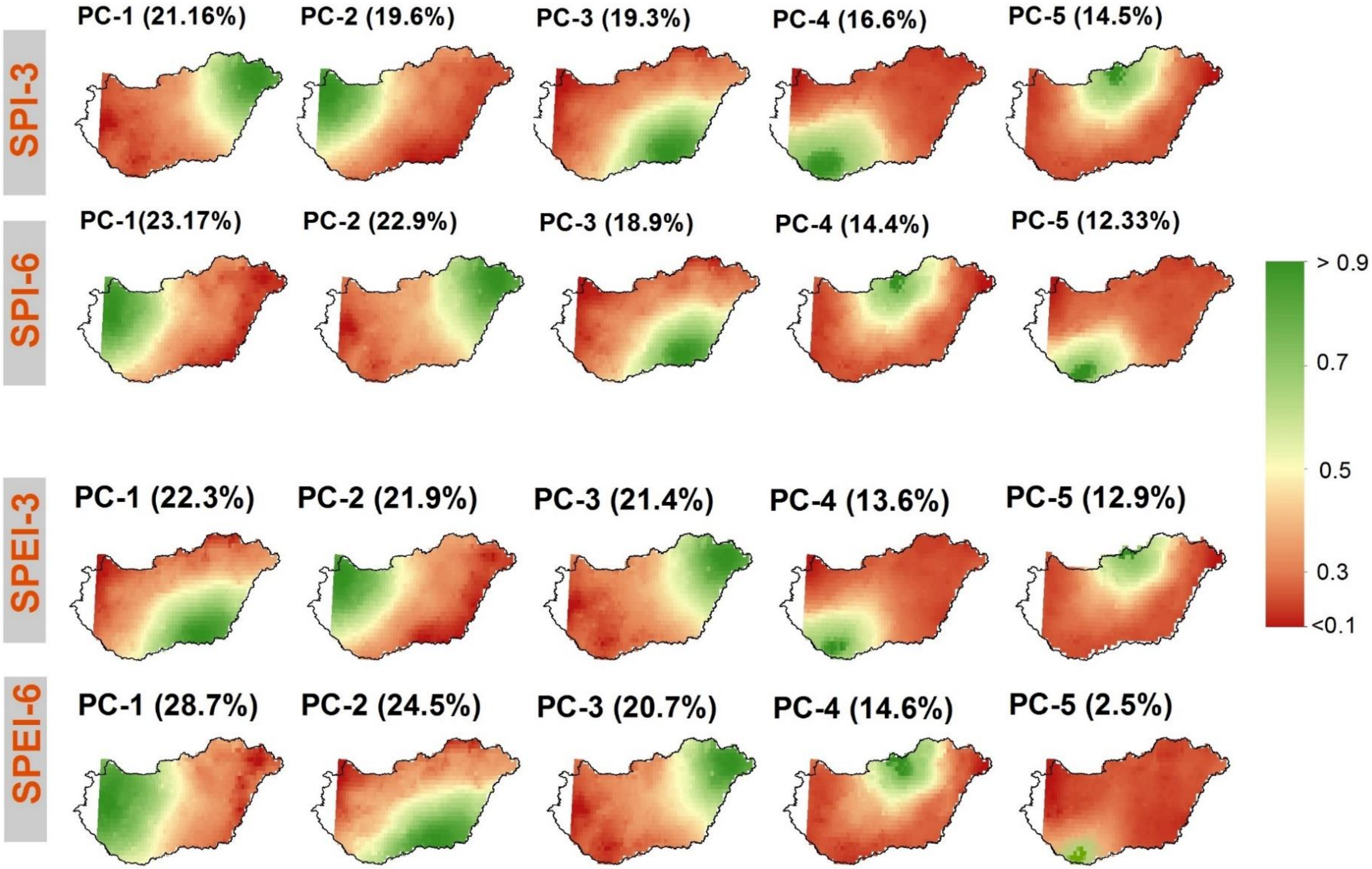

Figure 20. Subregional agricultural drought over Hungary based on SPI-3, SPI -6 and the SPEI-3, -6 based on Varimax rotated loadings for the 1045 gridded points

4.3.3. Temporal variability of agricultural drought in Hungary

As illustrated in Figure 21, the frequency of agricultural drought (TDD) between 1961 and 2010 for SPI-3 and SPEI-3 (i.e. the 3-month time-scale) demonstrates that the central part (Bács–Kiskun), and the eastern northern part (i.e. Veszprém) (red colour) were the areas most subjected to agricultural drought. Almost the same results were obtained for SPI-6 and SPEI-6, but with a greater spatial extent, as can be seen in Figure 21. Based on the TDD-SPEI-6, it can be concluded that Hungary tends to be frequently hit by waves of drought. However, the differences between the outputs of two indices (SPI, SPEI), here and in the other following sections, can mainly be attributed to the direct impact of evapotranspiration, which SPI did not calculate.

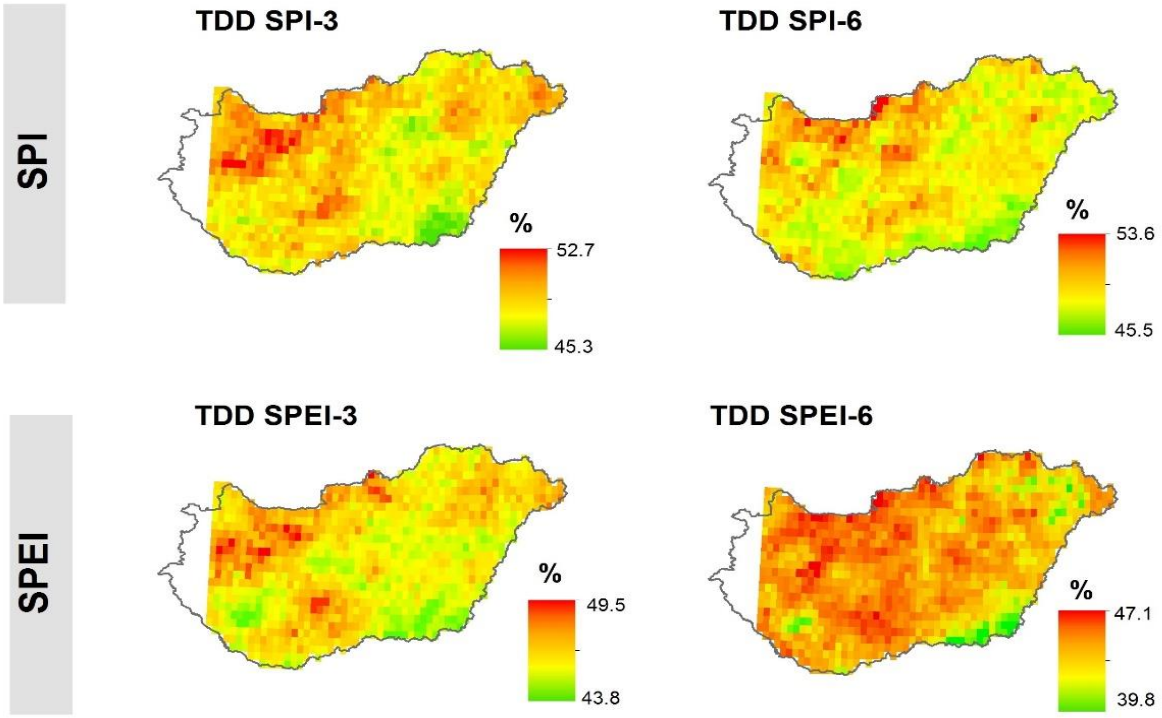

Figure 21. TDDs distribution of SPI/SPEI-3-6 in Hungary between 1961 and 2010.

As rainfed agriculture is the common agricultural system in Hungary, agricultural drought will have drastic consequences on agricultural production, where any changes in rainfall patterns will have negative impacts on the agricultural sector in Hungary (*Kovacs, et al.*, 2010). Within this context, *Jakuschné Kocsis, and Anda* (2017) reported a significant decrease in rainfall tendencies in Keszthely (western Hungary), making less favourable conditions for agricultural activities, while *Domonkos* (2003) noted an increase in summer drought frequency in Hungary. Interestingly, similar results could be found in Figure 28 (hydrological drought).

4.4. Hydrological drought

4.4.1 Trends of hydrological drought in Hungary

To track hydrological drought episodes over Hungary, the M-K test was used for analysing trends of the SPI-12 and the SPEI-12. Similarly, to the SPI (-3, -6), and the SPEI (-3, -6) (i.e. Figure 19), the results reveal that the western part of Hungary is more prone to drought. For SPI-12, the results showed a negative significant trend (p<0.05) at 11.5 % of the total gridded points in western Hungary, while eastern Hungary recorded a positive significant trend (p<0.05) in 359 gridded points (Figure 22). With SPEI-12, only 457 gridded points showed a significant trend, among them 452 points (98.9%) of which showed a significant negative trend (p<0.05) (Figure 22). Nonetheless, both indices highlighted that the western part of Hungary is subjected to hydrological drought.

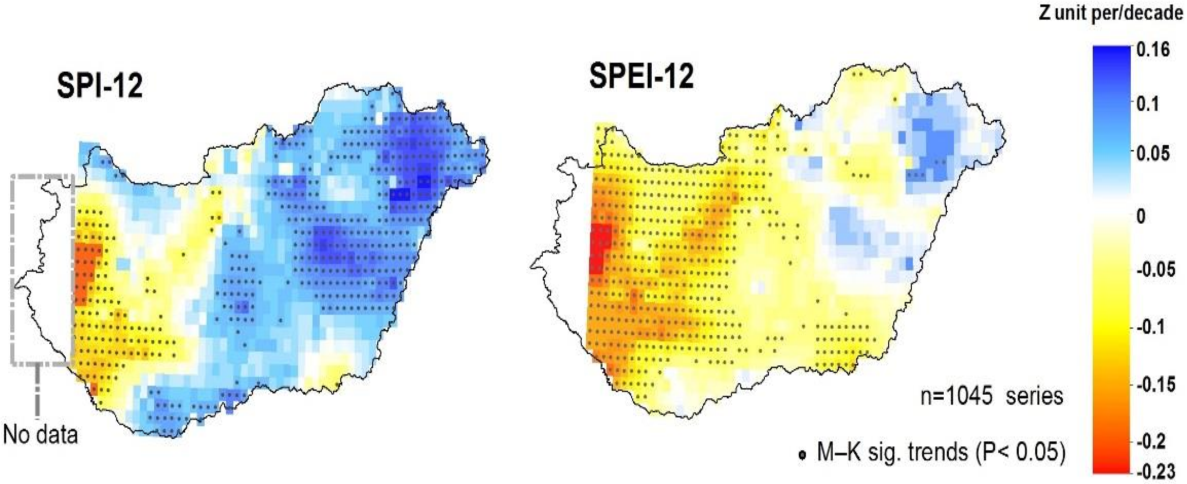

Figure 22. Hydrological drought trend (Sen's slope estimator M-K statistic test) in Hungary between 1961 and 2010; significant trends at P<0.05 illustrated by black points.

4.4.2. Spatial variability of hydrological drought in Hungary

Following the PCA analysis, the first six principal components (PCs) (Figure 23 and Figure 24). For the SPI-12, the PC1 contributes 28.5%, followed by the PC2, at 24.8%, and then the other PCs - i.e. PC3 (18.9%), PC4 (17.2%), PC5 (1.4%), and PC6 (0.9%) (Figure 23). For the SPEI, PC1 makes the greatest contribution to the total variance, at 29.4%, then the other PCs i.e. PC2 (21.5%), PC3 (20.7%,), PC4 (17.1%), PC5 (17.1%), and PC6 (1.6%) (Figure 24).

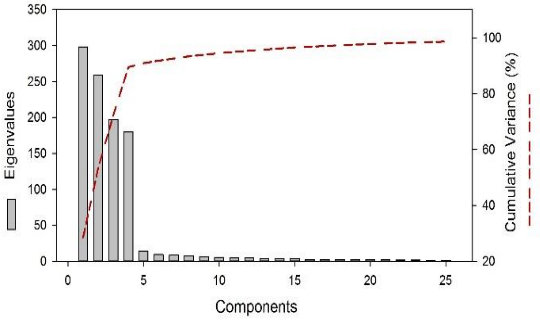

Figure 23. Cumulative variance clarified by the various components of the PCA analysis results for the SPI-12 in S-mode.

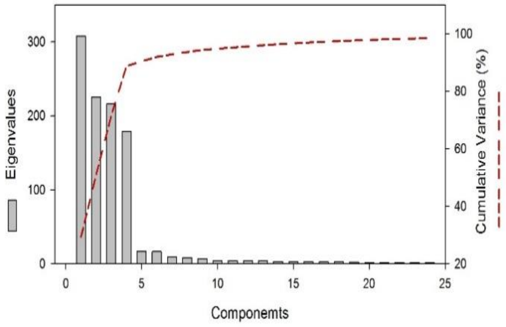

Figure 24. Cumulative variance clarified by the various components of the PCA analysis results for the SPEI-12 in S-mode.

Figure 25 depicts the spatial distribution of the rotated loading (the correlation matrix between PCA and the drought index in each gridded point), revealing that Hungary is divided into six different sub-regional areas, characterized by different drought variability. The first region (i.e. PC1) is in the western part, covering the Transdanubia region. PC2 predominates in the eastern part of Hungary, PC3 occurs in the Southern Great Plain, PC4 in Central Hungary, PC5 near to the Croatian border, and PC6 covers the city of Győr. For the SPEI-12, the PC1 predominates in the Transdanubia region (i.e. western Hungary), which covers Central Transdanubia, Western Transdanubia, and Southern Transdanubia, while the rest of PCs are distributed as follows: PC2 in the Southern Great Plain, PC3 in Northern Hungary, PC4 in the eastern part of Hungary, PC5 near to the Croatian border, with PC6 dominating in Central Hungary (Figure 25). Notably, PC1 was similar to SPI-12 and SPEI-12, and PC2 (SPI-12) to PC4 (SPEI-12) (*Mohammed et al*. 2020).

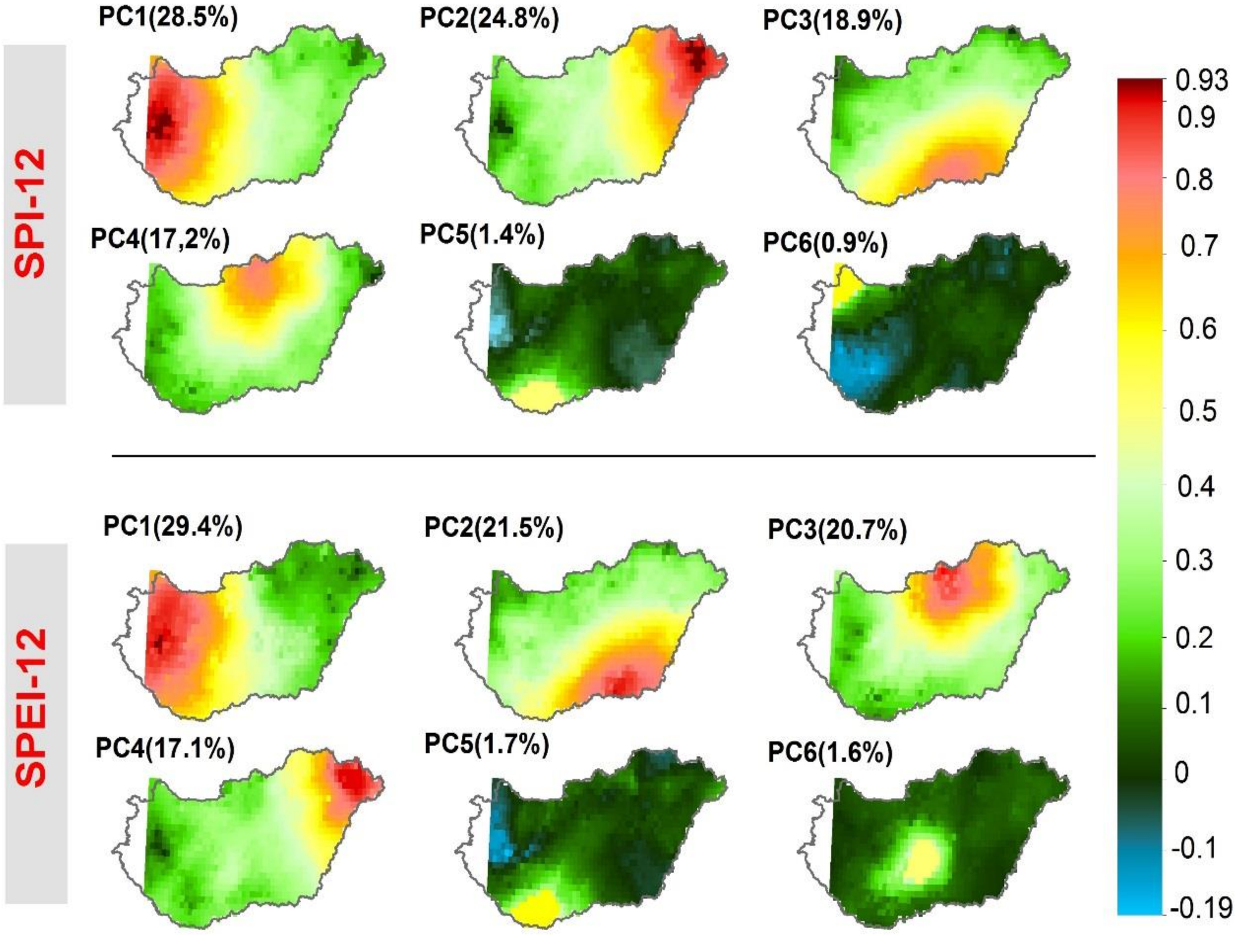

Figure 25. Subregional hydrological drought over Hungary based on SPI-12, and the SPEI-12 based on Varimax rotated loadings for the 1045 gridded points.

To track the dynamic interaction between different Hungarian sub-regions and drought, the spatial-temporal evolution of both the drought indices and drought events during the period 1961–2010 were analysed from the PC scores, as can be seen in Figure 26 and Figure 27. The results showed different interactions between different PCs and subregions which indicate different drought evaluations in Hungary during the study period. In terms of SPI-12, all PCs/sub-sets, except PC1 (western Hungary), were less prone to drought and a positive significant trend was recorded (Figure 26). However, a negative significant ($p<0.05$) trend was recorded in PC1 values (-0.13 unit/decade), indicating that the Transdanubia region is more subject to drought.

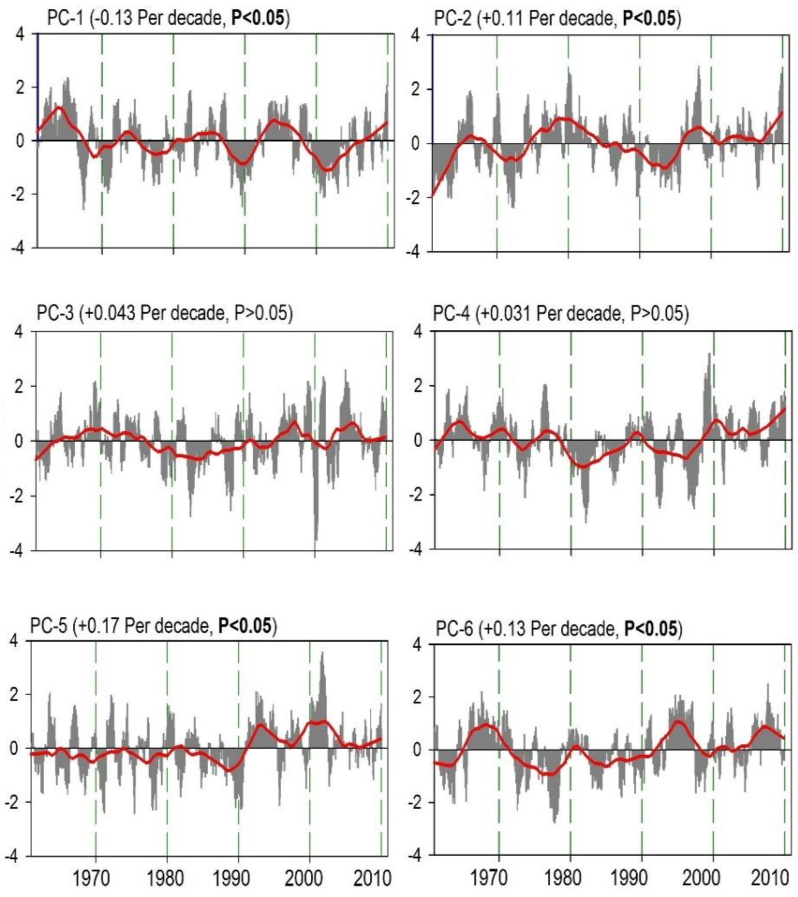

Figure 26. Drought evolution on the sub-regional scale (scores corresponding to PCs) for SPI-12. The red line shows drought evaluation

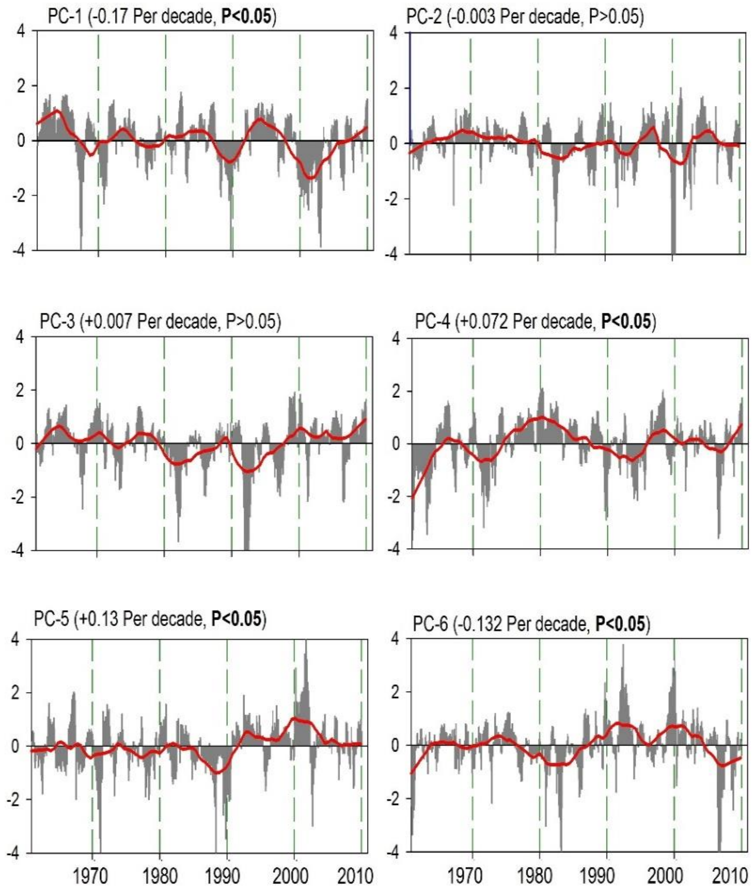

Figure 27. Drought evolution on the sub-regional scale (scores corresponding to PCs) for SPEI-12. The red line shows drought evaluation

Similarly, to SPI-12, SPEI-12 shows significant ($p<0.05$) declines in SPEI in the western part of Hungary (i.e. the Transdanubia region) and Central Hungary (PC6), by -0.17% per decade ($p<0.05$), and -0.13 per decade ($p<0.05$), respectively (Figure 27). However, drought was less pronounced in the PC2, PC3, PC4 ($p<0.05$), and PC5 ($p<0.05$) regions (Figure 27).

4.4.3. Temporal variability of hydrological drought in Hungary

As hydrological drought should be studied in a 12-month time span, the TDD analysis was carried out to show the frequency and concentration of each drought category. Figure 28 shows the frequency of hydrological drought (TDD) between 1961 and 2010 for SPI-12 and SPEI-12.

For SPI-12, the southwest (i.e. Somogy and Baranya) and western Hungary (Veszprém) were more subjected to very extreme droughts with values of about 5% to 7%; meanwhile, central parts and the far east were subjected to lower drought frequencies (about 1.5 to 3%). Markedly, the frequency of extreme and severe events tends to occur in Jász, Nagykun, Szolnok, Pest and Veszprém, e.g. the central and western part Hungary. In terms of SPEI-12 based TDDs, Somogy, Baranya, Jász, Nagykun, Szolnok, Veszprém, and Pest are the areas most subjected to very extreme and severe drought frequencies.

Comparing the TDDs-SPIs-12 and TDDs-SPEIs-12 time series indicates that both indices suggest western and southern Hungary are the areas most affected by severe and very extreme droughts, while the south east of Hungary is dominated by mild drought. However, a positive significant correlation ($r=0.59$, $p<0.05$) between different TDDs on the basis of SPIs-12 and SPEIs-12 was detected, as is shown in Figure 29.

Calculated results from the SPI and the SPEI show that both of them suggest that the western part of Hungary is the area most prone to drought, where a significant negative trend was recorded in all of the gridded points. In contrast, drought was less pronounced in the eastern part of Hungary. Nonetheless, the SPEI showed that only 5 gridded points in eastern Hungary have a positive trend ($p<0.05$), and 359 points have positive one (i.e. more rainfall and less drought).

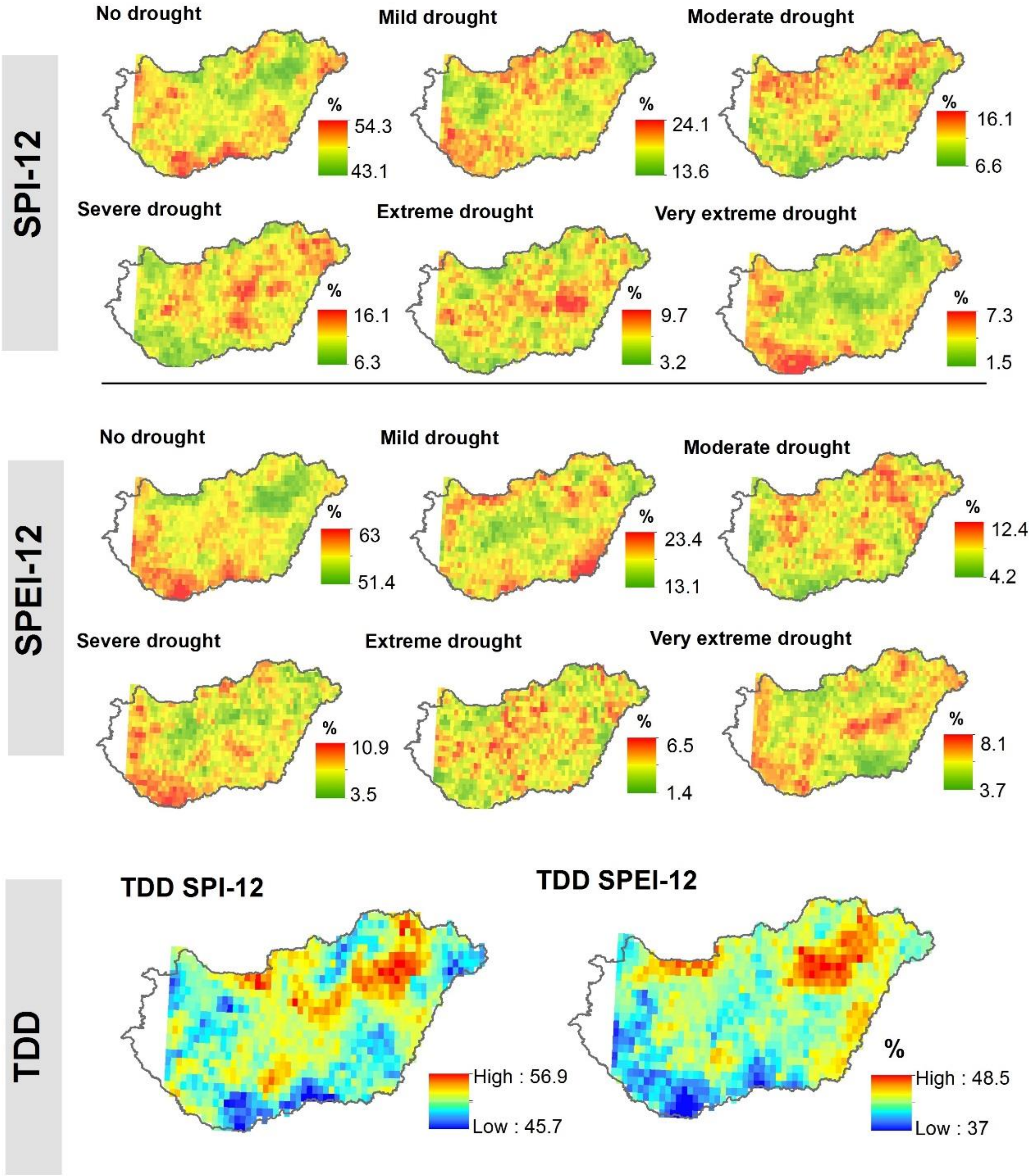

Figure 28. TDDs (number of months%) distribution of SPI/SPEI-12 over Hungary between 1961 and 2010

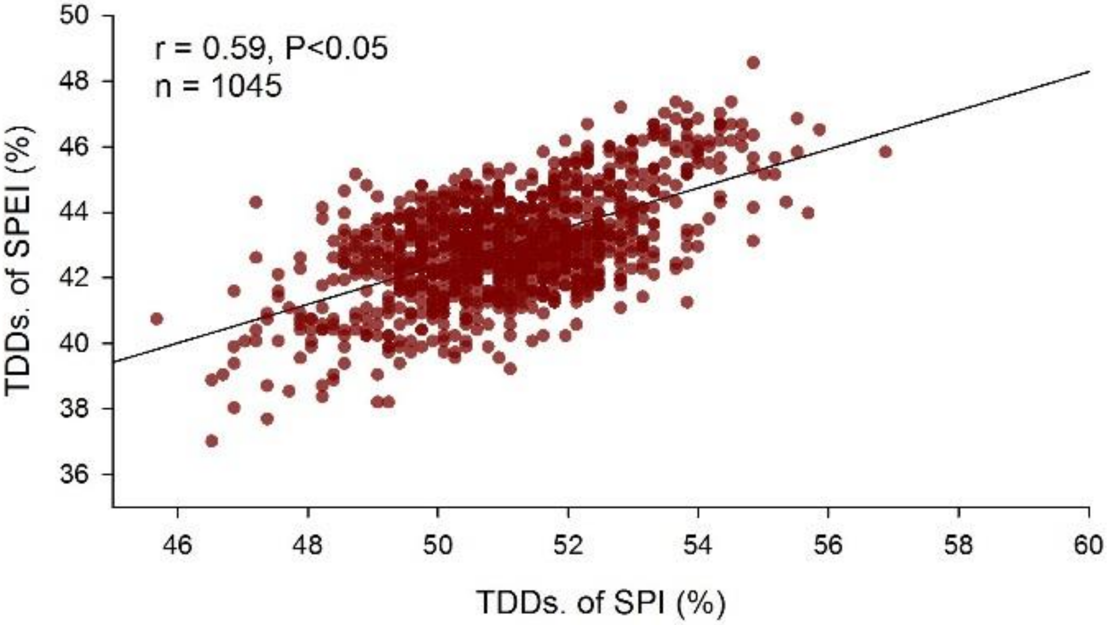

Figure 29. Correlation plot between TDDs of SPI-12 and TDDs of SPEI-12

These differences in results of drought explanation between both indexes originated to the way of drought calculation. It is clear that both indices agree that the western part was more subjected to drought, where a drought tendency (i.e. decreases in SPI-12 and SPEI-12 values) was recorded in the Transdanubia region (PC1) (p<0.05). However, we could notice that the east part of Hungary was less prone to drought. Within this context, *Szabó et al*. (2019) obtained the same results and similarly highlighted that western Hungary was the most sensitive to climate change (1961-2010). Similar results were obtained by *Bussay and Szinell* (1996) indicating that Veszprém, Somogy, Baranya, Jász, Nagykun, Szolnok and Pest were subjected to drought events based on TDDs. *Mohammed et al.* (2020) reported an increase in both agricultural droughts and hydrological droughts in the eastern of Hungary (Debrecen region) between 1950 and 2010.

Rainfall plays an important role in drought evolution (*Vicente-Serrano et al*. 2010); thus, we track the decadal change in Hungary. Results (*not shown*) reveal that the central part of Hungary receives less rainfall than the southern-western part, which could explain the results of TDDs in both regions (Fig 21 and 28). Within this context, *Bede-Fazekas and Szabó* (2018) claim that central Hungary is subjected to drought, as is 90% of Hungarian land.

In this section we have discussed both the SPI and SPEI as drought indices. However, each one has its own advantages and disadvantages. For the SPI, the disadvantages could be summarized as follows: 1) it is dependant only on rainfall data, 2) it does not show the start and end of drought events very well, and 3) it neglects rainfall distribution over time. One of the main disadvantages of the SPEI is using the Thornthwaite equation (*Thornthwaite*, 1948) for PET, which tack into consideration just temperature (*Wang et al.* 2015), thus, applying a different equation could produce different results. However, those models have been widely used all over the world, for tracking drought (*Alsafadi et al*. 2020).

4.5. Impact of drought on maize and wheat production in Hungary

Drought stress had a great impact on crop production, not only in Hungary, but also in many parts of the world. Thus, we analysed the interaction between drought and crop yield for maize and wheat by using two indices: the standardized yield residual series (SYRS), and the crop yield resilience to drought (CYR_T).

4.5.1. Results of the Standardized Yield Residual Series (SYRS) analysis

To carry out SYRS analysis, the polynomial equation for maize and wheat yield (kg/ha) in Hungary between 2000 and 2019 was extracted on a regional scale, as can be seen in Fig 30 and 31. As can be noticed, crop yields show a positive trend over different Hungarian regions, as has been shown by many researchers (*Potopová et al.*, 2015, *Vicente-Serrano et al*., 2010). By applying the Standardized Yield Residual Series (SYRS), we can demonstrate the following ideas:

1- The SYRS analysis for maize yield showed that the maize yield was badly affected by drought in 2000, 2003, 2007, 2012, and 2013. Also, the yield was partially affected by drought in 2003, 2015, and 2017 (Fig 32).

2- The lowest SYRS value (-2.43) was recorded in the Csongrád-Csanad region in 2012, followed by Tolna (-2.22), and Somogy (-2.20) in the same year (Fig 32). The highest yield losses (i.e. $\text{SYRS} \leq -1.50$) in 2003 were recorded in Csongrád-Csanad and Bekes. In 2007, the highest yield losses were recorded Baranya, Fejer, Gyor-Moson-Sopron, Komarom-Esztergom, Pest, Somogy, and Tolna. However, yield losses became more intense in 2007, when most regions in Hungary were subjected to high yield loss, as can be seen in Fig 32 In 2015, the lowest SYRS values (i.e. high yield losses) were observed in Szabolcs-Szatmar-Bereg, Nograd, Heves, and Budapest.

3- The western and southern regions of Hungary were more subject to maize yield losses, while they were less pronounced in the eastern region.

4- In terms of wheat, the yield reduction due to drought was less pronounced in comparison with maize. In other words, it seems that the wheat crop is more resilient to drought events than maize.

5- For wheat, yield losses due to drought were experienced in 2003 and 2010, while in 2000, 2003 and 2015 wheat yields in some regions were affected (Fig 33).

6- The lowest SYRS value (-2.8) (i.e. high yield losses) for wheat yield was recorded in Zala region in 2012, followed by Veszprem (-2.43), and Somogy (-2.21) in the same year (Fig 33). Notable SYRS reductions were noticed in Komarom-Esztergom, Nograd, Pest, and Fejer in 2012.

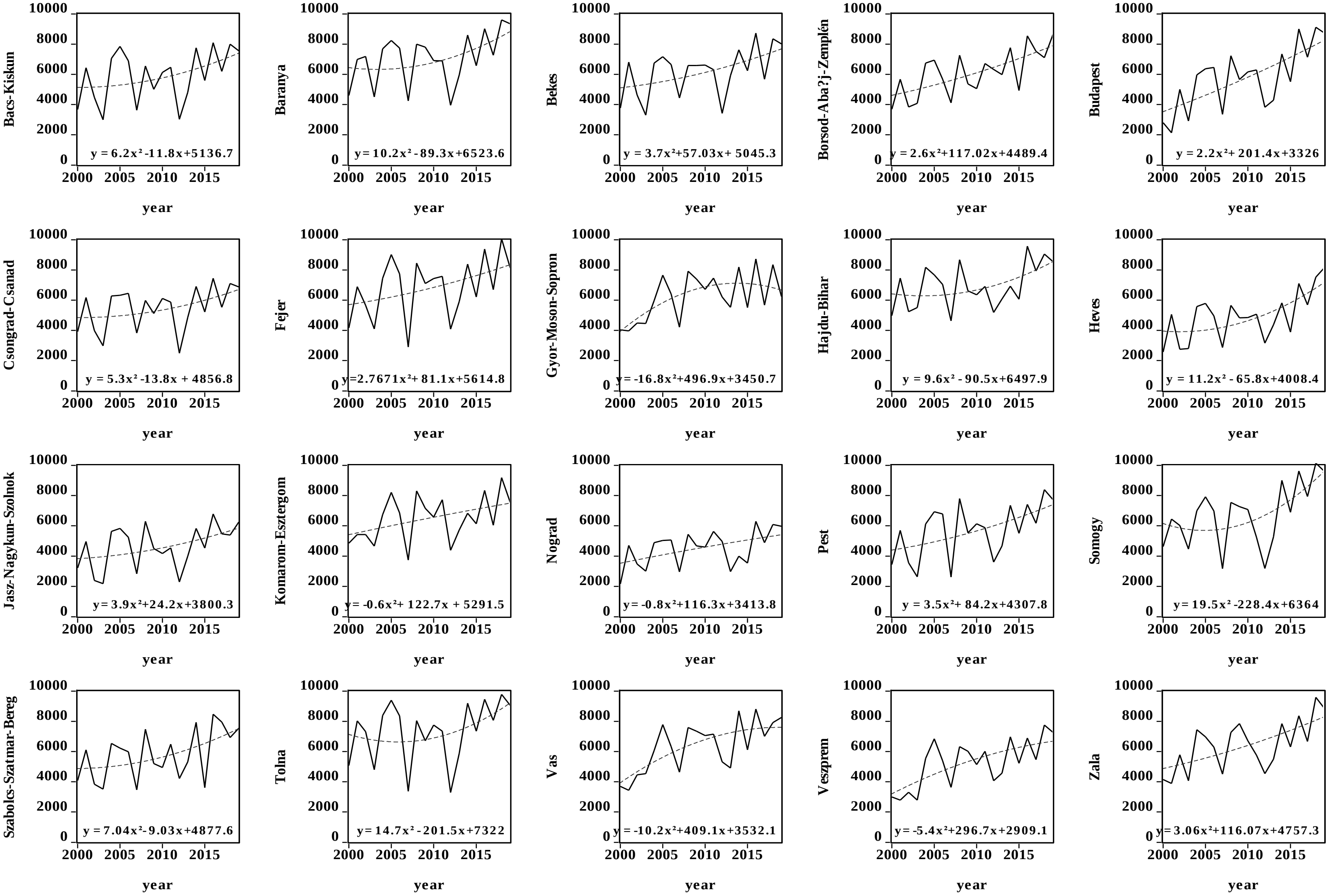

Figure 30. Maize yields (kg/ha) in Hungary between 2000 and 2019

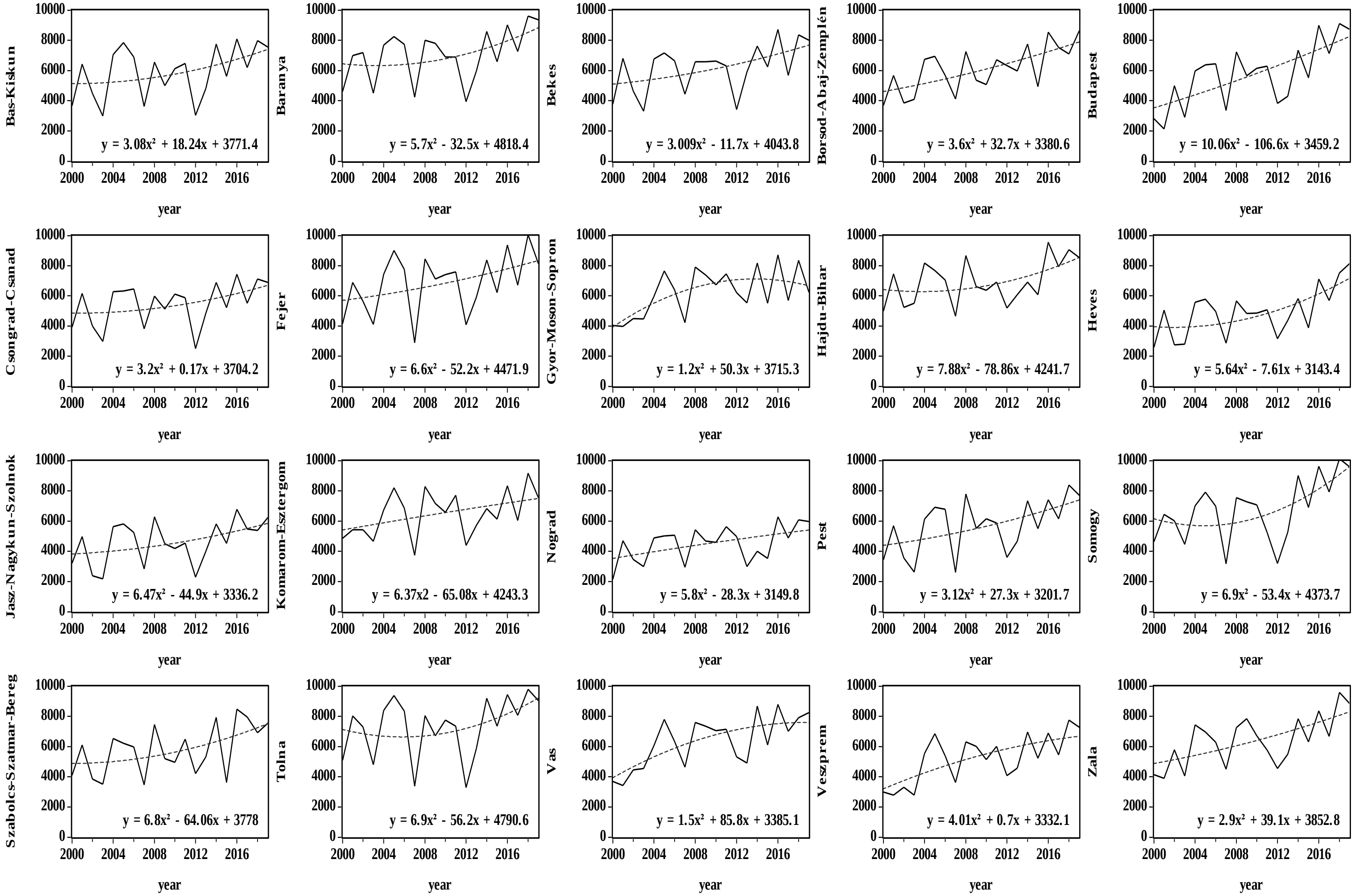

Figure 31. Wheat yields (kg/ha) in Hungary between 2000 and 2019

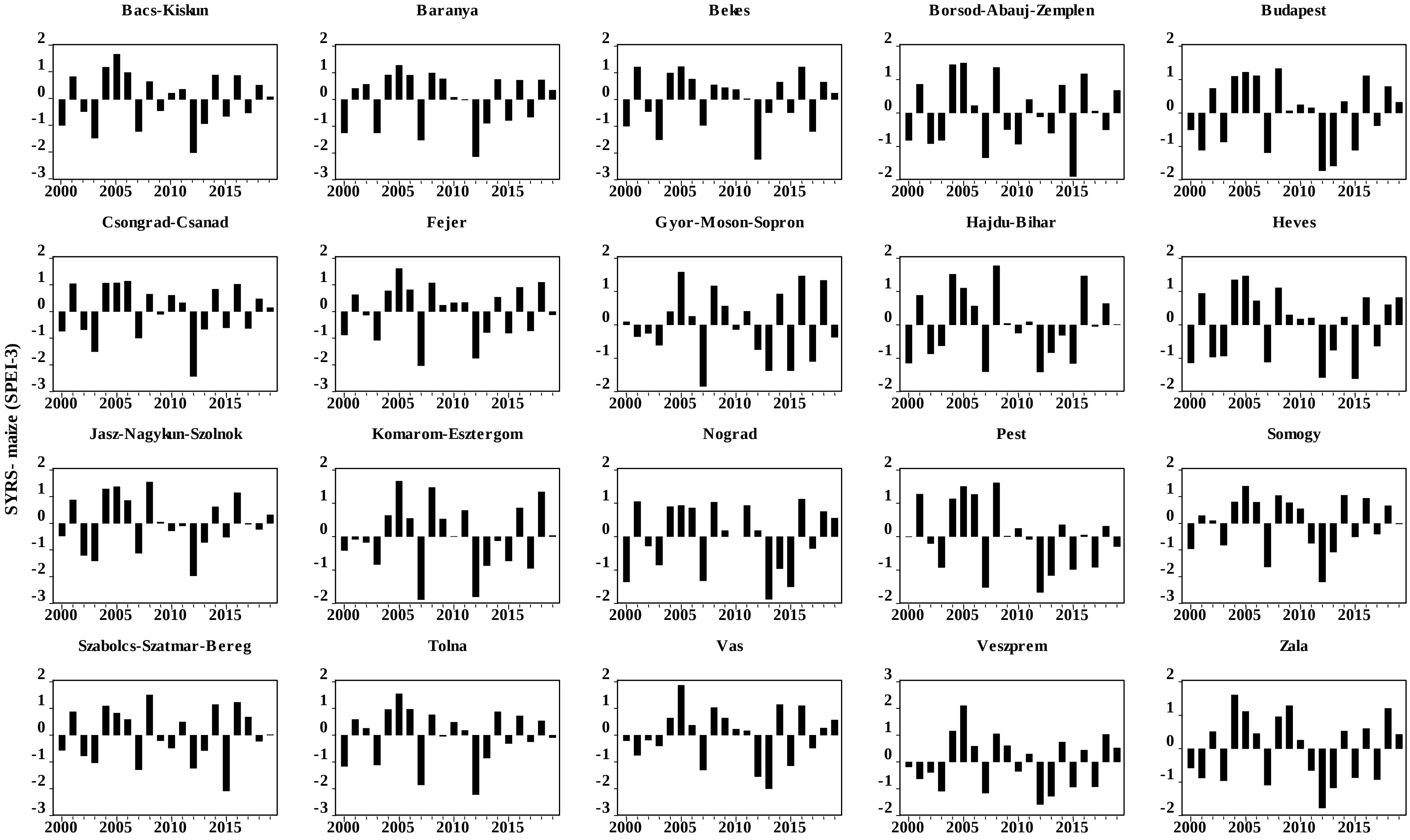

Figure 32. Temporal changes in SYRS-maize crops in Hungary between 2000 and 2019 (regional scale).

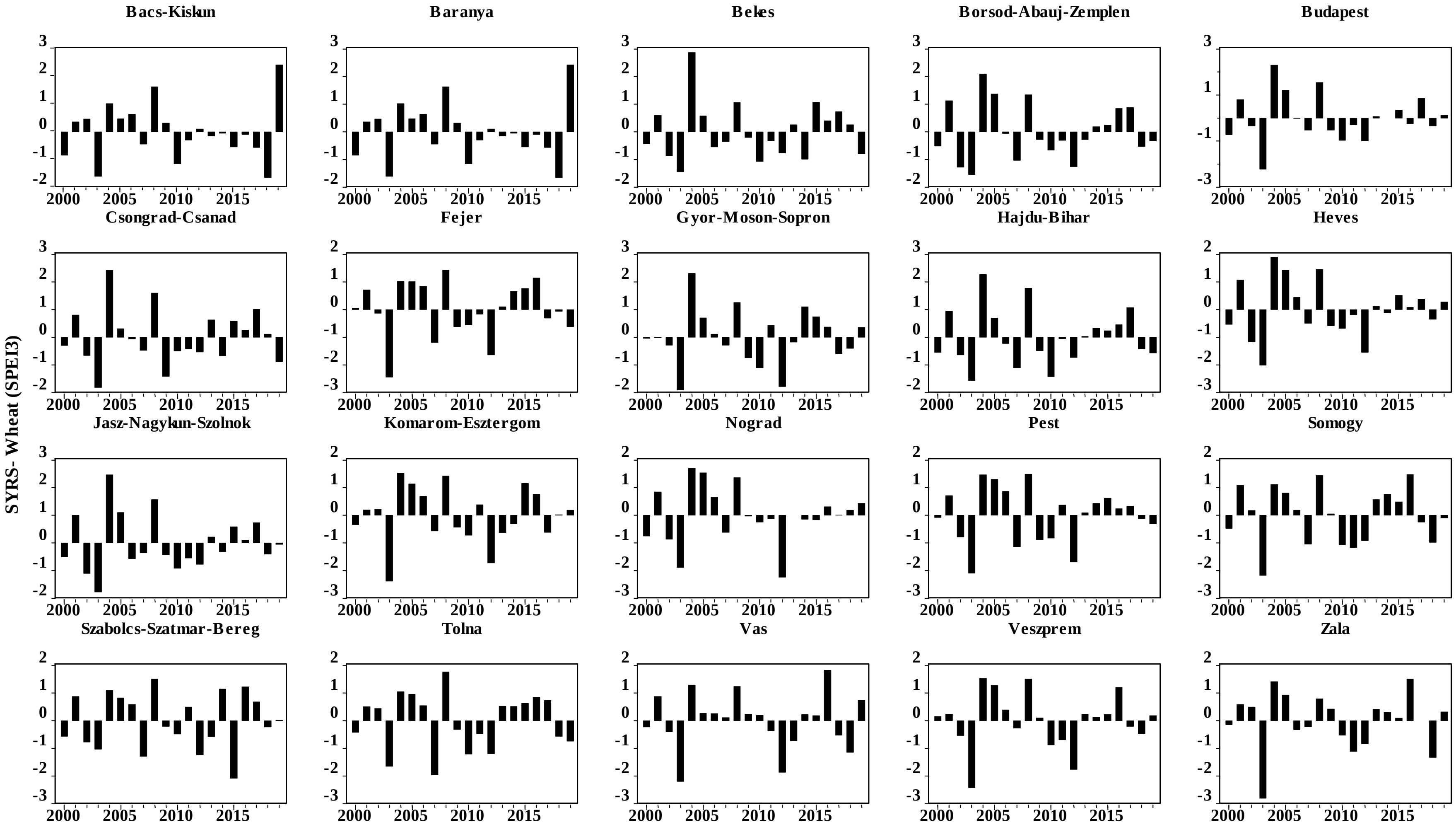

Figure 33. Temporal change in SYRS-wheat crops in Hungary between 2000 and 2019 (regional scale).

4.5.2. Results of the correlation analysis

To illustrate the impact of drought on crop yields, an analysis of agricultural drought indices (SPI-3, SPEI-3, SPI-6, SPEI-6) and SYRS was carried out on a regional scale over Hungary between 2000 and 2010. Unfortunately, the analysis cannot be expanded to cover any more years due to the lack of data sources. Crop yield data was available from 2000 to 2019, while data for agricultural drought indices (SPI-3, SPEI-3, SPI-6, SPEI-6) were available between 1960 and 2010. Consequently, the analysis has been restricted to the intersecting years between the studied variables. However, the Pearson correlation coefficients (r) between agricultural drought indices and the SYRS were analysed for wheat and maize on a monthly scale to reveal to the following:

1. A positive correlation between SYRS and agricultural drought indices (SPI-3, SPEI-3, SPI-6, SPEI-6) was recorded between April and September (i.e. the growing cycle for both wheat and maize), whereas the highest positive correlation was observed in August (Appendix 1-8).
2. A negative correlation between SYRS and agricultural drought indices (SPI-3, SPEI-3, SPI-6, SPEI-6) was recorded between November and February (i.e. the rainy season), whereas the highest negative correlation was observed in December (Appendix 1-8).
3. The highest correlation between SYRS (maize) and SPEI3 was recorded in Csongrad-Csanád ($r=0.92$, $p \leq 0.05$), Bekes ($r=0.92$, $p \leq 0.05$), and Bacs-Kiskun ($r=0.94$, $p \leq 0.05$) in August (Fig 34,35, Appendix 11). Similarly, the highest correlation between SYRS (wheat)-SPI3 was observed in Csongrad-Csanád ($r=0.88$, $p \leq 0.05$), Bekes ($r=0.91$, $p \leq 0.05$), and Bacs-Kiskun ($r=0.90$, $p \leq 0.05$) in August (Fig 36, 37, Appendix 12).
4. On a six-month time-scale, a positive correlation between SYRS (**maize**) and SPEI-6 was observed between June and September over all the regions. The highest correlation was observed in July, reaching $r=0.90$ ($p \leq 0.05$) in Bacs-Kiskun, Bekes ($r=0.93$, $p \leq 0.05$), and Csongrad-Csanád ($r=0.90$, $p \leq 0.05$) (Fig 34,35, Appendix 9).
5. In terms of **wheat**, the SYRS showed a positive correlation with SPI-6 between June and September over all the regions; meanwhile, a negative correlation was observed between December and March. The highest correlation was observed in Bacs-Kiskun,

Bekes (r=0.85, p≤0.05), Bekes (r=0.88, p≤0.05), Csongrad-Csanád (r=0.90, p≤0.05), and Jász-Nagykun-Szolnok (r=0.83, p≤0.05) (Fig 36, 37, Appendix 14).

As shown in Figure 34. the southern and central part of Hungary are the most affected regions in terms of maize yield reduction, where the highest correlation between agricultural drought indices (SPI-3, SPEI-3, SPI-6, SPEI-6) and SYRS was recorded. Notably, the drought impact was worse when we used the SPEI index (dark red area). However, the highest correlation was obtained in August when we used SPI-3 and SPEI-3, while the highest correlation was obtained in July for SPI-6 and SPEI-6 (Figure 35).

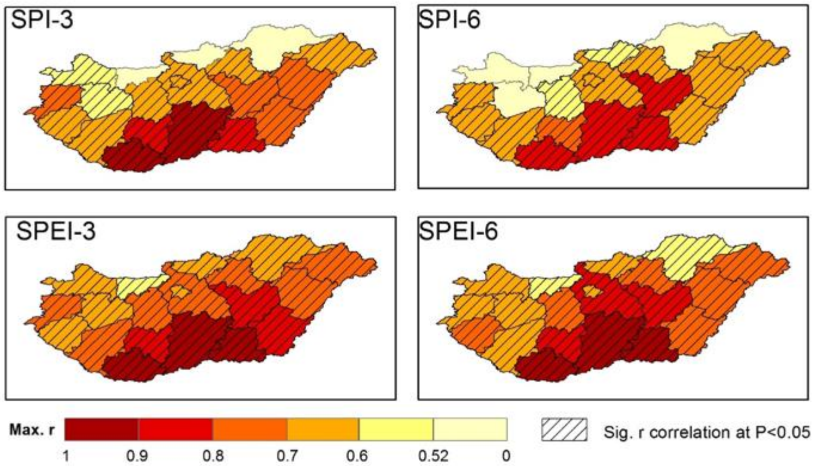

Figure 34. The highest correlations between agricultural drought indices (SPI-3, SPEI-3, SPI-6, SPEI-6) and SYRS for maize in the Hungarian regions between 2000 and 2010.

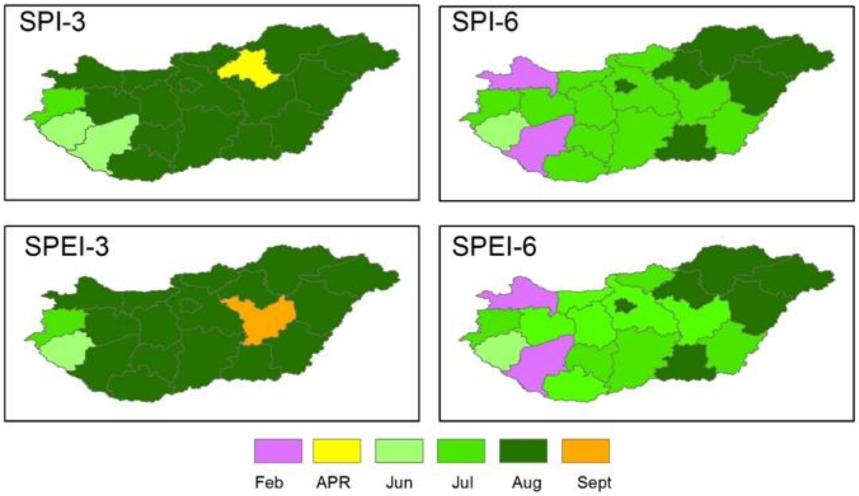

Figure 35. The highest correlations (agricultural drought indices vs. SYRS) obtained during the growing cycle for maize in the Hungarian regions between 2000 and 2010.

Similar to Figure 34, Figure 36 shows that the central parts of Hungary are the regions most affected by wheat yield reductions. Here, most regions showed a significant positive correlation during the growing cycle. Notably, the drought impact was worse when we used the SPEI index (yellow and orange). However, the highest correlation was obtained in April and August for SPI-3, and mainly August for SPI-6, and July and August for SPEI-6, while the highest correlations for SPEI-6 were divided across many months (Figure 37).

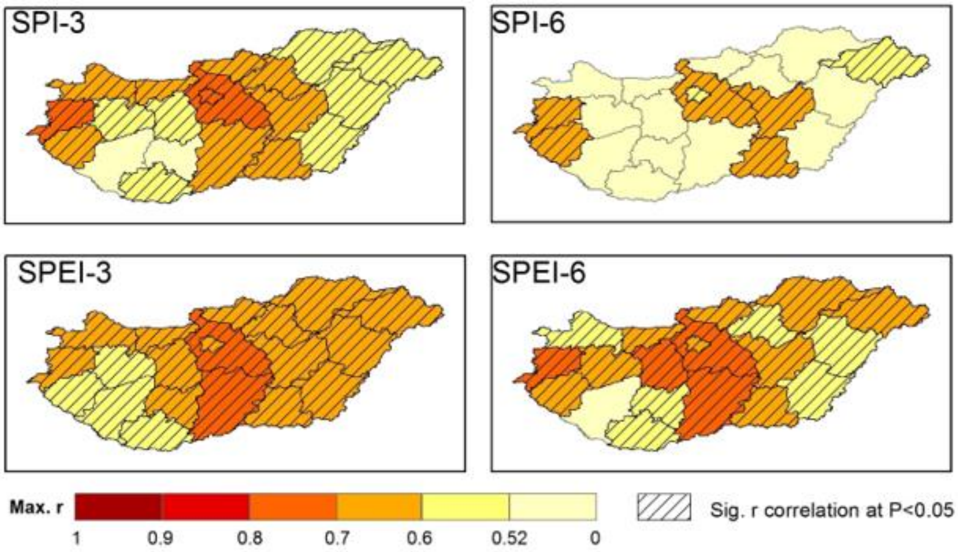

Figure 36. The highest correlations between agricultural drought indices (SPI-3, SPEI-3, SPI-6, SPEI-6) and SYRS for wheat in the Hungarian regions between 2000 and 2010.

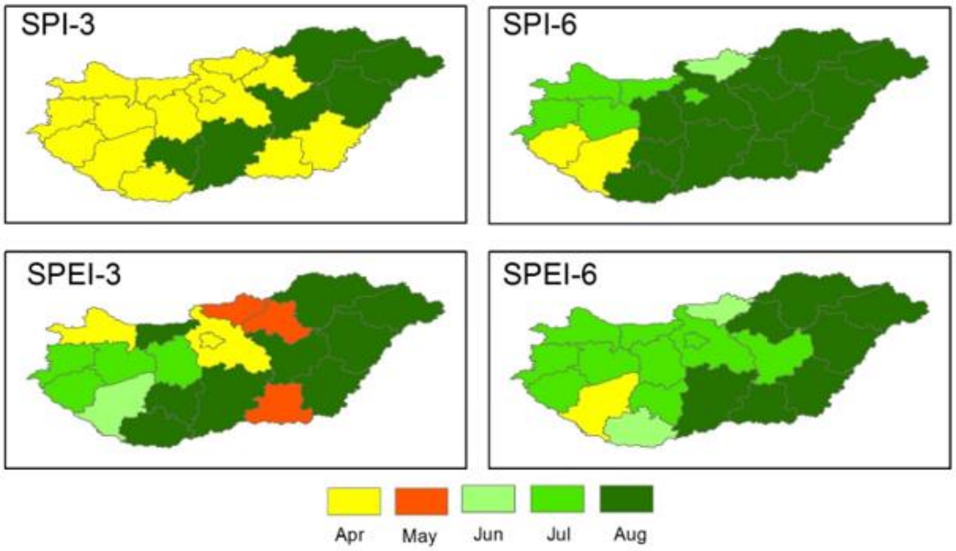

Figure 37. The highest correlations (agricultural drought indices vs. SYRS) obtained during the growing cycle for maize in the Hungarian regions between 2000 and 2010.

4.5.3 Results of Crop yield resilience to drought (CYR_T) analysis

In order to evaluate the impact of drought on crop yields, the crop yield resilience to drought (CYR_T) was analysed over Hungary on a regional scale between 2000 and 2010.

Figure 38 shows that maize yields were slightly affected by drought episodes (SPEI3) in Vas (0.90), while they were moderately non-resilient in Gyor-Moson-Sopron, Hajdu-Bihar, Jasz-Nagykun-Szolnok, Komarom-Esztergom, and Borsod-Abauj-Zemplen, while the rest of the regions were severely non-resilient. In the same conditions, wheat yield was less resilient to drought events (SPEI-3), where most regions were recorded as severely non-resilient, except for Borsod-Abauj-Zemplen (slightly non-resilient), and both Heves and Jasz-Nagykun-Szolnok which were moderately non-resilient (Figure 38). However, the lowest value of the CYR_T for maize was recorded in Bacs-Kiskun (0.57), while for wheat it fell to 0.50 in Budapest.

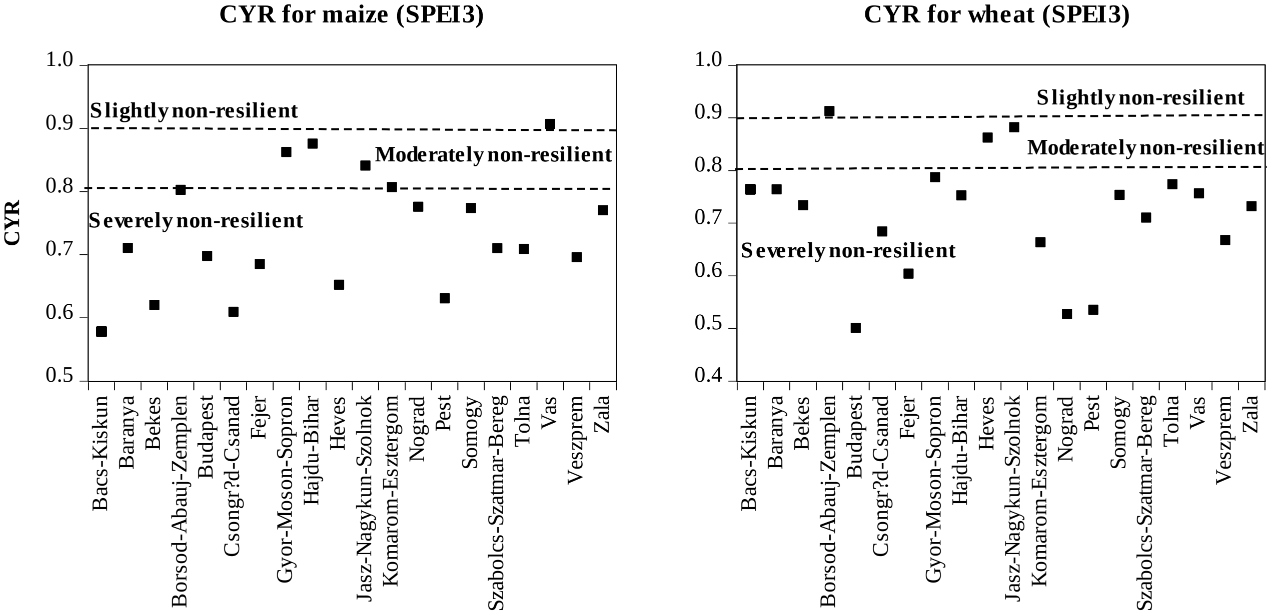

Figure 38. Crop yield resilience to drought (CYR_T) in terms of SPEI-3 for maize and wheat in Hungarian territory between 2000 and 2010.

In terms of SPI-3, the maize crop was slightly non-resilient in two regions (Vas, Veszprem), while four regions were moderately non-resilient (Borsod-Abauj-Zemplen, Gyor-Moson-Sopron, Komarom-Esztergom, Csongrád-Csanad) (Figure 39). For wheat, four regions were slightly non-resilient (Bekes, Borsod-Abauj-Zemplen, Hajdu-Bihar, Csongrád-Csanad), while four regions were moderately non-resilient (Bacs-Kiskun, Heves) (Figure 39). The rest of the regions for both crops were evaluated as severely non-resilient, as can be seen in Figure 39.

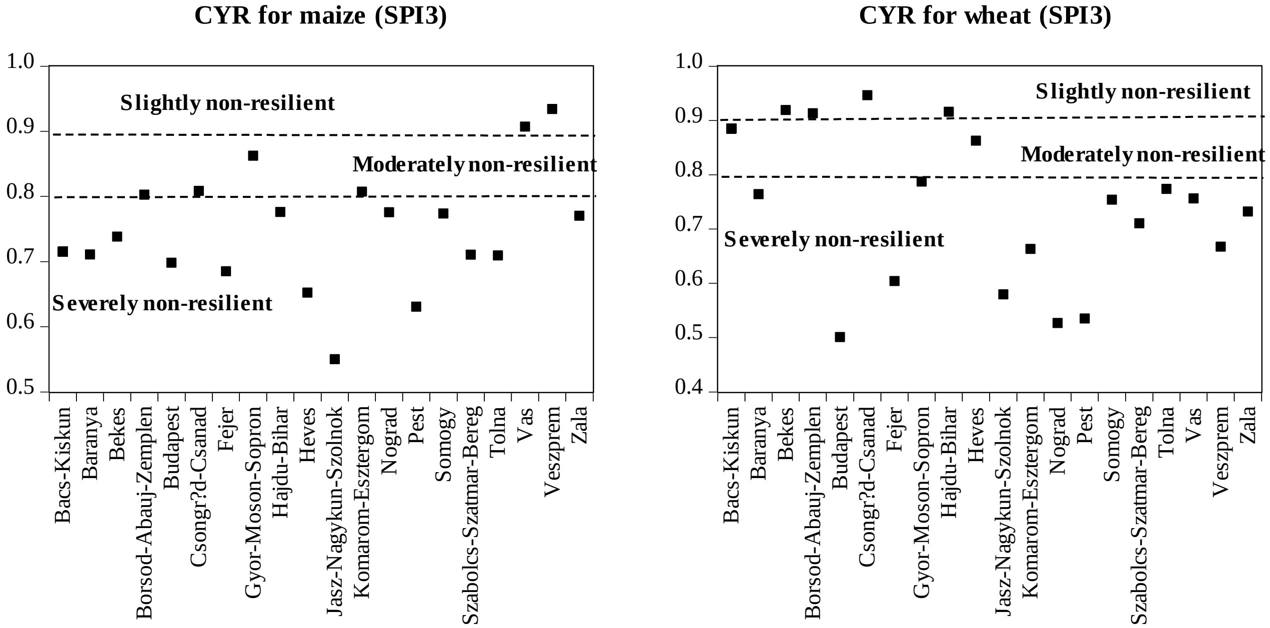

Figure 39. Crop yield resilience to drought (CYR_T) in terms of SPI-3 for maize and wheat in Hungarian territory between 2000 and 2010.

By tracking the interaction between crop yield (maize, wheat) and the six months drought cycle (i.e. SPEI-6, SPI-6), the following points could be made:

1- Wheat yield was less vulnerable to drought in Bekes, Borsod-Abauj-Zemplen, Csongrád-Csanad, and Hajdu-Bihar (Figure 40, Figure 41).

2- Maize yield was less vulnerable to drought in Vas and Veszprem (Figure 40, Figure 41).

3- The lowest value of the CYR_T-SPEI-6 for maize was recorded in Bacs-Kiskun (0.57), and fell to 0.55 in Jasz-Nagykun-Szolnok for CYR_T-SPI-6.

4- The lowest values of the CYR_T-SPEI-6 and CYR_T-SPI-6 for wheat were recorded in Budapest (0.50).

The agricultural drought indices (SPI-3, SPEI-3, SPI-6, SPEI-6) for the CYR_T showed that the crop yields for both maize and wheat were severely non-resilient ($CYR_T < 0.8$) in the following regions: Baranya, Budapest, Fejer, Nograd, Pest, Somogy, Szabolcs-Szatmar-Bereg, Tolna, and Zala.

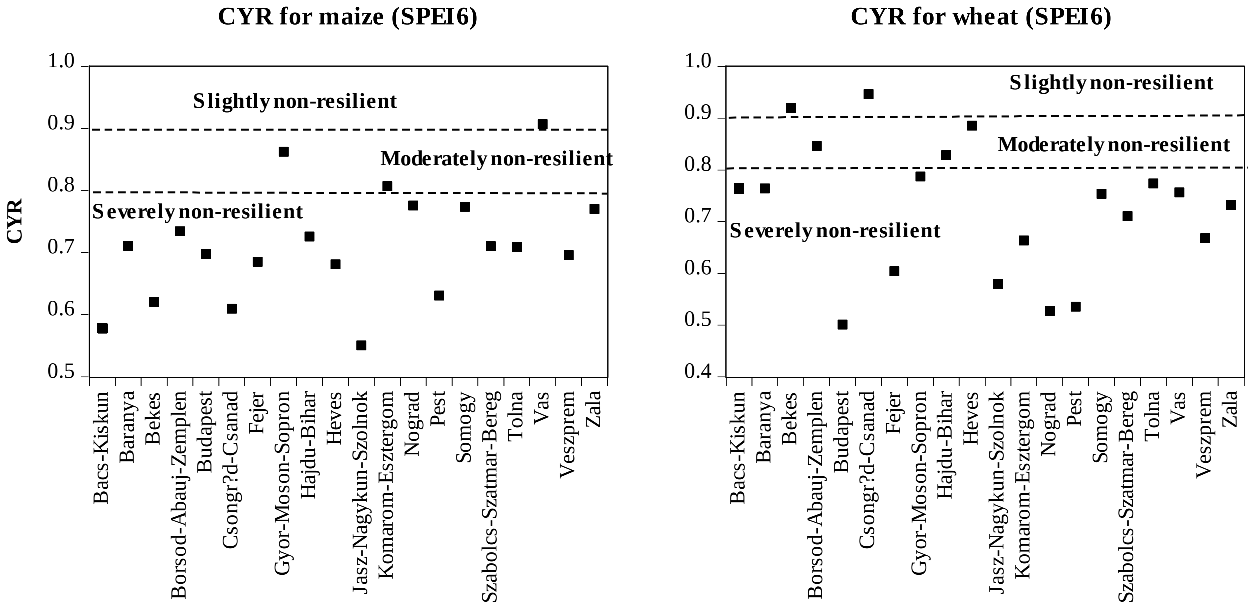

Figure 40. Crop yield resilience to drought (CYR_T) in terms of SPEI-6 for maize and wheat in Hungarian territory between 2000 and 2010.

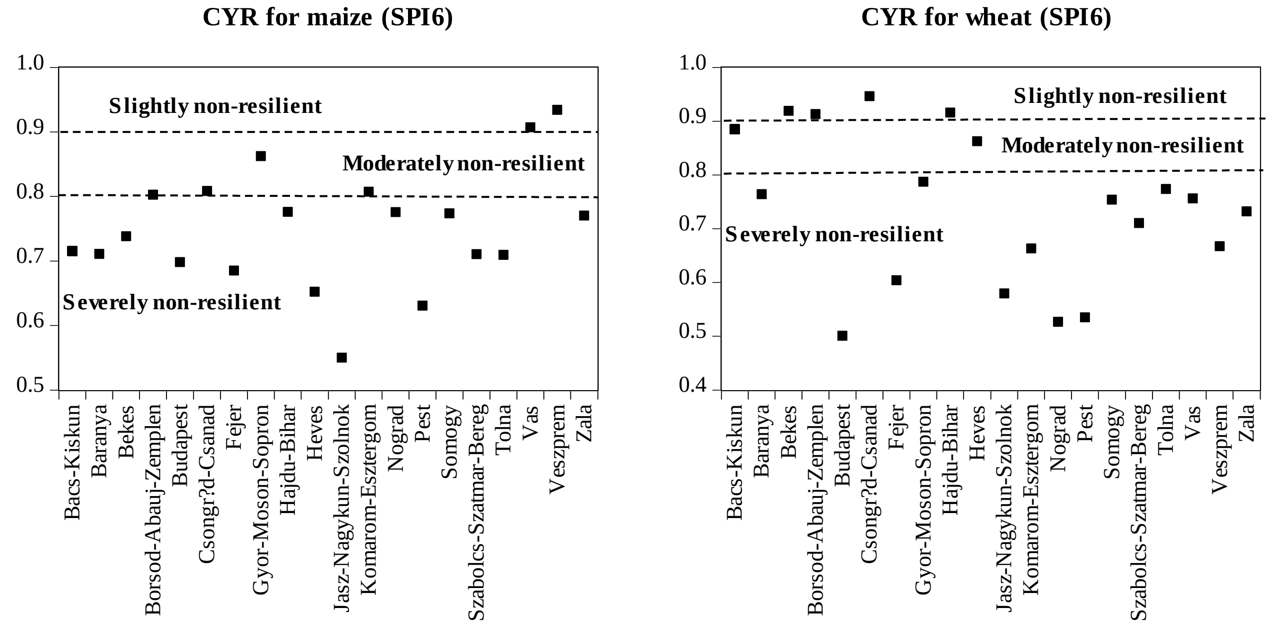

Figure 41. Crop yield resilience to drought (CYR_T) in terms of SPI-6 for maize and wheat in Hungarian territory between 2000 and 2010

Drought is one of the challenges for crop production in many parts of the word (*Zipper et al*. 2016). In this section the CYR_T approach was used to highlight the impact of drought on crop yields. Corresponding to our analysis of the period between 2000 and 2010, most regions in Hungary showed that crop yields for both maize and wheat were severely non-resilient to drought. However, to cope with maize yield variations, irrigation could be one of the possible solutions to obtain high yields and to minimize the impact of climate, especially in the Great plain of Hungary (*Nagy* 2006, *Nagy* 2010), since water supply plays a great role in achieving the maximum yield in Hungary (*Nagy* 2006).

Previously, *Széles and Nagy* (2012) noticed a reduction in a crop yields in Hungary due to drought, with roughly 500,000 ha requiring irrigation. Meanwhile, *Juhász et al* (2013) demonstrated that between 2003 and 2013 rainfall changes (i.e. climate change) caused a crop yield reduction of 25-30%.

Most results reveal that the highest correlation (agricultural drought indices vs. SYRS) were obtained in July or August, which corresponds to the tasselling stage of maize during the growing cycle between 2000 and 2010. Within this context, *Széles and Nagy* (2012) reported that drought events during the tasselling stage of maize could possibly reduce the yield by between 40% and 50%. Also, as maize is a heat sensitive crop (Kovacs et al. 2010), this may be an issue, which could explain the higher correlation values between SPEI-3, -6 and SYRS, especially in the northern Great Plain of Hungary, where SPEI takes temperature into consideration. However, many scholars have reported on the sensitivity of maize to drought, for instance in Serbia (*Kresović et al*. 2016), the USA (*Zipper et al*. 2013), and Europe (*Webber et al*. 2018).

By comparing the results obtained for the CYR_T for wheat and maize, we can demonstrate that wheat is more resilient than maize. This result agrees with global scale research conducted by *Daryanto et al*. (2016), which concluded that wheat is less sensitive to drought than maize, especially in its reproductive phase. It is important to mention here that the different interactions of maize and wheat with drought could mainly be attributed to their different origins. In this regard maize originated from a wet region (*Van Heerwaarden et al*. 2011), while wheat originated from a dry region (*Haudry et al*. 2007). Thus, the inherited adaptability traits of maize and wheat could play a crucial role in crop adaptation (*Daryanto et al*. 2016).

4.6. Results of the comparative analysis of CO_2 emissions from two different agricultural ecosystems

Since fluxes of CO_2 from soil are the second largest component of the global carbon cycle, which has altered climate on a global scale, and led to climate change (Reth et al. 2005), we designed this part of the research to evaluate fluxes of CO_2 from two different crop management fields in two different regions. The main aim of this section is to give an overview of difference in emissions between two agroecosystems. The first one is a continental region represented by Debrecen (Latokep field), while the second is an arid region represented by Tehran (field of the Faculty of Agriculture). The measurements were carried out in two different maize fields: 1) tillage (T), 2) and non-tillage (N), between 02.08.2018, and 13.09.2018.

4.6.1. Daily CO_2 emissions

On a daily scale, the results showed a statistical difference ($p<0.05$) among treatments in the first, second, fourth, and fifth sampling dates (Table 11). For the third sampling date (10.08.2018), no significant differences were detected between the Tehran treatments, while in the sixth sampling date a statistical difference ($p<0.05$) was detected among locations (i.e. Debrecen vs. Tehran) regardless of the treatment types (i.e. T, N) (Table 12). Notably, the highest emissions were recorded in the tillage field in Tehran (C3), which ranged between 648±270 and 445±202. Meanwhile, the lowest emissions were recorded in the non-tillage field in Debrecen (C1), which ranged between 159± 48.8 and 66.33±16.20 (Figure 42).

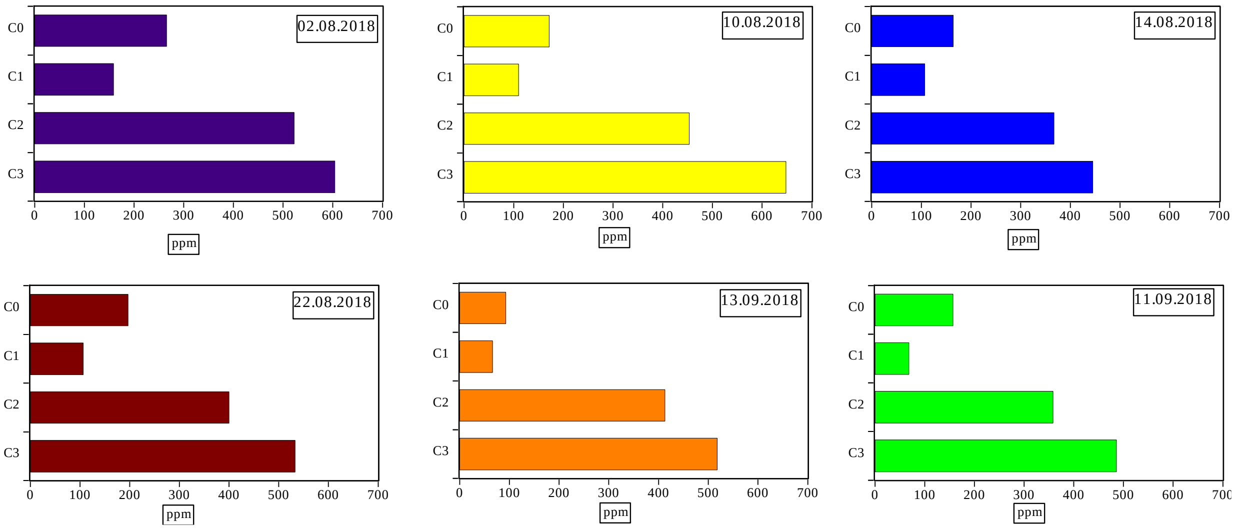

Figure 42. Daily soil CO_2 emissions data (ppm) with respect to treatments; C0: tillage field in Debrecen; C1: non-tillage field in Debrecen; C2: non-tillage field in Tehran; C3: tillage field in Tehran.

Table 11. Statistical analysis of soil CO_2 emissions data (ppm) using the Fisher LSD test. Means with the same letter are not significantly different ($p<0.05$).

Field*	**Code**	**02.08.2018**	**10.08.2018**	**14.08.2018**	**22.08.2018**	**11.09.2018**	**13.09.2018**
T. Debrecen	C0	$265.7^{A}\pm 82.7$	$171.7^{A}\pm41.4$	$164.3^{A}\pm60.1$	$196.7^{A}\pm128.5$	$157.0^{A}\pm68.4$	$93.00^{A}\pm7.55$
N. Debrecen	C1	$159^{B}\pm 48.8$	$110.0^{B}\pm26.1$	$107^{B}\pm15.13$	$106.7^{B}\pm20.6$	$68.0^{B}\pm17.3$	$66.33^{A}\pm16.20$
N. Tehran	C2	$522^{C}\pm 190$	$453.5^{C}\pm123.$	$367^{C}\pm200$	$400.0^{C}\pm124$	$358.2^{C}\pm143.2$	$413^{B}\pm179$
T. Tehran	C3	$604^{D}\pm 176$	$648^{D}\pm270$	$445^{C}\pm202$	$533^{D}\pm210$	$486^{D}\pm196$	$518.0^{B}\pm158.8$

(T: tillage, non-tillage N) (n= 3 for each sampling date)

For further investigation of the difference among the means of the treatments, we applied the Fisher individual tests as presented in Table 12. The results can be summarized as follows:

1- On a daily scale, no statistical differences ($p<0.05$) were detected among treatments from the same geographical locations e.g. C1 - C0, and C3 - C2.

2- No statistical differences ($p<0.05$) were detected between the non-tillage field in Tehran (C2), and the tillage field in Debrecen (C0), which reveals that emissions from non-tillage agricultural lands in dry and semi-dry regions are almost similar to emissions from tillage fields in continental regions.

Table 12. Fisher individual tests for differences in the means of the treatments ($p<0.05$)

Difference of Levels	**02.08.2018**	**10.08.2018**	**14.08.2018**	**22.08.2018**	**11.09.2018**	**13.09.2018**
	P-Value					
C1 - C0	0.372	0.629	0.642	0.448	0.413	0.792
C2 - C0	0.052	0.051	0.126	0.109	0.087	**0.011**
C3 - C0	**0.017**	**0.005**	**0.045**	**0.018**	**0.013**	**0.002**
C2 - C1	**0.012**	**0.023**	0.060	**0.032**	**0.023**	**0.008**
C3 - C1	**0.004**	**0.002**	**0.021**	**0.005**	**0.004**	**0.002**
C3 - C2	0.490	0.153	0.528	0.271	0.252	0.313

(C0: tillage field in Debrecen; C1: non-tillage field in Debrecen; C2: non-tillage field in Tehran; C3: tillage field in Tehran)

3- A statistical difference ($p<0.05$) was detected among treatments from different geographical locations e.g. C3 - C0, C2 – C1, and C3 - C1 which clearly emphasizes the role of climate conditions in CO_2 emission processes.

Table 13. Statistical analysis of soil temperature (T_{soil}), and soil moisture (M_{soil}) using the Fisher LSD test. Means with the same letter are not significantly different ($p<0.05$).

		02.08.2018		**10.08.2018**		**14.08.2018**		**22.08.2018**		**11.09.2018**		**13.09.2018**	
		T_{soil}	M_{soil}	T_{soil}	M_{soil}	T_{soil}	M_{soil}	T_{soil}	M_{soil}	T_{soil}	M_{soil}	T_{soil}	M_{soil}
T.Debrecen	C0	24.00^{A}	22.82^{A}	25.70^{A}	17.83^{A}	25.30^{A}	11.55^{A}	24.40^{A}	15.26^{A}	19.60^{A}	22.82^{A}	20.40^{A}	23.47^{A}
N.Debrecen	C1	23.80^{A}	20.41^{B}	25.60^{A}	24.76^{B}	25.40^{A}	20.41^{B}	19.70^{B}	27.01^{A}	19.70^{A}	27.01^{B}	19.70^{B}	22.98^{A}
N. Tehran	C2	23.07^{B}	19.26^{C}	20.48^{B}	22.69^{C}	17.67^{B}	17.33^{C}	18.48^{C}	19.28^{B}	15.66^{B}	15.84^{C}	16.24^{C}	18.30^{B}
T. Tehran	C3	25.37^{C}	18.30^{C}	23.18^{C}	18.07^{D}	18.70^{C}	12.88^{D}	18.62^{D}	14.67^{C}	18.11^{C}	12.77^{C}	18.63^{D}	14.62^{C}

(T: tillage, non-tillage N) (n= 3 for each sampling date)

Table 14. Fisher individual tests for differences in the means of the factors studied (i.e. soil temperature (T_{soil}), and soil moisture (M_{soil})) ($p<0.05$)

	02.08.2018		**10.08.2018**		**14.08.2018**		**22.08.2018**		**11.09.2018**		**13.09.2018**	
	$p(T_{soil})$	$p(M_{soil})$	$p(T_{soil})$	$p(M_{soil})$	$p(T_{soil})$	$p(M_{soil})$	$p(T_{soil})$	$p(M_{soil})$	$p(T_{soil})$	$p(M_{soil})$	$p(T_{soil})$	$p(M_{soil})$
C1 - C0	0.537	0.129	0.762	**0.000**	0.187	**0.006**	**0.000**	**0.000**	0.770	**0.032**	0.256	0.829
C2 - C0	**0.002**	**0.002**	**0.000**	**0.001**	**0.000**	**0.043**	**0.000**	**0.023**	**0.002**	**0.003**	**0.015**	**0.044**
C3 - C0	**0.017**	**0.013**	**0.000**	0.822	**0.000**	0.596	**0.000**	0.691	**0.000**	**0.000**	**0.000**	**0.004**
C2 - C1	**0.001**	**0.000**	**0.000**	0.080	**0.000**	0.236	**0.000**	**0.001**	**0.001**	**0.000**	0.099	0.062
C3 - C1	**0.047**	0.177	**0.000**	**0.000**	**0.000**	**0.014**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.005**
C3 - C2	**0.000**	**0.000**	**0.000**	**0.002**	**0.000**	0.101	0.169	**0.012**	**0.000**	0.093	**0.003**	0.129

(C0: tillage field in Debrecen; C1: non-tillage field in Debrecen; C2: non-tillage field in Tehran; C3: tillage field in Tehran)

Since the total CO_2 emissions are affected by soil temperature (T_{soil}) and soil moisture (M_{soil}) we applied the Fisher LSD test to distinguish the difference between the factors. The results are presented in Tables 13 and 14 and can be summarized as follows:

1- In terms of soil temperature, no significantly difference ($p<0.05$) was recorded between N and T in Debrecen for almost all sampling dates, while a significant difference ($p<0.05$) in soil temperature was observed between N and T in Tehran.

2- The differences in the soil moisture were more obvious, which could be expected due to the differences between the tillage and non-tillage techniques.

3- During the study period, the average daily soil temperature in Debrecen ranged from 19.6 to 25.7°C. Meanwhile, the average daily soil moisture ranged from 11.66 to 23.4 % in the T-system, and from 20.41 to 27.01% in the N-system.

4- In the semiarid climate, soil temperature ranged from 16.42 to 23.07°C in the N-system and 18.11 to 25.37°C in the T-system. The average daily soil moisture ranged from 12.77 to 18.30% in the T-system, and from 15.84 to 22.69% in the N-system.

5- When the measurements were carried out in two adjustment locations, the (Tsoil) and (M_{soil}) were significantly different ($p<0.05$) between the N and the T systems in the semiarid climate. This emphasizes the important role of agricultural practice in some soil properties.

6- Pair means comparison showed that tillage practice has a greater impact on soil moisture than on soil temperature (Table 14)

4.6.2. Seasonal CO_2 emissions

Results revealed that the highest emission in both agroecosystems were recorded in the T-system, where the average was 314.92± 63.19 ppm in Tehran, and 155.60 ±36.45 ppm in Debrecen, while in the N-system the average was 239.48± 60.34 ppm in Tehran, and 121.83±46.60 ppm in Debrecen. The recorded emissions can be tracked in Fig 43, 44.

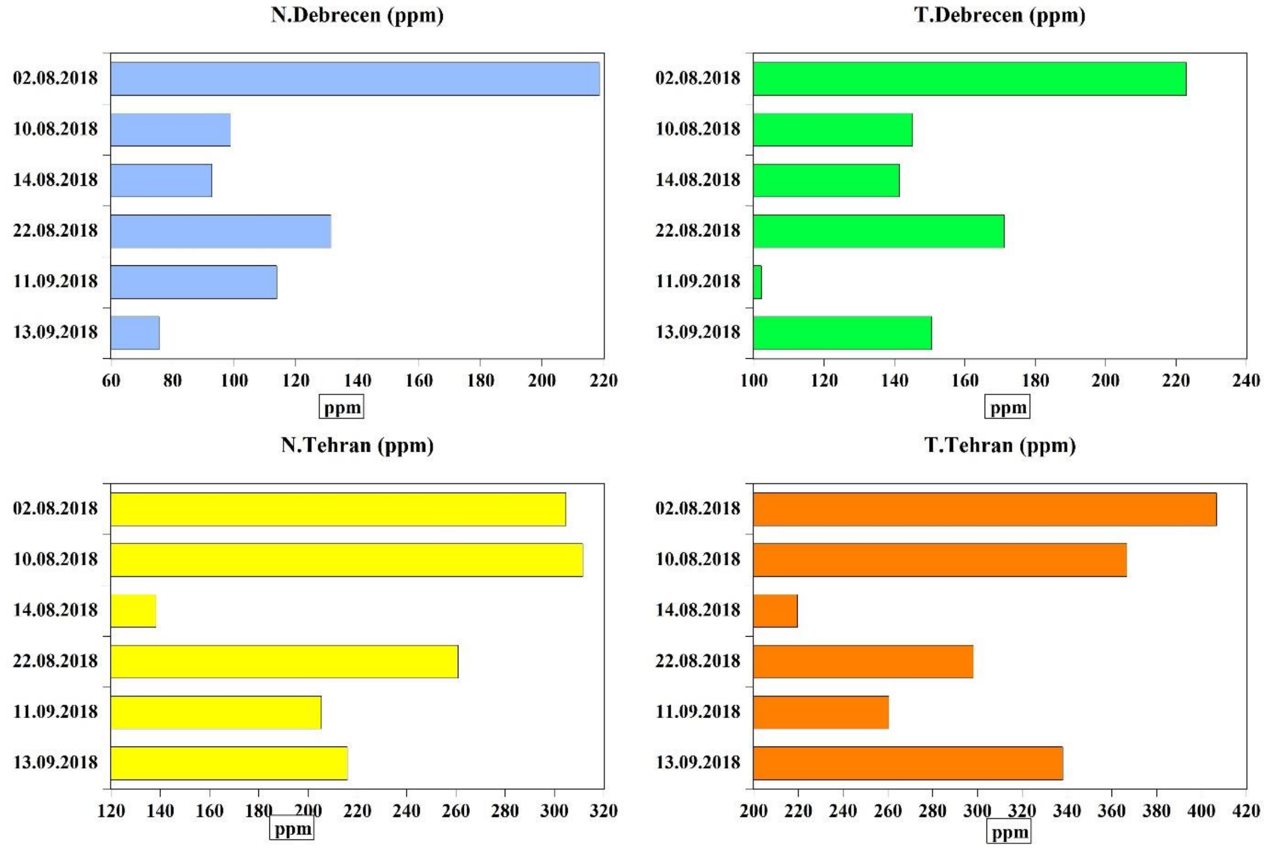

Figure 43. Average values of CO_2 emissions in the studied plots on a regional scale (Debrecen vs Tehran) in maize fields under two different crop managements: 1) tillage (T), 2) and non-tillage (N)**.**

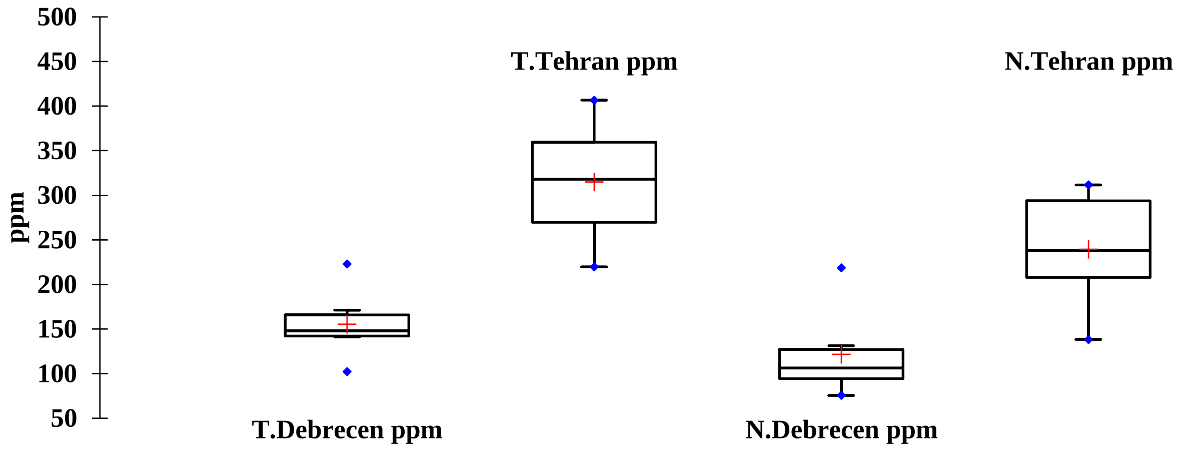

Figure 44. Boxplot of recorded values of CO_2 emissions in the plots studied on a regional scale (Debrecen vs Tehran) in maize fields under two different crop managements: 1) tillage (T), 2) and non-tillage (N)

For a further investigation of the differences between emissions in both fields we applied the Mann–Whitney U test (*Mann and Whitney*, 1947). The results showed that no significant differences were recorded between tillage farms in both Debrecen and Tehran, while significant differences were recorded in non-tillage farms in both Debrecen and Tehran (Table 15). Nonetheless, no significant differences were recorded in each region regardless of the crop management, as can be seen in Table 15.

Table 15. Comparison between CO_2 emissions in the plots studied using the Mann–Whitney U test ($p<0.05$)

Test	Treatment	U	z	p (same med.)
Mann-Whitn	Tillage (Debrecen Vs. Tehran)	7	2.6421	0.092696
Mann-Whitn	Non-Tillage (Debrecen Vs. Tehran)	0	2.8022	**0.0050749**
Mann-Whitn	Debrecen (Tillage VS. Non-Tillage)	7	1.6813	0.092696
Mann-Whitn	Tehran (Tillage VS. Non-Tillage)	8	1.5212	0.12821

Figure 45 shows the correlation between emissions in different distributions. In this regard, the lower correlation ($R^2=0.29$) was recorded in the N-system (Debrecen vs. Tehran), followed by the T-system (Debrecen vs. Tehran) ($R^2=0.48$). Interestingly, a higher correlation was recorded in the same farm regardless of the crop system.

In this final part of this research, CO_2 emissions were tracked in two different climate regions with almost the same conditions (except for the climate). The results reveal that CO_2 emissions from the conventional tillage system (CT) were higher than from the no-tillage system (NT). Also, CO_2 emissions were higher in the arid region represented by Tehran (field of the Faculty of Agriculture), and lower in the continental region represented by Debrecen (Latokep field).

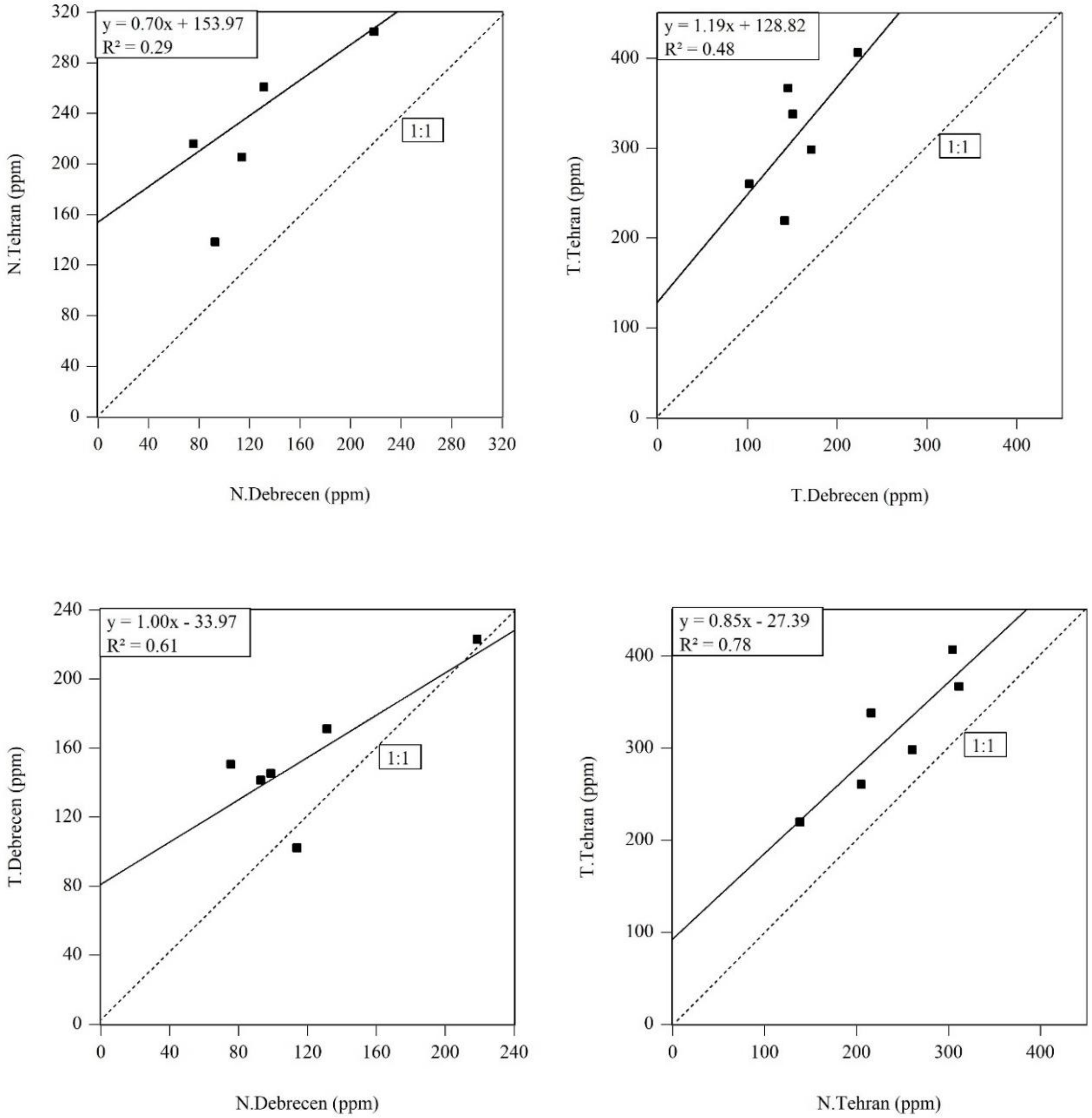

Figure 45. Scatter plot matrix for CO_2 emissions in different distributions**.**

The output of this research showed the significant effect of tillage system (i.e. NT and CT) on the total CO_2 emissions. In this sense, Moldboard plowing disintegration of soil aggregates, which improves soil aeration and enhances microbial activities (*de Oliveira Silva et al*. 2019). Also, smaller aggregates accelerate the decomposition of soil organic matter (SOM), and enhance CO_2 emission, which support our finding in Fig.42 and Table 11. Our results come along with *La Scala et al*. (2006) noticed that the highest emissions were recorded with conventional tillage compared to other cropping systems, such as reduced tillage and no-tillage. Similarly, *Omonode et al.* (2007) highlighted that CO_2 emissions from tillage corn fields were significantly higher than in a no-tillage system, and concluded that the N system is the lowest system that drives CO_2 to the atmosphere. *Silva-Olaya et al.* (2013) reach the same conclusion as we reached with our results and reported that CO_2 emissions were higher in a conventional tillage plot, compared with other systems (i.e. minimum tillage, non- tillage, and reduced tillage).

Temperature is one of the factors that dramatically affects SOM decomposition, and consequently CO_2 emissions. Scientifically, increasing soil temperature accelerates SOM decomposition, as well as emissions of CO_2 (*Li et al*. 2017, *Razavi et al*., 2015), which agrees with the results presented in Table 13, Table 14, and Fig.43. Our results are in line with many scholars who reveal that the peak of soil emissions occurs in summer (*Gasche et al*. 2002, *Kitzler et al*. 2006, *Schaufler et al*. 2010). Nonetheless, lower T_{soil} normally lead to lower emissions and to the dynamic interaction (i.e. the exponential response) between T_{soil} and CO_2 efflux (*Cox et al.*, 2000; *Reth et al.* 2005, *Dowhower et al*. 2020). M_{soil} affects gas diffusivity, thus more emissions are expected in dryer conditions, as can be seen in Table 14. *Šimek et al.* (2004) reported a significant correlation between emissions of CO_2 from the soil and soil moisture. However, it is important to emphasize that CO_2 flux rates could not be derived from one single factor (i.e. T_{soil}, M_{soil}); thus, we cannot separate the whole process into sub processes (*Schaufler et al.* 2010). Anyway, we have separated T_{soil} and M_{soil} to simplify our results. Ultimately, both T_{soil} and M_{soil} affect soil GHGs emissions (CO_2, CH_4, N_2O) due to their direct impact on plant health, root systems, nutrient recycling, and microbial activities (*Smith et al.* 2003; *Levine et al*. 2011, *Dowhower et al*. 2020). However, climate change (i.e. global warming) is rapidly increasing soil temperature, and altering soil water content due to drought, which will markedly alter the carbon cycle (*Fang et al*. 2016; *Wang et al*. 2019).

Scientifically, T_{soil} accelerates the release of CO_2 from organic matter particles in the soil, where CO_2 emissions increase exponentially with increases in T_{soil} under different M_{soil} levels. Nonetheless, emissions become a function of M_{soil} as a soil dries out (Wang et al. 2019; Smith et al. 2003). In this regard, a combination of T_{soil} under different M_{soil} states in the field studied could be detected in Tables 13 and 14, which reveal that T_{soil} drives CO_2 emission, and soil moisture is suitable for this process. This point could be explained by the fact that soil in the semiarid region was irrigated every seven days, which keeps the M_{soil} at an optimal level for both plant growth and CO_2 emissions. However, more research is required to identify the key roles of both T_{soil}, $M_{soil.}$. On a daily scale, our observations in the Debrecen field reveal that T_{soil} was almost similar in the CT and the NT systems, while M_{soil} varied between them, which leads to a minimizing of CO_2 emissions from the NT system. Similar results were obtained from the Tehran fields; nevertheless, significant differences were noticed among plots in terms of T_{soil} and M_{soil}. However, claiming that the differences in emissions between treatments is only attributable to soil water content and soil temperature requires more research and field measurements.

Emission from Hungarian soils were previously established by many schoolers. For instance, *Toth et al.* (2020) reported that CO_2 flux from Hungarian soils (Józsefmajor) was 0.060 ± 0.088 mg $m^{-2}s^{-1}$. *Bilandžija et al.* (2016) reported that CO_2 from corn field in Croatia (near to Hungary) significantly affected by tillage treatment, which is align with our results in Figure 43 and 44. Similarly, *Radicetti et al*. (2020) noticed that deep tillage had the highest CO_2 from eggplant filed in Viterbo, Italy. In this sense, *Birkás* (2008) confirmed that traditional tillage directly released 50% of soil organic carbon due to microbial respiration, which could explain the superior emission in TC treatment in both locations. Overall, assessment of the impact of soil tillage and soil management practices on SOM and CO_2 emissions is a complex issue, which needs long time monitoring period to draw any conclusions about the interaction between different practices and CO_2 emissions. Nonetheless, our main goal in this research was to give an overview of CO_2 emissions in two different climate regions, and this study could be a baseline for further research in this area.

5. CONCLUSIONS

Minimizing GHG emissions is one of the issues that should be considered to fight against global warming and climate change. In this regard, this research was designed to investigate GHG emissions from the agricultural sector within the studied EU countries. However, this research was extended to analyse GHGs from the agricultural sector in Hungary. Also, this study attempts to track the evolution of drought in Hungary between 1960 and 2010 as one of the consequences of a global increase in GHG emissions.

GHGs emissions (thousands of tonnes of CO_2 eq.) dropped significantly over most studied counties of the EU, which confirms the effectiveness of the environmental programs and policies pursued by the European Union to reduce GHGs emissions. In contrast, current and future CO_2 emission was increased; while, CH_4 showed a negative trend from the Hungarian agricultural sector. Nonetheless, Future projections by ARIMA indicate a gradual increase in CO_2 emission from the agricultural sector in Hungary till 2040. In contrast, CH_4, and N_2O showed a remarkable decrease between 2016-2040.

In terms of climate change (i.e. drought), drought episodes were evolved in the eastern part of Hungary between 1961 and 2010, while drought episodes were less pronounced in the western part. However, the frequency of agricultural drought (TDD) between 1961 and 2010 demonstrates that the central part (Bács–Kiskun), and the eastern northern part (i.e. Veszprém) were the areas most subjected to agricultural drought. In this sense, drought has a bad consequence on maize and wheat production. However, the CYR_T showed that the crop yields for both maize and wheat were severely non-resilient (CYRT < 0.8) in the following regions: Baranya, Budapest, Fejer, Nograd, Pest, Somogy, Szabolcs-Szatmar-Bereg, Tolna, and Zala. Thus, more attention should be paid to these counties for climate adaptation programs.

On a field scale, the climate seems to have a significant impact on carbon dioxide emissions. In this regard, CO_2 emissions were higher in the semi-arid region rather than the continental region.

The outcome of this research could help planners and discission makers for improving strategies regarding climate change adaptation and mitigation. And give general insights about the most vulnerable areas to drought and its impact in Hungary.

6. NEW SCIENTIFIC RESULTS

This research demonstrates the following new scientific results:

1. Most of the studied EU countries witnessed a significant ($p< 0.05$) reduction of GHGs from the agricultural sector between 1990 and 2016. Remarkably, a negative GHGs emission from the agricultural sector was recorded in all studied countries. Nonetheless, a negative but not significant trend was detected in all EU countries except for Estonia, Hungary, Iceland, Latvia, Lithuania, and Spain.
2. Analysis of GHGs emissions from the agricultural sector reveals that the M-K test results showed that CO_2 emissions were increased significantly ($p<0.05$) by +368.72 thousand tonnes/year. While CH_4 emission was subject to a significant decrease ($p<0.05$) by -2.37 thousand tonnes/year
3. Future projection by ARIMA indicates a gradual increase of CO_2 emission from the agricultural sector in Hungary till 2040. In contrast, CH_4, and N_2O showed a remarkable decrease between 2016-2040.
4. Climate change (i.e. drought) analysis showed that the eastern northern part and central part of Hungary are more subjected to the drought cycle. The drastic years are 1970-1973, 1990-1995, 2000-2003, and 2007.
5. In terms of the consequences of climate change on the agricultural sector, the western and southern regions of Hungary were more subject to maize yield losses (SYRS), while wheat yield reduction was less pronounced in comparison with maize. The highest maize yield losses (i.e. $\text{SYRS} \leq -1.50$) in 2003 were recorded in the southern part. Wheat yield losses due to drought were experienced in 2003 and 2010. However, the highest impact of drought on crop reduction (i.e. highest correlation between SYRS and crop yield) was recorded in August for the central and eastern parts of Hungary.
6. The outcome of this research, under the current climate of Hungary, the wheat crop is more resilient to drought events than maize. Nonetheless, the CYR_T showed that the maize and wheat yields were severely non-resilient ($CYRT < 0.8$) in the central and western parts of Hungary. Thus, expanding wheat cultivation area could be one of the solutions to mitigate climate change.

7. On a field scale, results showed that measured CO_2 emissions in semiarid plots (Tehran) were higher in comparison with continental ones (Debrecen). Also, in both climate conditions emissions from the tillage system were higher than the no-tillage one.

7. PRACTICAL UTILIZATION OF THE RESULT

1- GHGs reduction across Hungary and national strategy

Until recently, policies in many countries were driven by economic growth; meanwhile, few plans were drawn out to mitigate environmental degradation, including minimizing GHGs emissions. As Hungary is required to reduce GHGs emission by 10 % by 2020 compared to 2005 levels (the baseline), the output of this research highlighted the most emitted sectors across Hungary. Thus, the outcome could serve as a starting point or baseline for implementing some actions toward minimizing GHGs from various sectors. Also, this research could be used to develop a national plan for climate adaptation and climate mitigation from different sectors in Hungary. Notably, the results could support the government work through the Hungarian Adaptation Strategy (NAS); the National Decarbonization Roadmap (NDR); and the Climate Awareness Plan in a national level (CAP).

2- Risk assessment of climate change on agricultural sector

This study demonstrates the most affected subregion by drought and highlighted the affected crops by agricultural drought in terms of agriculture. Maize and wheat were severely non-resilient to drought (CYR_T< 0.8) in the following regions: Baranya, Budapest, Fejer, Nograd, Pest, Somogy, Szabolcs-Szatmar-Bereg, Tolna, and Zala. Such a result stresses the importance of a climate change adaptation plan for the sustainability of the agroecosystem. Thus, a national plan accompanies by some action on a sub-regional scale could mitigate climate change. Also, the adaptation of some agricultural technology such as precision agriculture in the affected area by drought could increase crop resilience and enhance natural resource management.

3- Minimizing GHGs emission from agricultural sector over Hungary

Our results showed that the CO_2 emission from traditional system was higher than conservation one. Thus, the output recommended the conservation agricultural system (CAS) for reducing the total emission. Along with: 1) enhancements of Climate-Smart Agriculture (CSA), and 2) application of management practices that reduces soil organic matter decomposition rates.

All in all, our work come along with the new National Climate Change Strategy NCCS-2 action plan of Hungary, especially with NDR and CAP.

8. SUMMAY

Climate change is one of the challenges humanities needs to cope with by reducing GHGs emissions from different sectors to preserve the earth from the gradual increase of surface temperature. In this aspect, this research aimed to analyse GHG emissions in the EU countries, focusing on Hungary, and track the evolution of drought in Hungary between 1960 and 2010 as one of the consequences of a global increase in GHGs emissions. This research also addressed the impact of climate conditions (Debrecen vs. Tehran) and agricultural practice (Tillage vs. Non-tillage) on Soil carbon dioxide emissions. Available data were collected from different sources. Some analyses such as SPI-3, -6, -12 timescale; SPEI-3, -6, -12 timescales, TDD, M-K, $\mathrm{SYRS}_{c,r,y,t}$, **,** and LSD were applied to fulfil the study output.

The results showed a remarkable decrease in GHGs emissions from agricultural and industrial sectors in most EU countries. The most significant ($p< 0.05$) reduction from the agricultural sector was noticed in the Netherlands (-336.4756 thousand tonnes of CO_2 equivalent). By employing the M-K test, results showed that most sectors witnessed a significant reduction in CO_2 emissions between 1985 and 2016, except for biomass emissions (i.e. agriculture) and the transportation sector. This study also highlighted the direct impact of drought events on maize and wheat yield on a subregional scale. Hungary's southern and central parts are the most affected regions in maize and wheat yield reduction. Notably, the drought impact was worse when we used the SPEI index. Interestingly, this research reveals that climate conditions (Debrecen vs. Tehran) and agricultural practice (Tillage vs. Non-tillage) significantly impact CO_2 emission from agricultural soil.

Overall, this study presents new insights about GHGs trend in Hungary and the direct impact of climate change on crop production.

Key words: Climate change, GHG emissions, Drought, Hungary.

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10. PUBLICATION LIST

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Candidate: Safwan Mohammed
Doctoral School: Kálmán Kerpely Doctoral School
MTMT ID: 10065524

List of publications related to the dissertation

Foreign language scientific articles in Hungarian journals (1)

1. **Mohammed, S.**, Harsányi, E.: Drought cycle tracking in Hungary using Standardized Precipitation Index (SPI).
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3. **Mohammed, S.**, Alsafadi, K., Ali, H., Mousavi, S. M. N., Kiwan, S., Hennawi, S., Harsányi, E., Pham, Q. B., Linh, N. T. T., Ali, R., Anh, D. T., Thai, V. N.: Assessment of Land Suitability Potentials for Winter Wheat Cultivation by Using a Multi Criteria Decision Support-Geographic Information System (MCDS-GIS) approach in Al-Yarmouk Basin (S Syria).
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11. **Mohammed, S.**, Alsafadi, K., Mousavi, S. M. N., Harsányi, E.: Drought Trends in Syria from 1900 to 2015.
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13. Mousavi, S. M. N., **Mohammed, S.**, Nagy, J.: Study Impacts of Drought Waves on Agricultural from 1991 to 2015 in Iran.
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16. **Mohammed, S.**, Khallouf, A., Kiwan, S., Alhenawi, S., Ali, H., Harsányi, E., Kátai, J., Habib, H.: Characterization of Major Soil Orders in Syria.
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Reg Sci Policy Pract. 12 (3), 519-537, 2019. ISSN: 1757-7802.
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24. Mousavi, S. M. N., Bramdeo, K., **Mohammed, S.**, Nagy, J.: Studying the relationships of various agronomic traits in maize using correlation analysis.
In: Abstract book 18th Alps-Adria Scientific Workshop. Ed.: Zoltán Kende, Csaba Bálint, Viola Kunos, Szent István Egyetemi Kiadó Nonprofit Kft., Gödöllő, 116-117, 2019. ISBN: 9789632698182

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    In: 1st Young Researchers' Conference - Erosion and Torrent Control ETC 2018, Belgrade University, Belgrade, 1, 2018. ISBN: 9788672992823

Total IF of journals (all publications): 22,48
Total IF of journals (publications related to the dissertation): 13,799

The Candidate's publication data submitted to the iDEa Tudóstér have been validated by DEENK on the basis of the Journal Citation Report (Impact Factor) database.

07 January, 2021

11. DECLARATION

I prepared this dissertation within the framework of Kálmán Kerpely doctoral school of the University of Debrecen, in order to obtain a doctoral (PhD) degree from the University of Debrecen.

Debrecen, 20 …………………….

....

signature of the candidate

DECLARATION

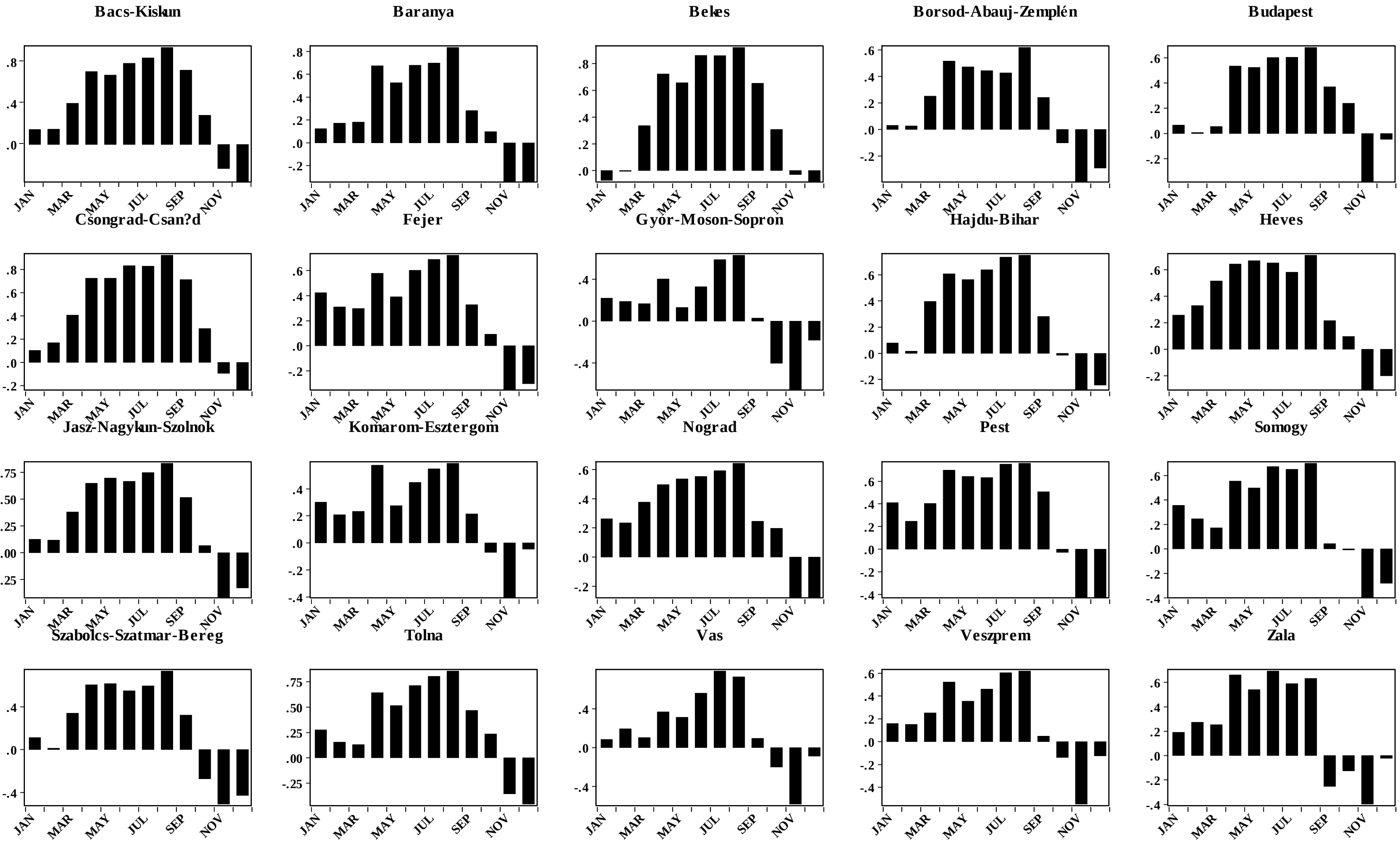
I certify that Safwan Mohammed; a doctoral candidate between 2017-2021, and within the framework of the above-mentioned doctoral school, has carried out his work under my guidance / direction. The independent contribution of the candidate to the results included in the dissertation, the dissertation is the independent work of the candidate. I suggest / recommend the acceptance of the dissertation.

Debrecen, 20 ………………………… ..

....

signature of the supervisor (s)

12. LIST OF APPENDICES



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Komarom-Esztergom

Nograd

Pest

Somogy

Szabolcs-Szatmar-Bereg

Tolna

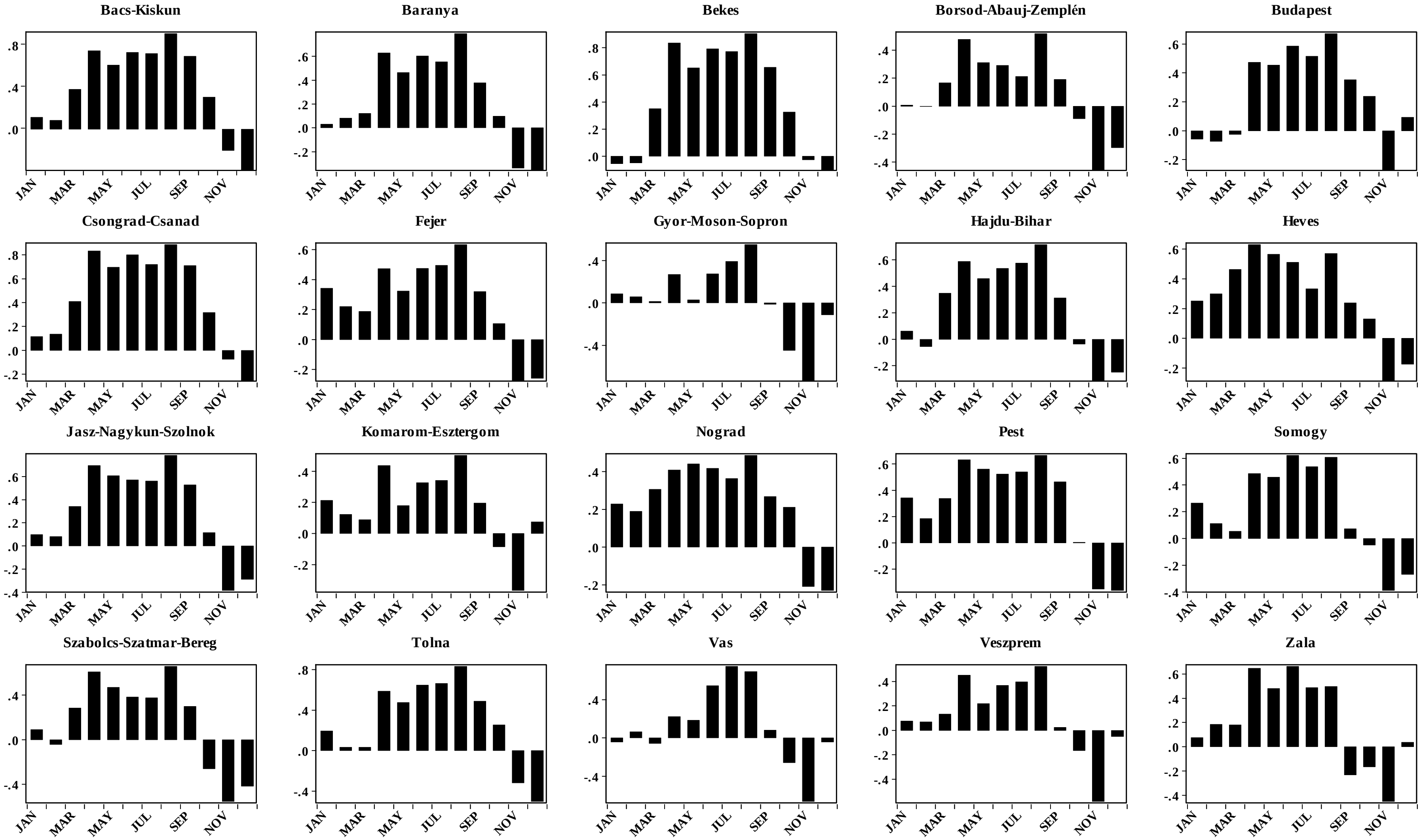
Vas

Veszprem

Zala

13.

Appendix 1. Correlation between SPEI-3 and SYRS between 2000-2010 for all regions in Hungary for maize



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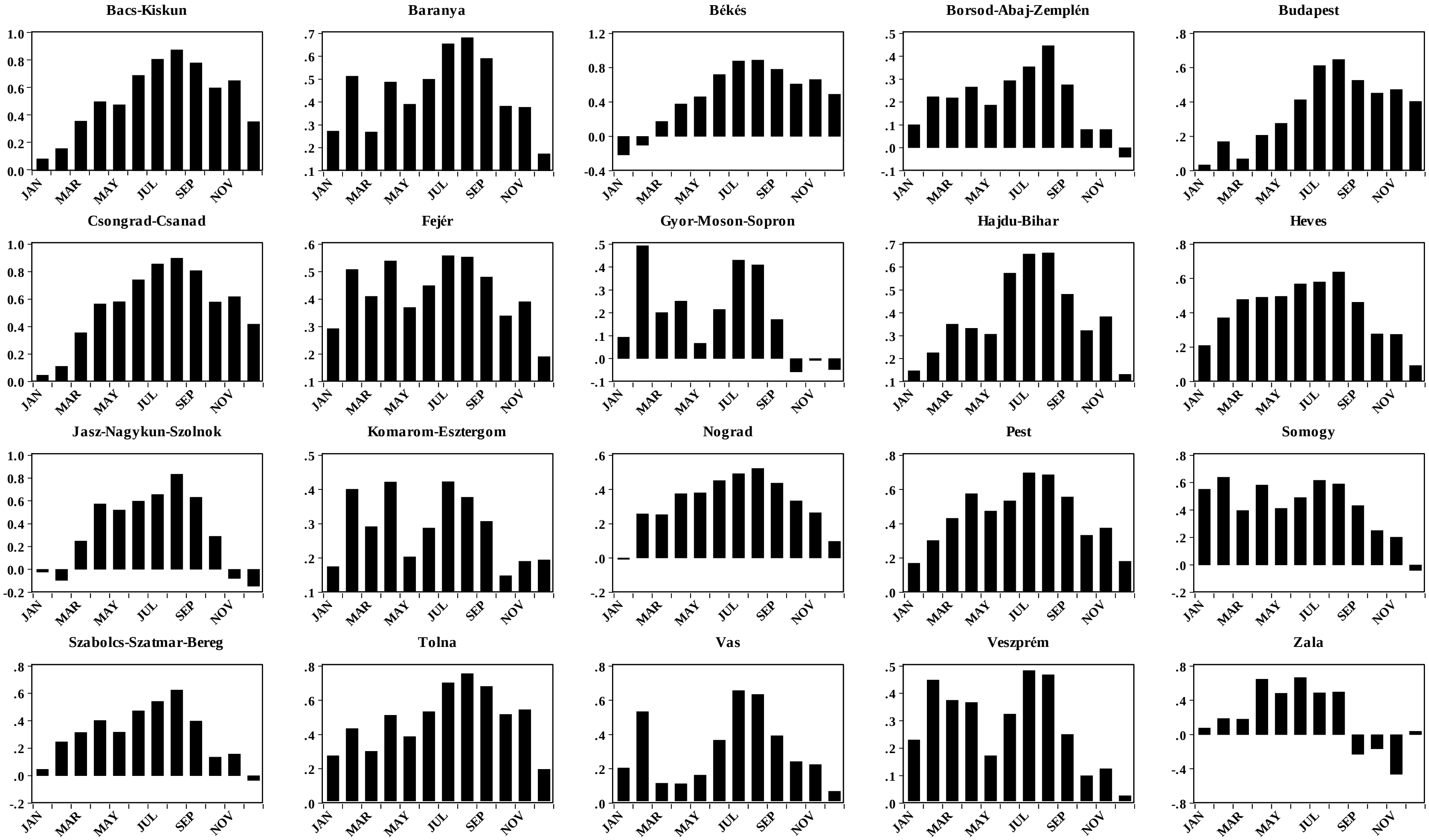

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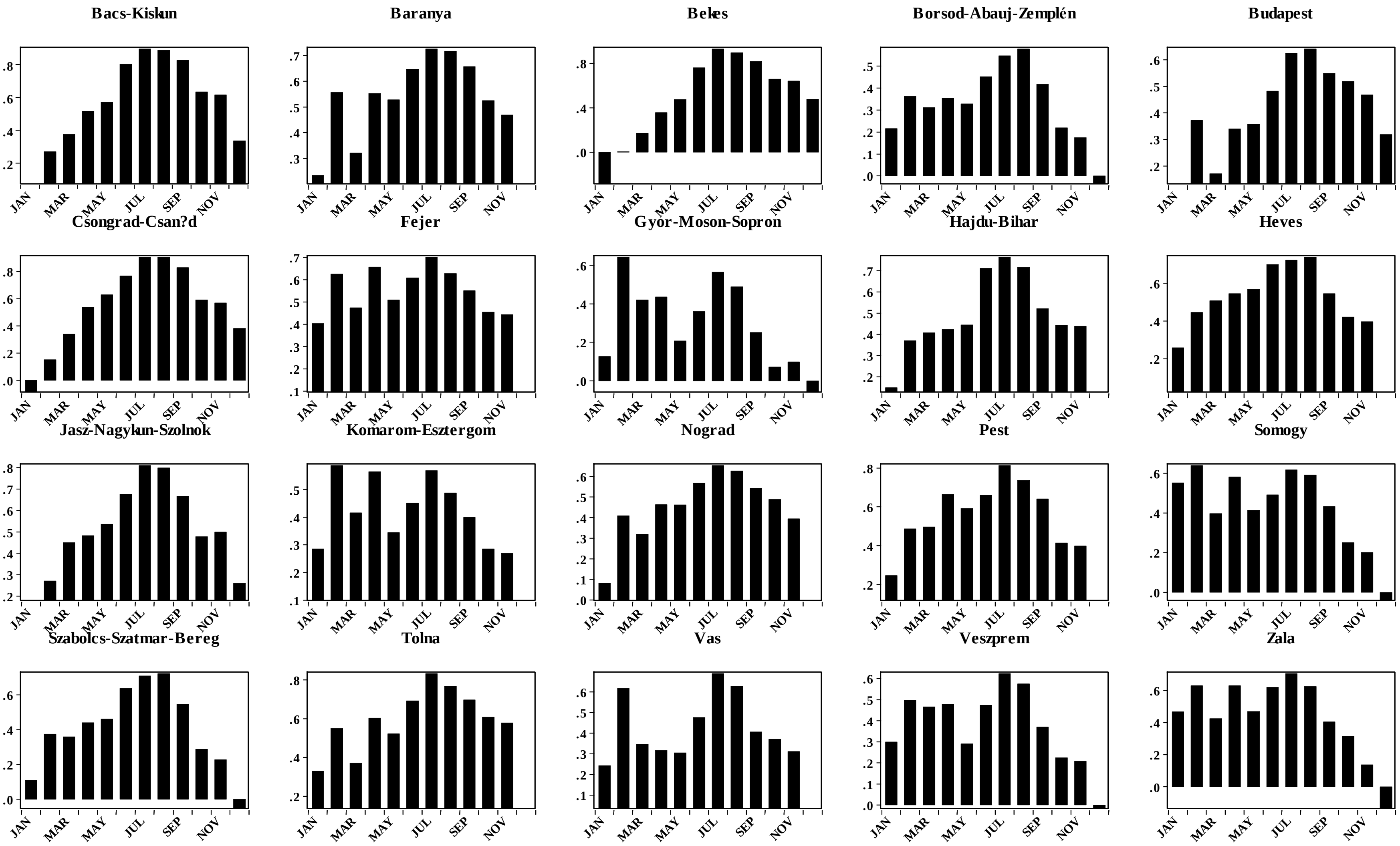

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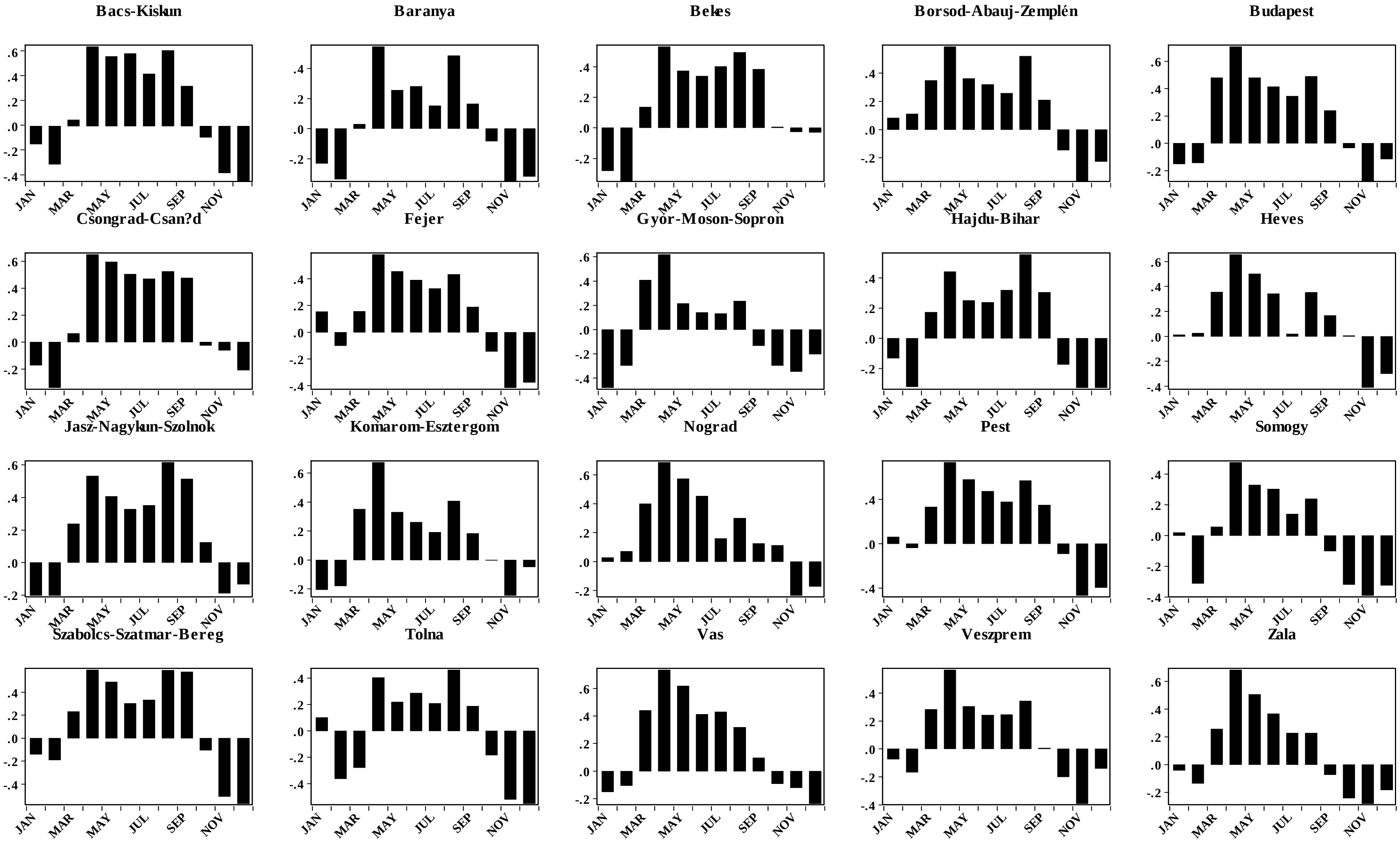

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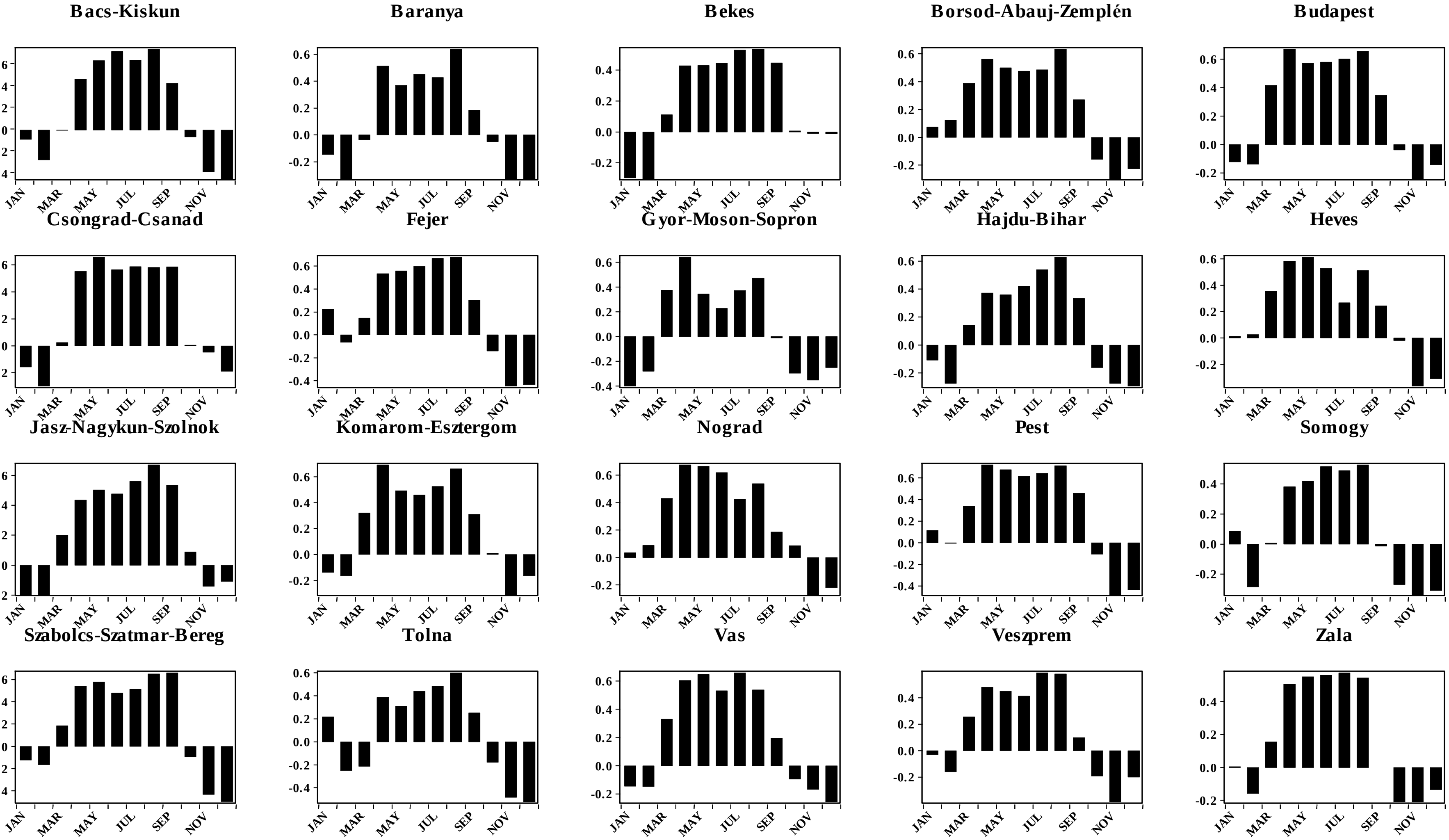
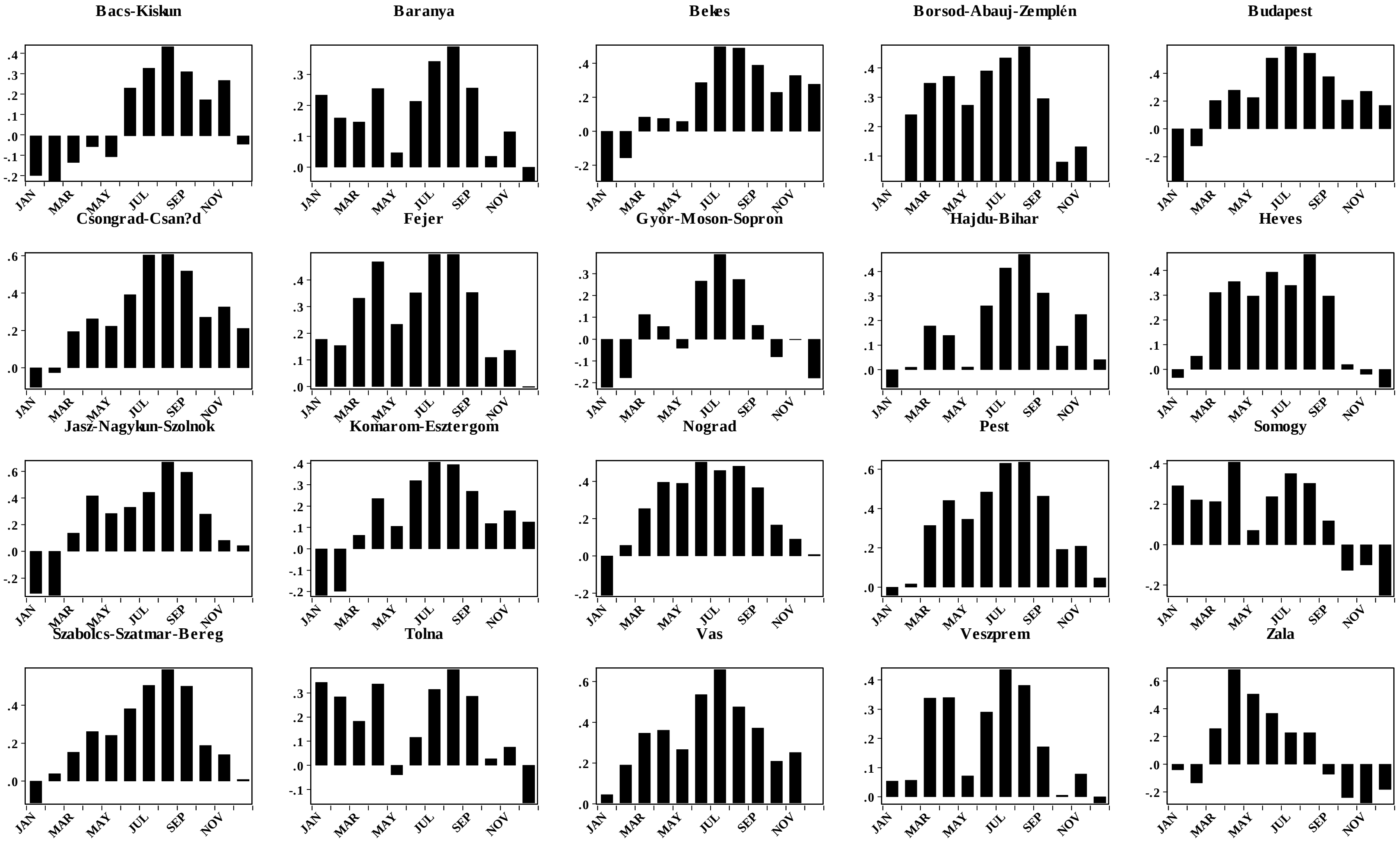
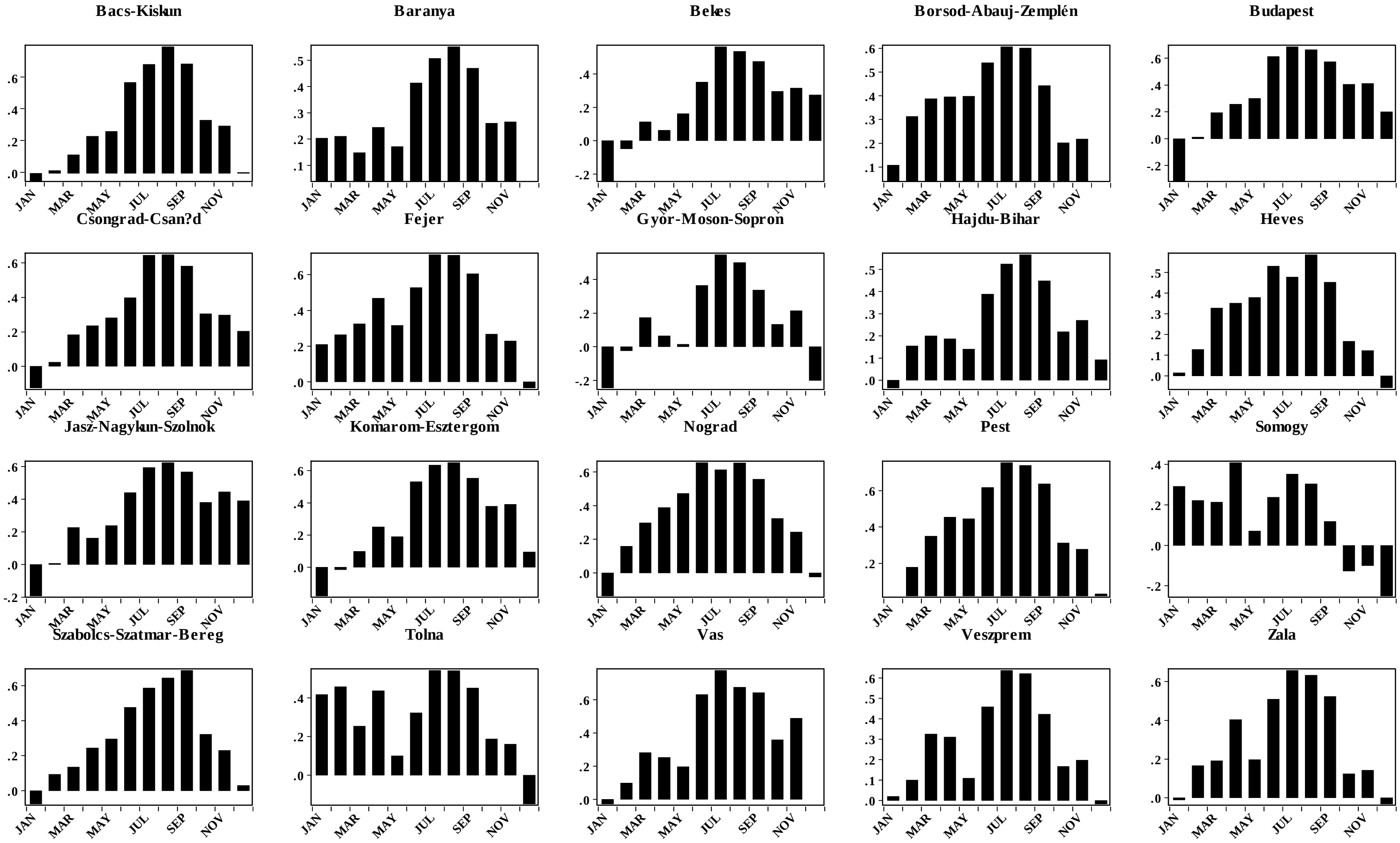


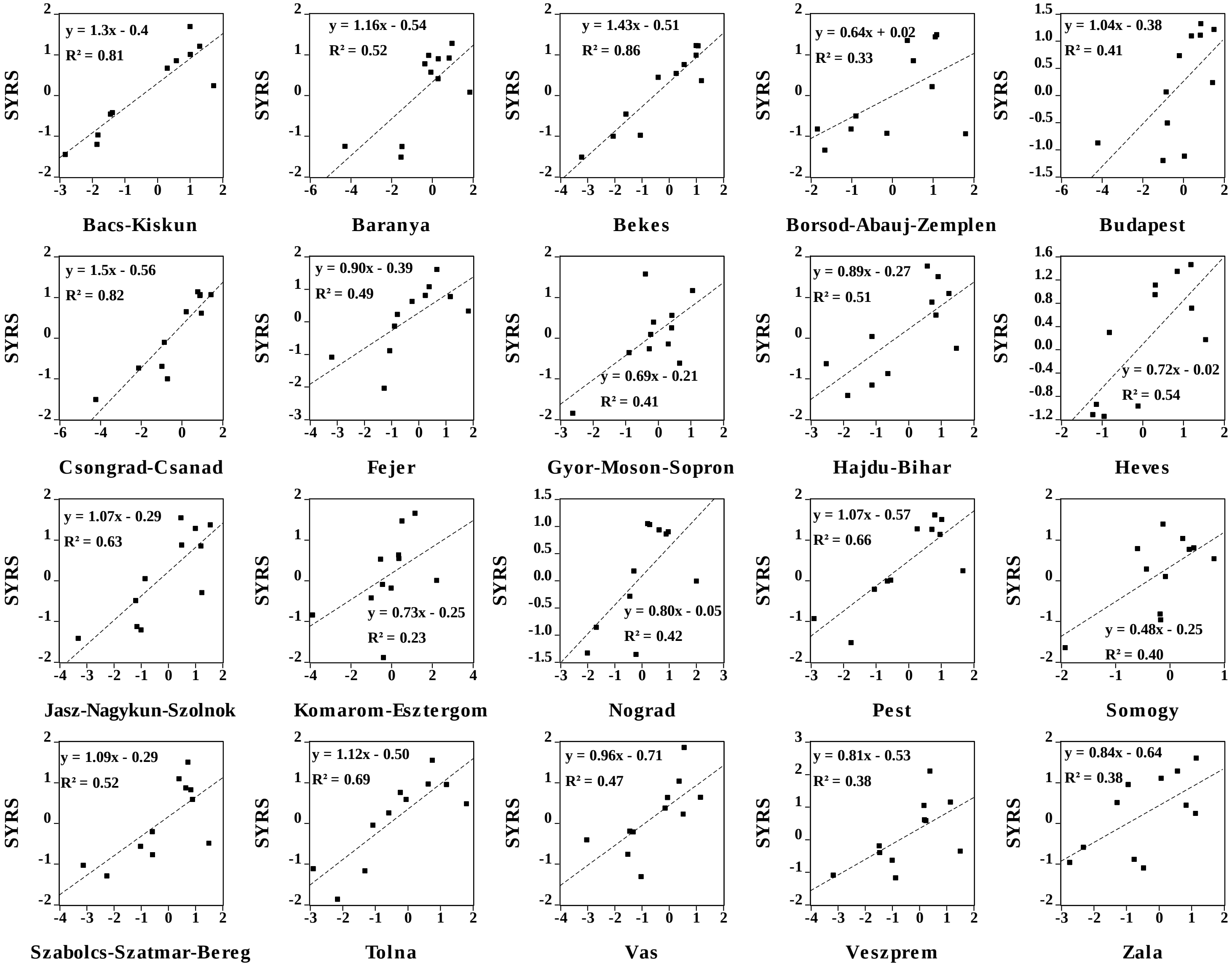
Appendix 6. Correlation between SPEI-3 and SYRS between 2000-2010 for all regions in Hungary for wheat



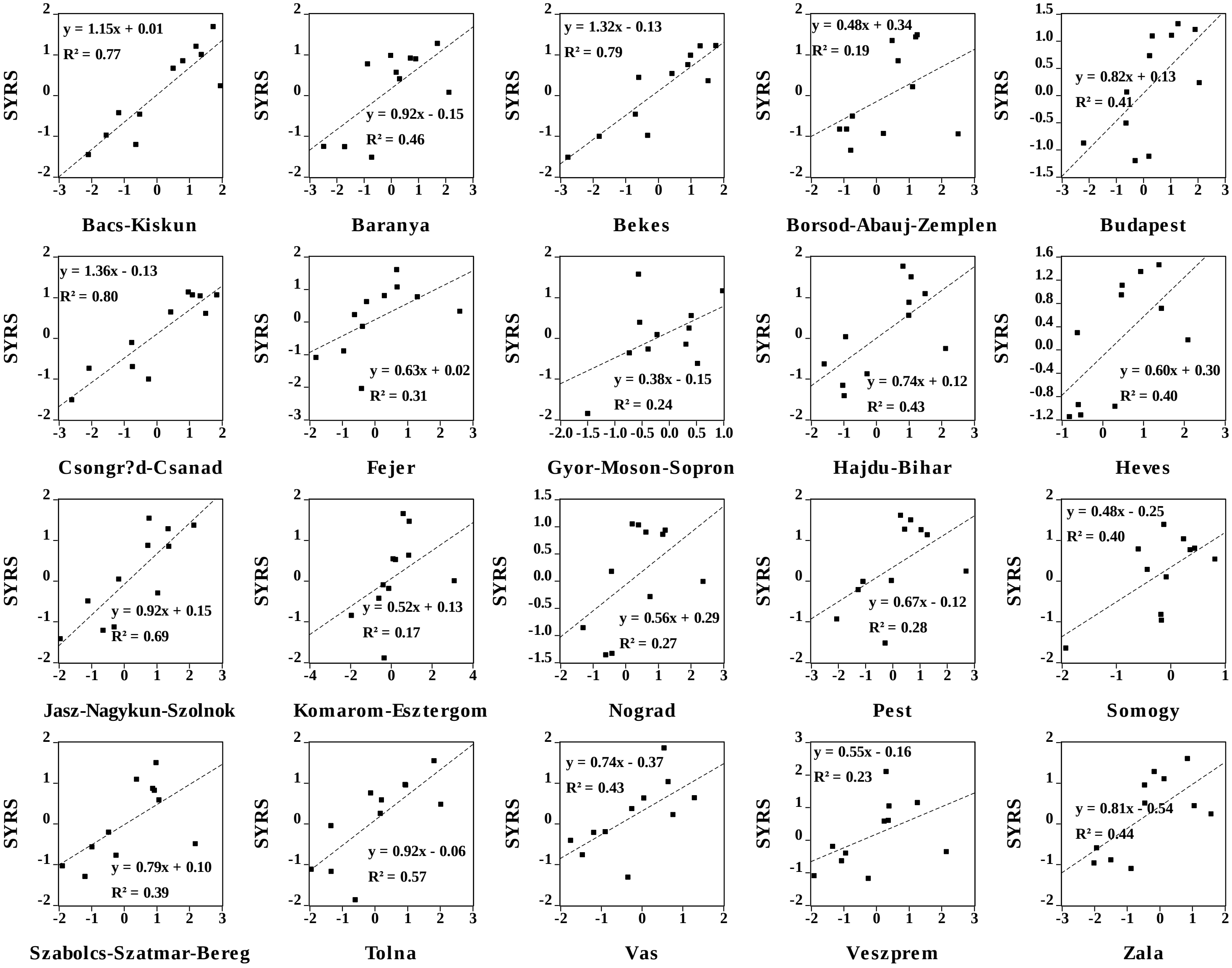
Appendix 7. Correlation between SPI-6 and SYRS between 2000-2010 for all regions in Hungary for wheat



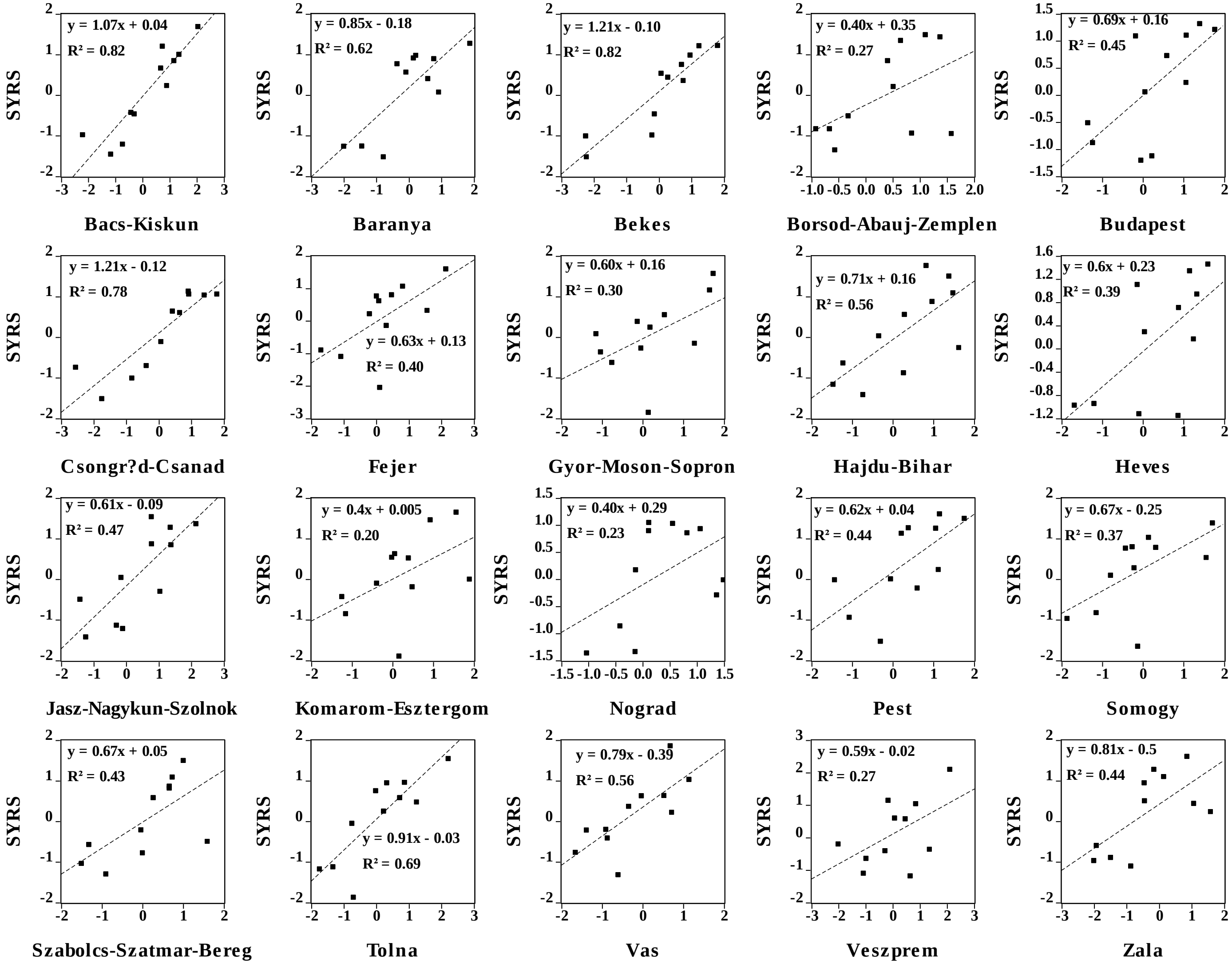
Appendix 8. Correlation between SPEI-6 and SYRS between 2000-2010 for all regions in Hungary for wheat



Appendix 9. Highest correlation between SPEI-6 and maize-SYRS between 2000-2010 for all regions in Hungary



Appendix 10. Highest correlation between SPI-6 and maize-SYRS between 2000-2010 for all regions in Hungary



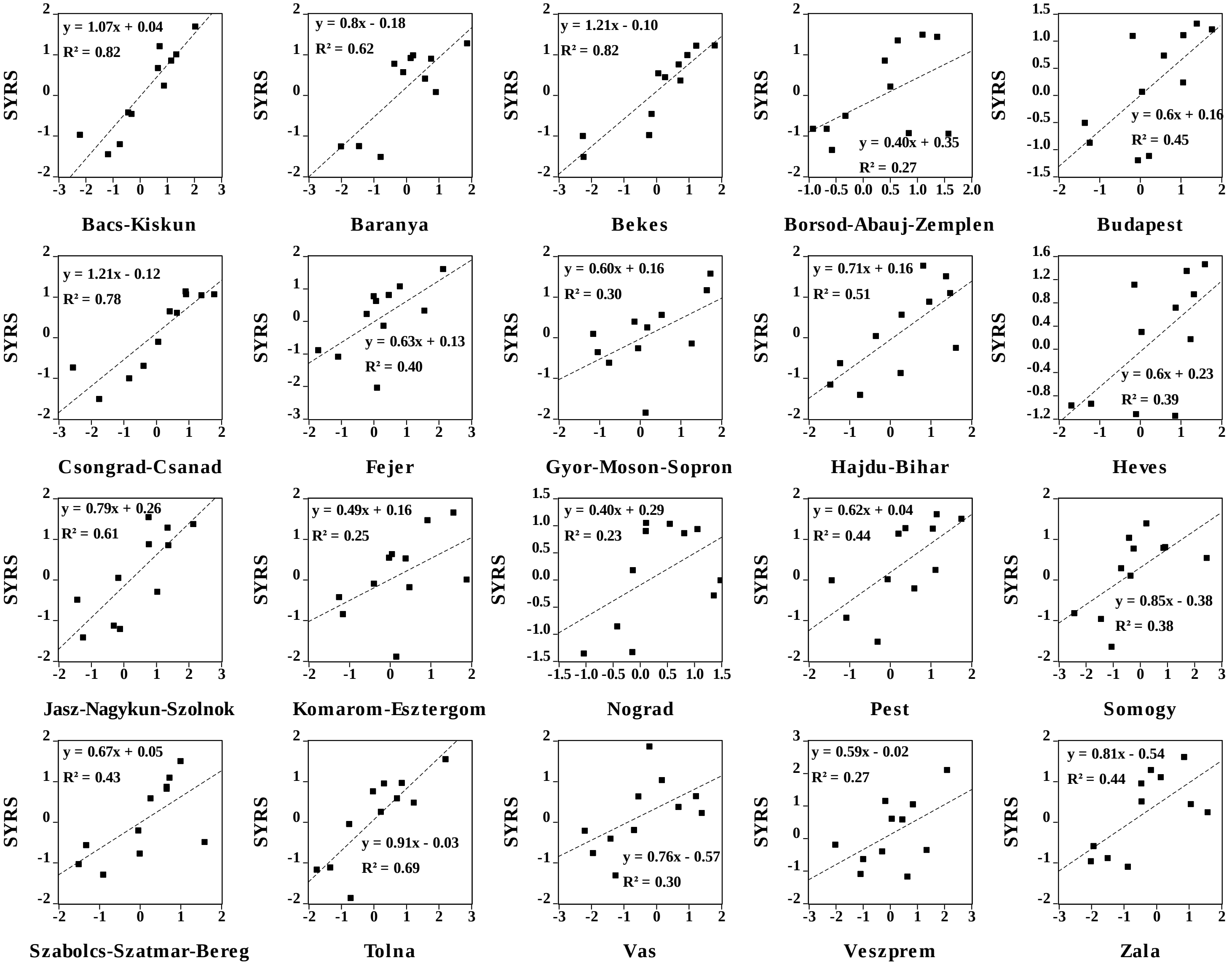
Bacs-Kiskun Baranya Bekes Borsod-Abauj-Zemplen Budapest

Csongr?d-Csanad Fejer Gyor-Moson-Sopron Hajdu-Bihar Heves

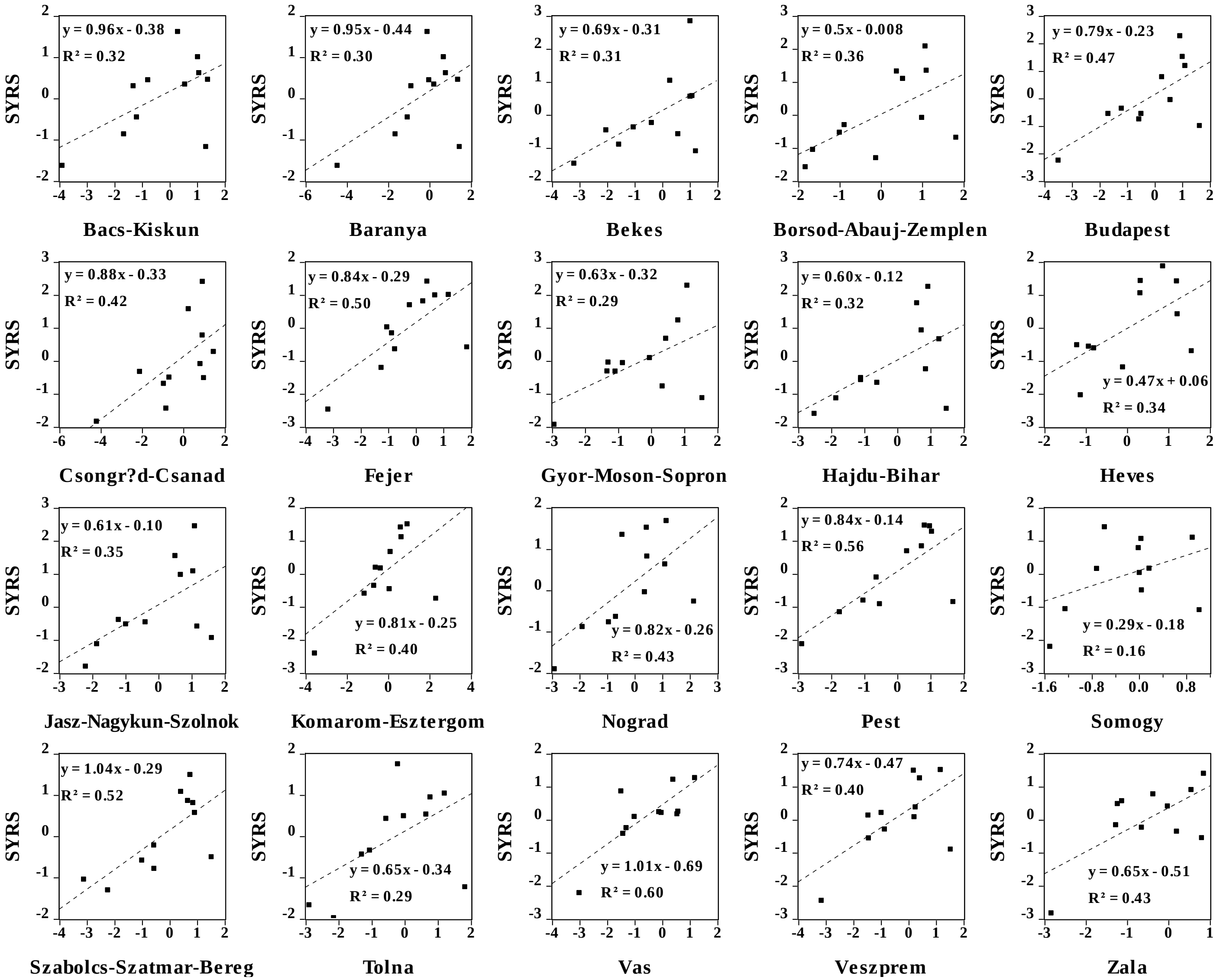
Jasz-Nagykun-Szolnok Komarom-Esztergom Nograd Pest Somogy

Szabolcs-Szatmar-Bereg Tolna Vas Veszprem Zala

Appendix 11. Highest correlation between SPEI-3 and maize-SYRS between 2000-2010 for all regions in Hungary



Appendix 12. Highest correlation between SPI-3 and maize-SYRS between 2000-2010 for all regions in Hungary



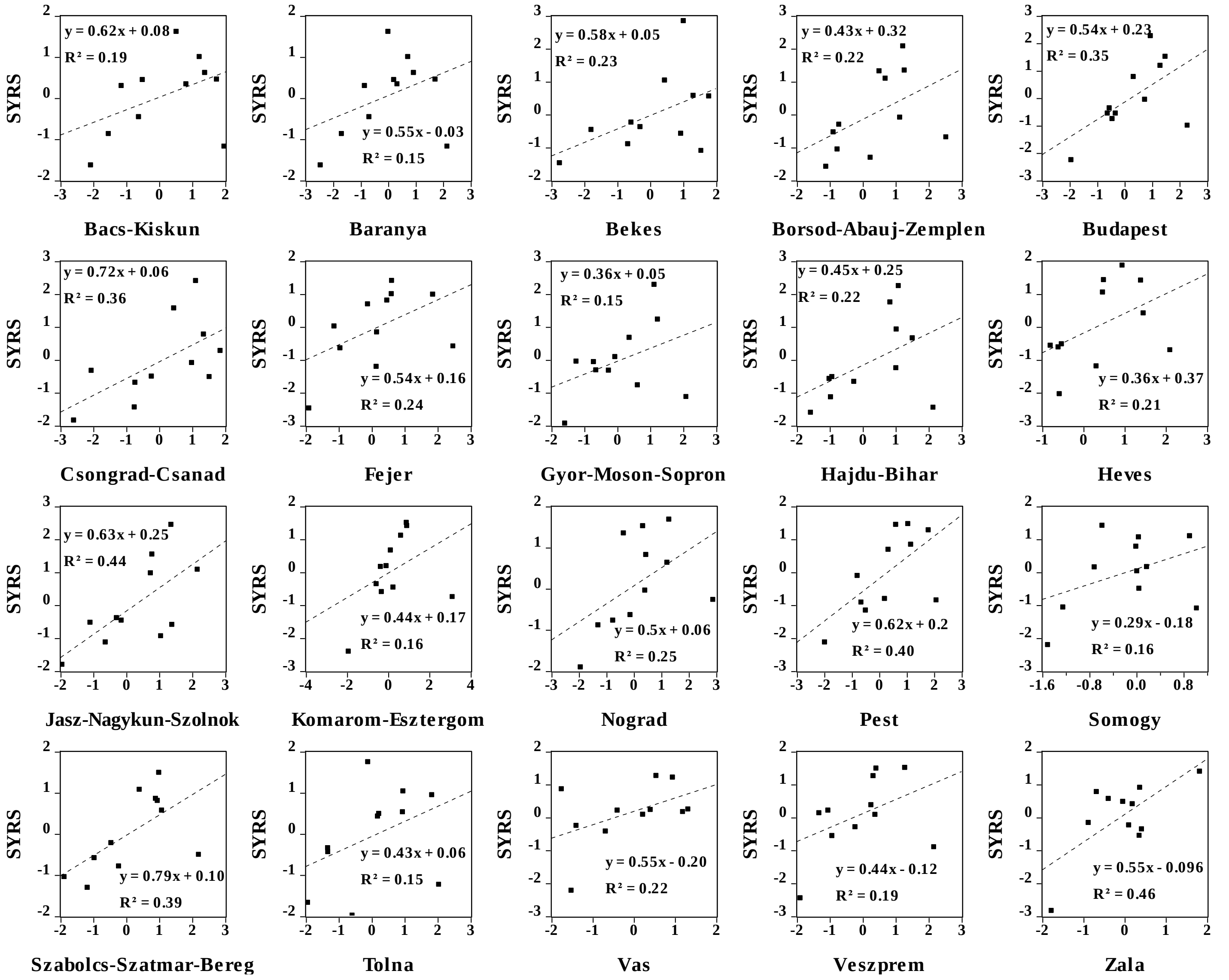
Bacs-Kiskun Baranya Bekes Borsod-Abauj-Zemplen Budapest

Csongr?d-Csanad Fejer Gyor-Moson-Sopron Hajdu-Bihar Heves

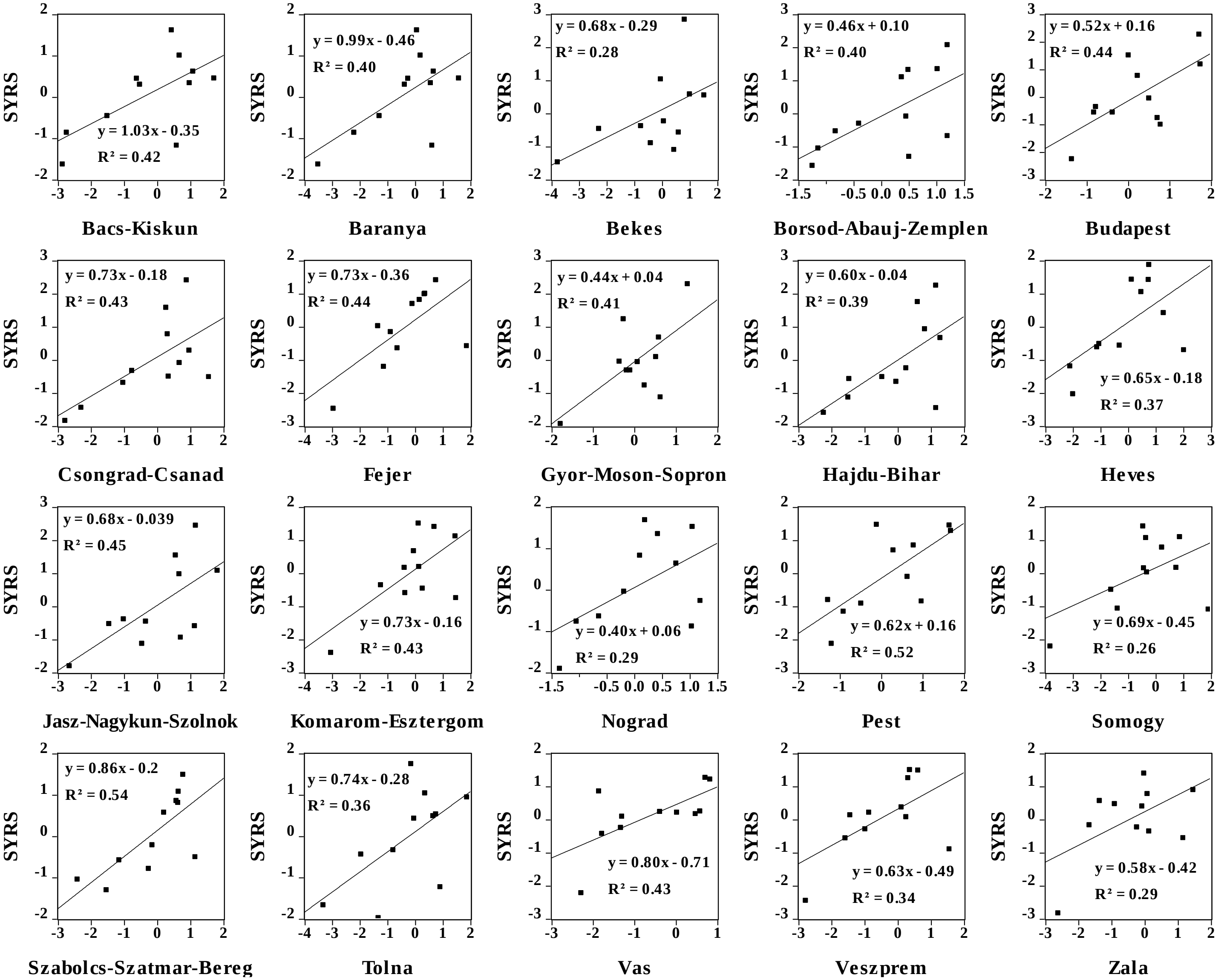
Jasz-Nagykun-Szolnok Komarom-Esztergom Nograd Pest Somogy

Szabolcs-Szatmar-Bereg Tolna Vas Veszprem Zala

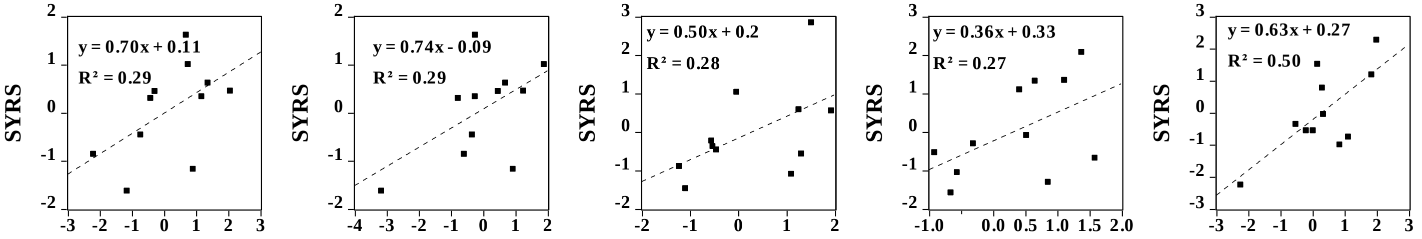
Appendix 13. Highest correlation between SPEI-6 and wheat-SYRS between 2000-2010 for all regions in Hungary



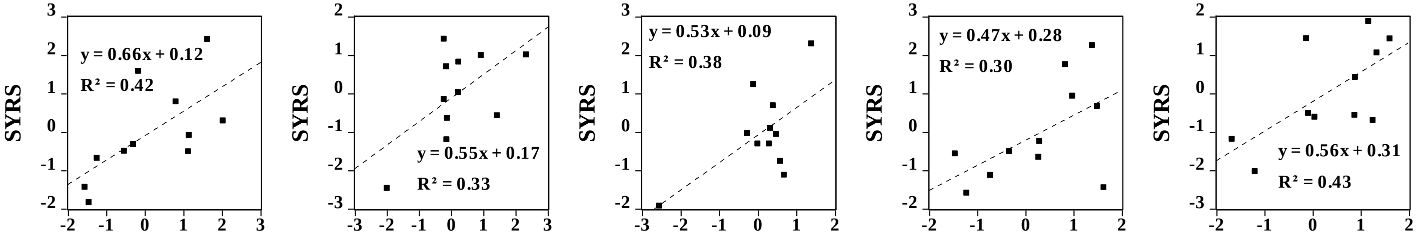
Appendix 14. Highest correlation between SPI-6 and wheat-SYRS between 2000-2010 for all regions in Hungary



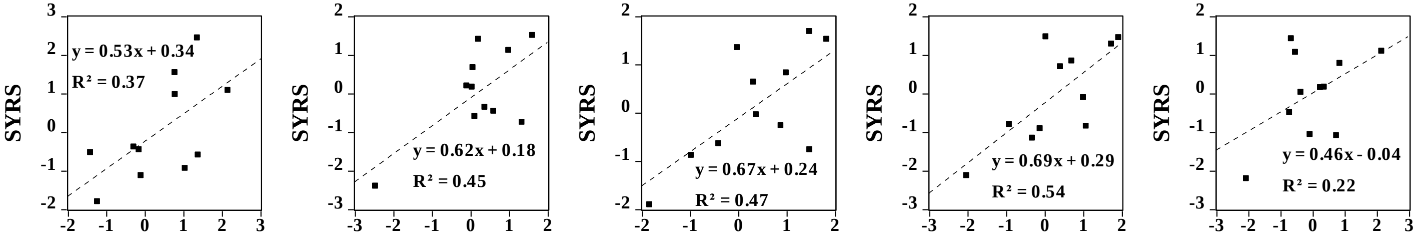
Appendix 15. Highest correlation between SPEI-3 and wheat-SYRS between 2000-2010 for all regions in Hungary



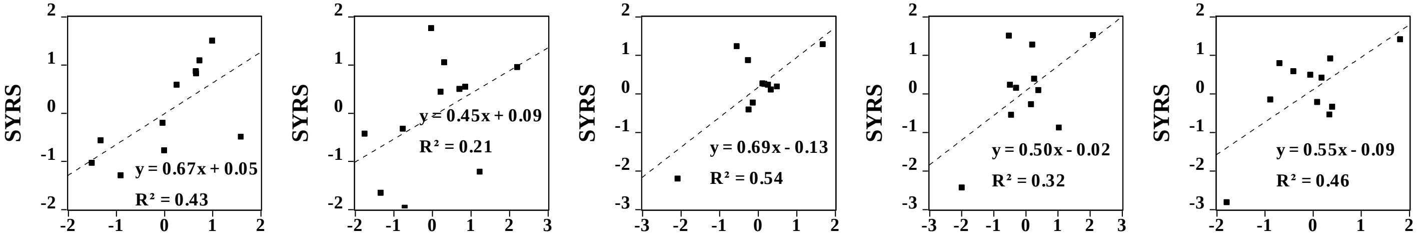
Bacs-Kiskun Baranya Bekes Borsod-Abauj-Zemplen Budapest



Csongrad-Csanad Fejer Gyor-Moson-Sopron Hajdu-Bihar Heves



Jasz-Nagykun-Szolnok Komarom-Esztergom Nograd Pest Somogy



Szabolcs-Szatmar-Bereg Tolna Vas Veszprem Zala

Appendix 16. Highest correlation between SPI-3 and wheat-SYRS between 2000-2010 for all regions in Hungary